AUSTENITIC CHROMIUM-NICKEL STAINLESS STEELS AT SUBZERO TEMPERATURES — MECHANICAL AND PHYSICAL PROPERTIES

A PRACTICAL GUIDE TO THE USE OF NICKEL-CONTAINING ALLOYS

Nº 313

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AISI and ACI Standard Composition Ranges for Wrought and Cast Chromium-Nickel Stainless Steels

American Iron and Steel Institute Classification of Chromium-Nickel Stainless Steels

AISI Type	Composition, %								
	C max	Mn max	p max	S max	Si max	Cr	NI	Mo	Other
201	0.15	5.50-7.50	.060	.030	1.00	16.00-18.00	3.50-5.50	-	N 0.25 max
202	0.15	7.50-10.00	.060	.030	1.00	17.00-19.00	4.00-6.00	-	N 0.25 max
301	0.15	2.00	.D45	.030	1.00	16.00-18.00	6.00-8.00	-	-
302	0.15	2.00	.045	.030	1.00	17.00-19.00	8.00-10.00	-	-
302B	0.15	2.00	.045	.030	2.00-3.00	17.00-19.00	8.00-10.00	-	-
303	0.15	2.00	0.20	0.15 min	1.00	17.00-19.00	8.00-10.00	0.60 max	-
303Se	0.15	2.00	0.20	.06	1.00	17.00-19.00	8.00-10.00	-	Se 0.15 min
304	.08	2.00	.045	.030	1.00	18.00-20.00	8.00-12.00	-	-
304L	.03	2.00	.045	.030	1.00	18.00-20.00	8.00-12.00	-	-
305	0.12	2.00	.045	.030	1.00	17.00-19.00	10.00-13.00	-	-
308	.08	2.00	.045	.030	1.00	19.00-21.00	10.00-12.00	-	-
309	0.20	2.00	.045	.030	1.00	22.00-24.00	12.00-15.00	-	-
309S	.08	2.00	.045	.030	1.00	22.00-24.00	12.00-15.00	-	-
310	0.25	2.00	.045	.030	1.50	24.00-26.00	19.00-22.00	-	-
310S	.08	2.00	.045	.030	1.50	24.00-26.00	19.00-22.00	-	-
314	0.25	2.00	.045	.030	1.50-3.00	23.00-26.00	19.00-22.00	-	-
316	.08	2.00	.045	.030	1.00	16.00-18.00	10.00-14.00	2.00-3.00	-
316L	.03	2.00	.045	.030	1.00	16.00-18.00	10.00-14.00	2.00-3.00	-
317	.08	2.00	.045	.030	1.00	18.00-20.00	11.00-15.00	3.00-4.00	-
D319	.07	2.00	.045	.030	1.00	17.50-19.50	11.00-15.00	2.25-3.00	-
321	.08	2.00	.045	.030	1.00	17.00-19.00	9.00-12.00	-	Ti 5 x C min
347	.08	2.00	.045	.030	1.00	17.00-19.00	9.00-13.00	-	Cb-Ta 10 x C min
348	.08	2.00	.045	.030	1.00	17.00-19.00	9.00-13.00	-	Cb-Ta 10 x C min; Ta 0.10 max; Co 0.20 max
384	.08	2.00	.045	.030	1.00	15.00-17.00	17.00-19.00	-	-
385	.08	2.00	.045	.030	1.00	11.50-13.50	14.00-16.00	-	-

Alloy Casting Institute Division (SFSA) Classification of Chromium-Nickel Stainless Steel Castings

Cast Alloy Designation	Wrought Alloy Type[1]	Composition, %								
		C max	Mn max	p max	S max	Si max	Cr	Ni	Mo	Other
CA-6NM	-	.06	1.00	.04	.04	1.00	11.5-14	3.5-4.5	0.40-1.0	-
CD-4MCu	-	.04	1.00	.04	.04	1.00	25-26.5	4.75-6.00	1.75-2.25	Cu 2.75-3.25
CE-30	-	0.30	1.50	.04	.04	2.00	26-30	8-11	-	-
CF-3	304L	.03	1.50	.04	.04	2.00	17-21	8-12	-	-
CF-8	304	.08	1.50	.04	.04	2.00	18-21	8-11	-	-
CF-20	302	0.20	1.50	.04	.04	2.00	18-21	8-11	-	-
CF-3M	316L	.03	1.50	.04	.04	1.50	17-21	9-13	2.0-3.0	-
CF-8M	316	.08	1.50	.04	.04	1.50	18-21	9-12	2.0-3.0	-
CF-12M	316	0.12	1.50	.04	.04	1.50	18-21	9-12	2.0-3.0	-
CF-SC	347	.08	1.50	.04	.04	2.00	18-21	9-12	-	Cb8xCmin, 1.Omax or Cb-Ta 10 x C min, 1.35 max
CF-16F	303	0.16	1.50	0.17	.04	2.00	18-21	9-12	1.5 max	Se 0.20-0.35
CG-8M	317	.08	1.50	.04	.04	1.50	18-21	9-13	3.0-4.0	-
CH-20	309	0.20	1.50	.04	.04	2.00	22-26	12-15	-	-
CK-20	310	0.20	1.50	.04	.04	2.00	23-27	19-22	-	-
CN-7M	-	.07	1.50	.04	.04	1.50	18-22	27.5-30.5	2.0-3.0	Cu 3-4

1Wrought alloy type numbers are included only for the convenience of those who wish to determine corresponding wrought and cast grades. The chemical composition ranges of the wrought materials differ from those of the cast grades.

Mechanical and Physical Properties of the Austenitic Chromium-Nickel Stainless Steels at Subzero Temperatures

IN general, as the temperature is reduced, the strength and hardness of metals increase, the magnitude depending on the material. However, ductility may or may not decrease markedly. Metals having a face-centered cubic structure, such as nickel and the austenitic stainless steels, remain tough and ductile to very low temperatures whereas metals having a body centered cubic structure, such as iron and the constructional steels, undergo a marked decrease in ductility in some temperature range which varies with the material and the testing conditions.

This bulletin is a compilation of the effects of subzero temperatures on the properties of the chromium-nickel stainless steels. The data have been collected from various sources and are presented in graphical and tabular form. Since low temperature properties are sensitive to variations in composition and treatment, these graphs are merely representative of the properties to be expected.

The Kelvin temperatures, given at the top of the graphs, indicate the boiling points of various liquids and frequently are the temperatures selected for low temperature testing. These temperatures and their Fahrenheit equivalents are listed in the following table:

Environment	Fixed Point	Temperature	
		F	K
Helium	BP	-452	4
Hydrogen	BP	-423	20
Nitrogen	BP	-321	77
Methane	BP	-258	112
Carbon Dioxide	Sublimation	-108	195
Freon 22 (CHCIF2)	BP	- 40	233
Water	MP	32	273

TENSILE PROPERTIES

The tensile strengths of chromium-nickel stainless steels increase markedly with decreasing temperatures; yield strengths also increase but to a lesser degree. There is some reduction in ductility as measured by the elongation and reduction of area. However, the ductility remains sufficiently high to justify the assumption that the austenitic chromium-nickel stainless steels remain ductile to the lowest temperature for which data are available.

The tensile properties of standard grades of chromium-nickel stainless steels, in the annealed and cold worked conditions, are given in Figures 1 to 17, inclusive. Tensile strengths of weldments also increase as shown in Figure 18. Tensile strength of standard cast Type CF-8 is given in Figure 19.

MODULUS OF ELASTICITY

There is a definite increase in the modulus of elasticity with falling temperature although the effect is not so marked as the increase in tensile strength. Data on the modulus of elasticity in tension for several stainless steels are given in Table I.

NOTE: The room temperature moduli of elasticity values reported in Table I are low and should not be used for design purposes. The reader is referred to another bulletin* for more representative values.

*Bulletin I-A: "Mechanical and Physical Properties of Austenitic Chromium-Nickel Steels at Ambient Temperatures."

TABLE I

Effect of Temperature on Young's Modulus of Elasticity of Cold-Worked Stainless Steels

AISI Type	Tenslle Strength at Room Temper!'ture; psi	Modulus of Elasticity (psi) in Tension at	
		Room Temperature	-320 F
301	189,000	25.4 X 106	28.6 X 106
301	231,000	25.8	27.8
302	162,000	26.2	27.2
304	192,000	24.4	26.2
347	155,000	25.0	27.0
347	169,000	23.3	27.6

Krivobok

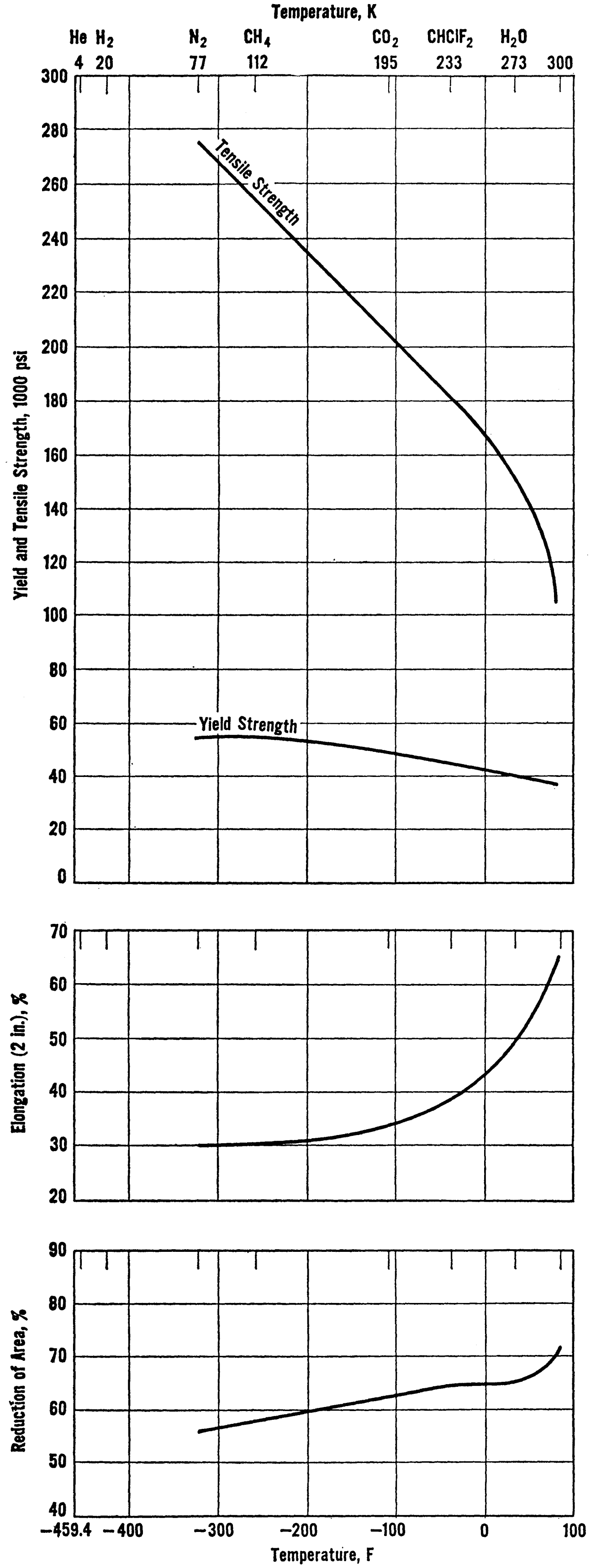

FIG. 1—Tensile properties of annealed Type 301 stainless steel[1, 2, 3]

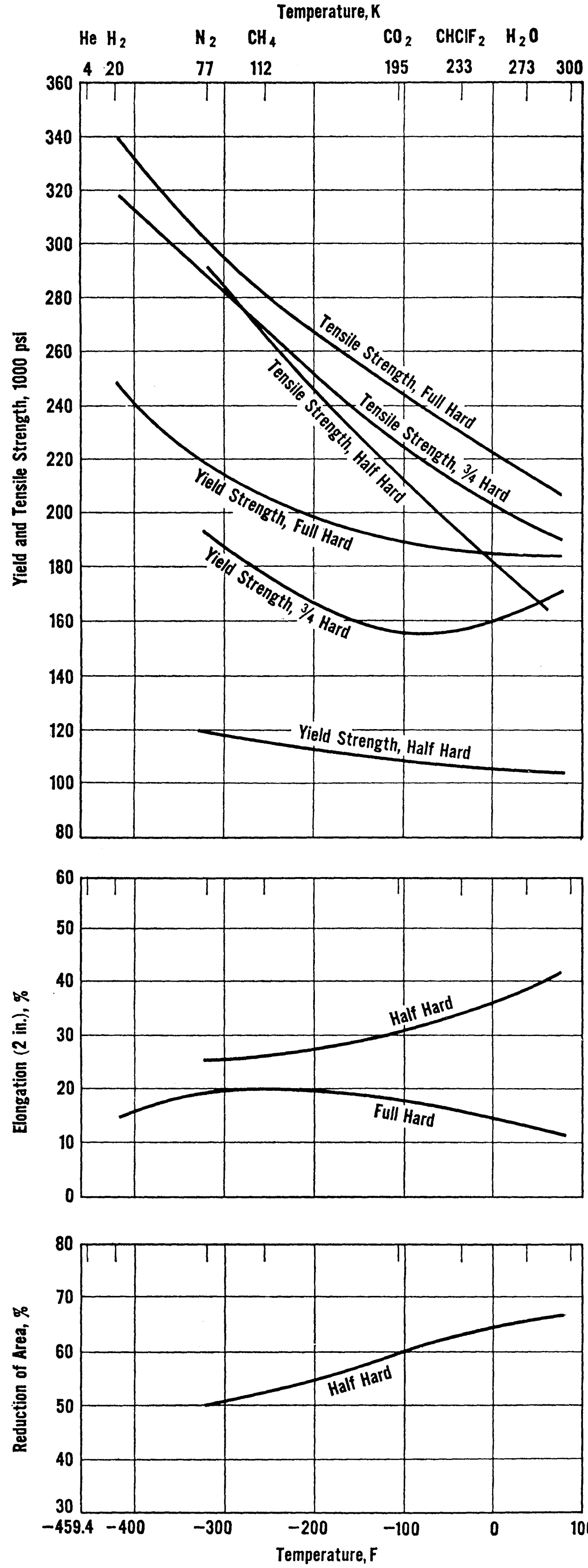

FIG. 2—Tensile properties of cold worked Type 301 stainless steel[1, 2, 3, 39]

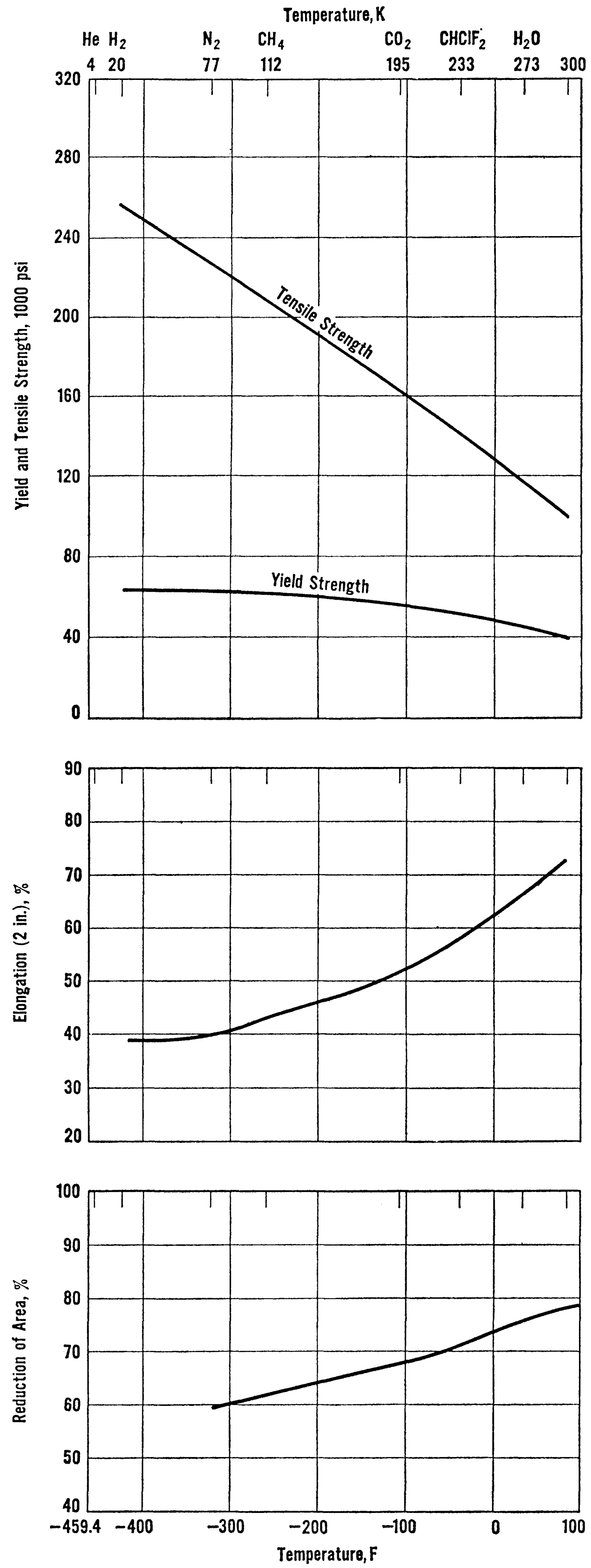

FIG. 3—Tensile properties of annealed Type 302 stainless steel[1,2,3,4]

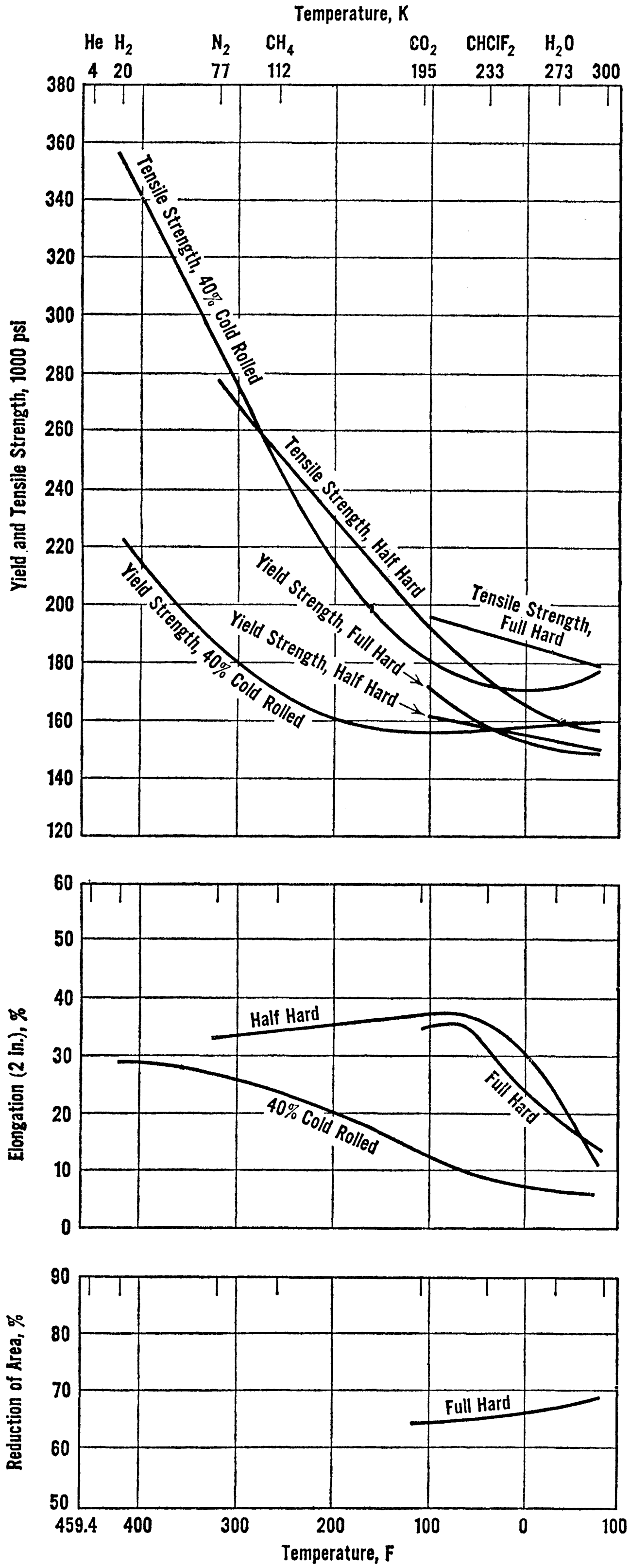

FIG. 4—Tensile properties of cold worked Type 302 stainless steel[2,3,39]

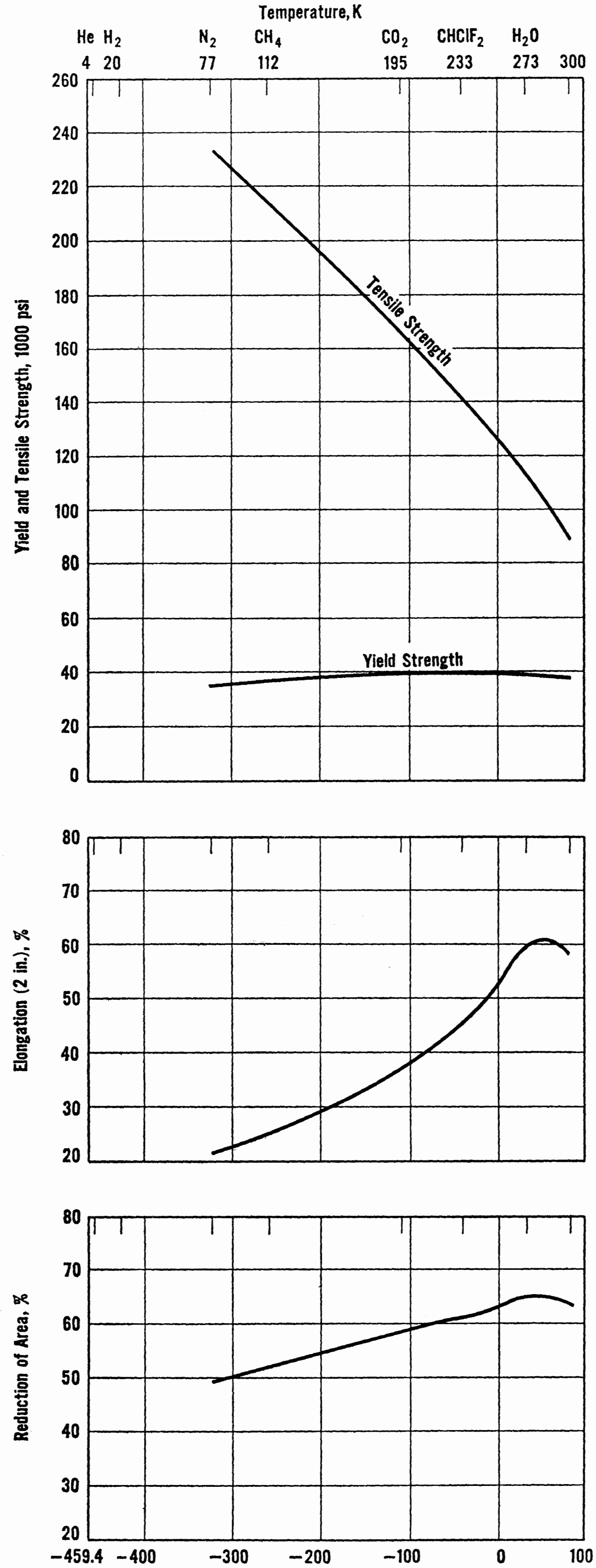

Fig. 5—Tensile properties of annealed Type 303 stainless steel[1]

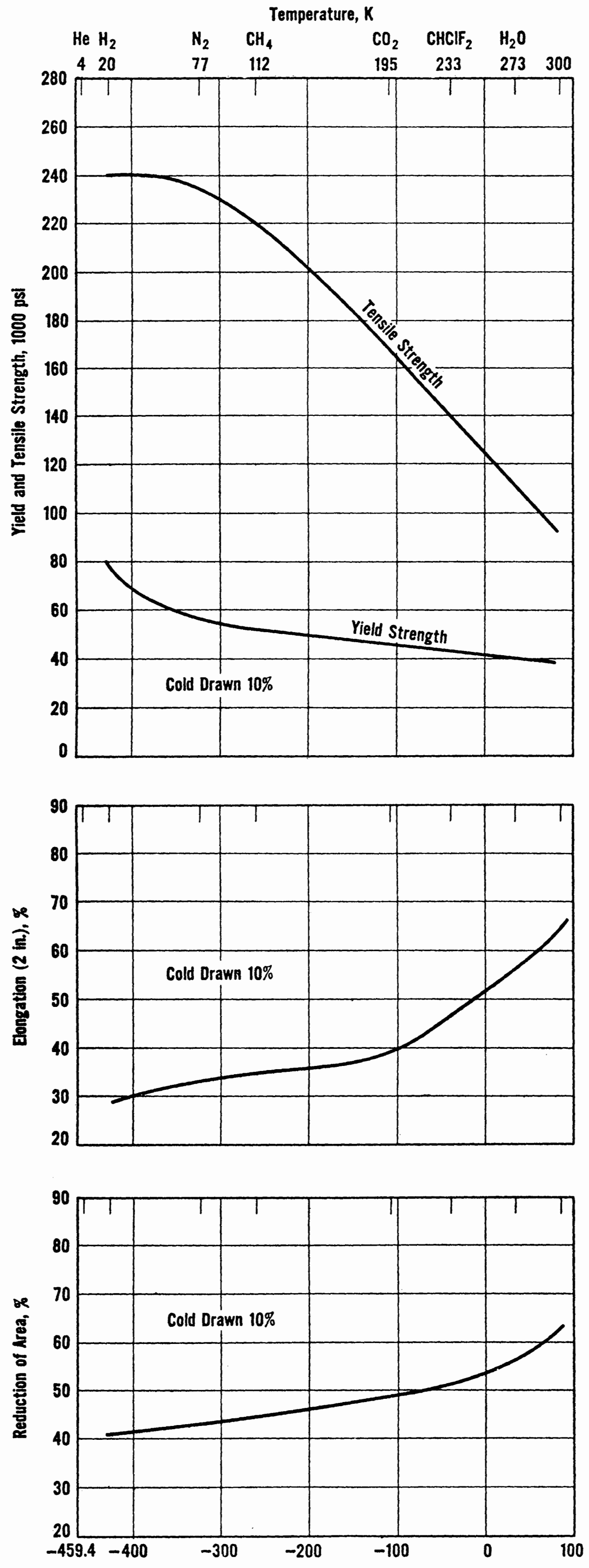

Fig. 6—Tensile properties of cold worked Type 303 stainless steel[5]

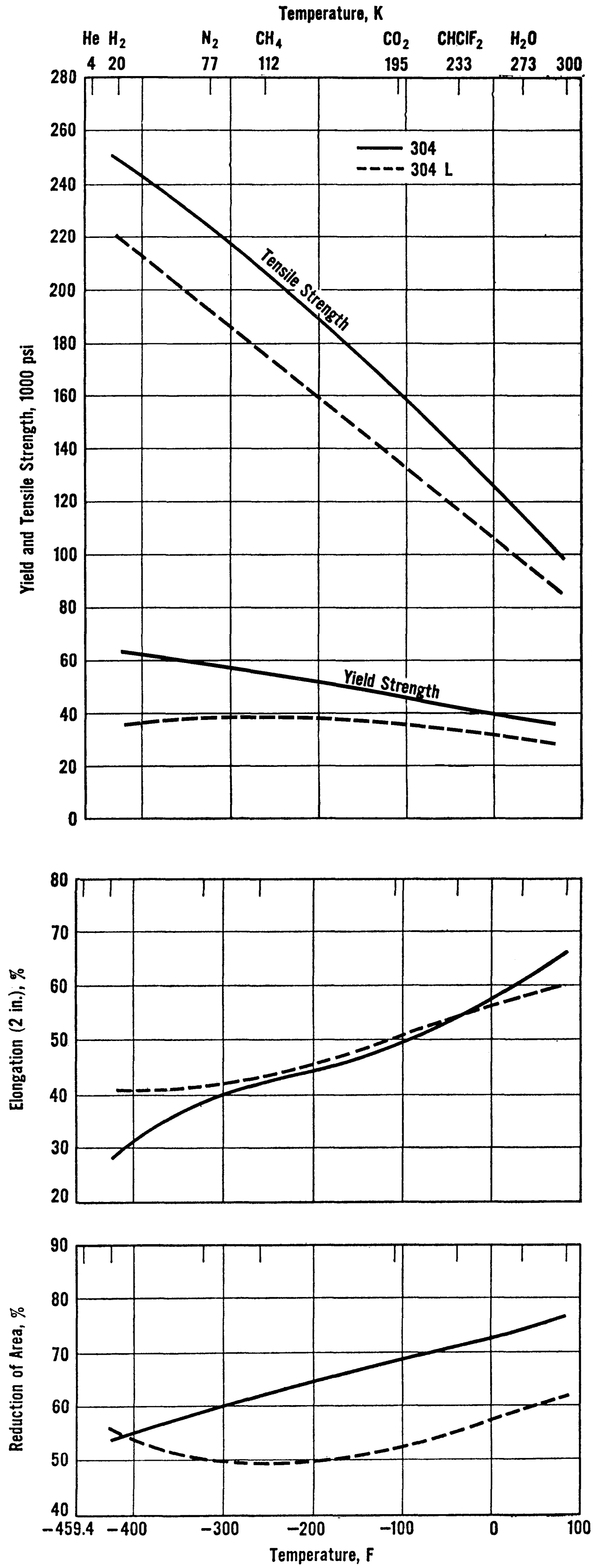

FIG. 7 — Tensile properties of annealed Types 304 and 304L stainless steel[1, 2, 6, 7, 41]

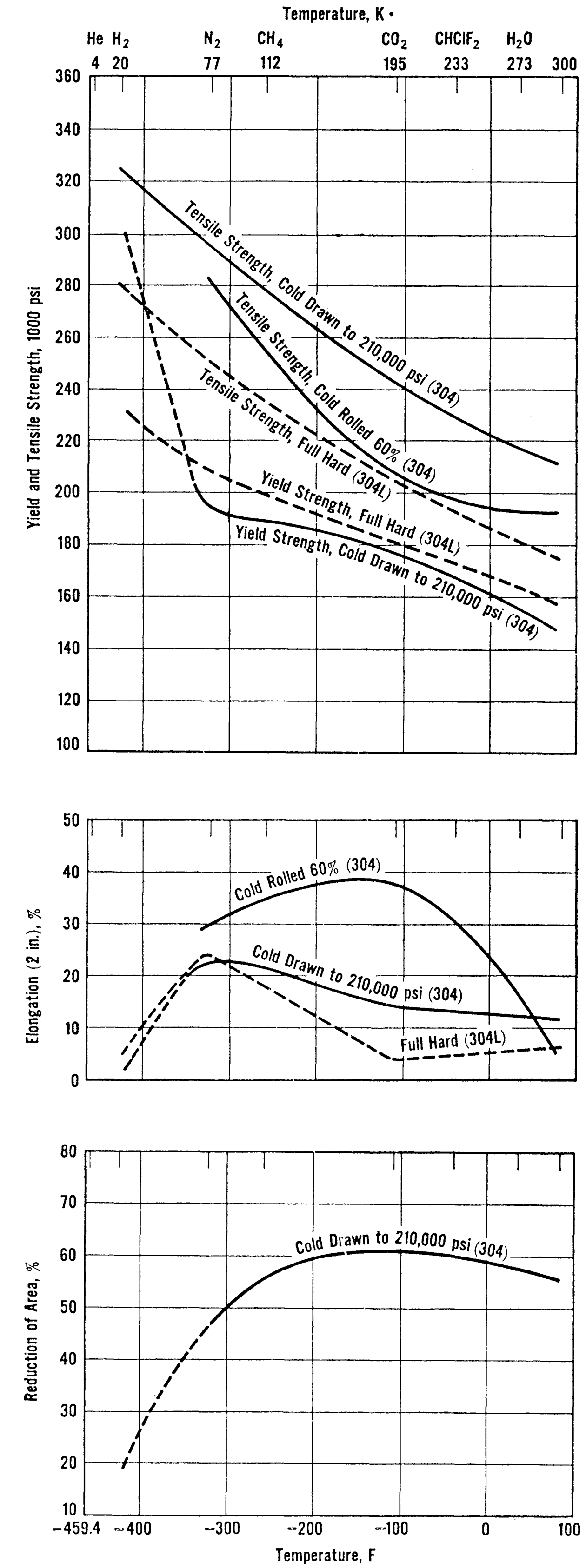

FIG. 8—Tensile properties of cold worked Types 304 and 304L stainless steel[3, 8, 9, 39]

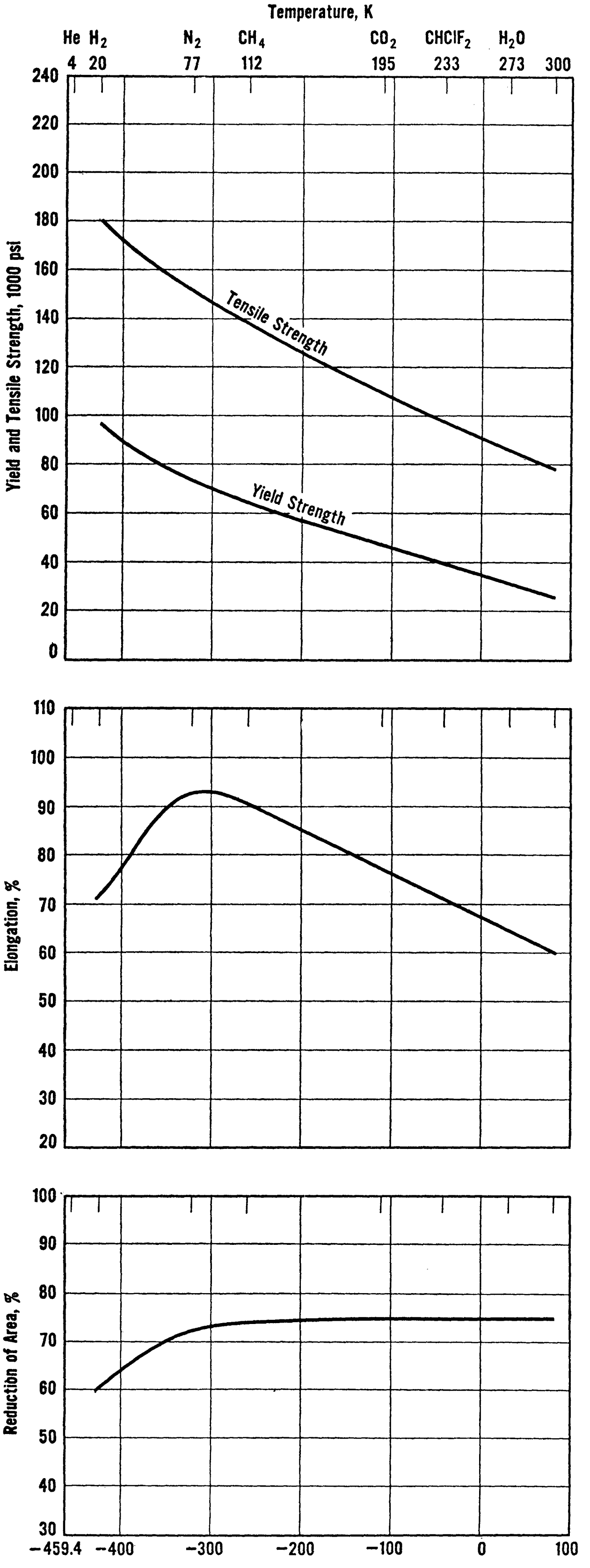

FIG. 9—Tensile properties of annealed Type 310 stainless steel[10, 40]

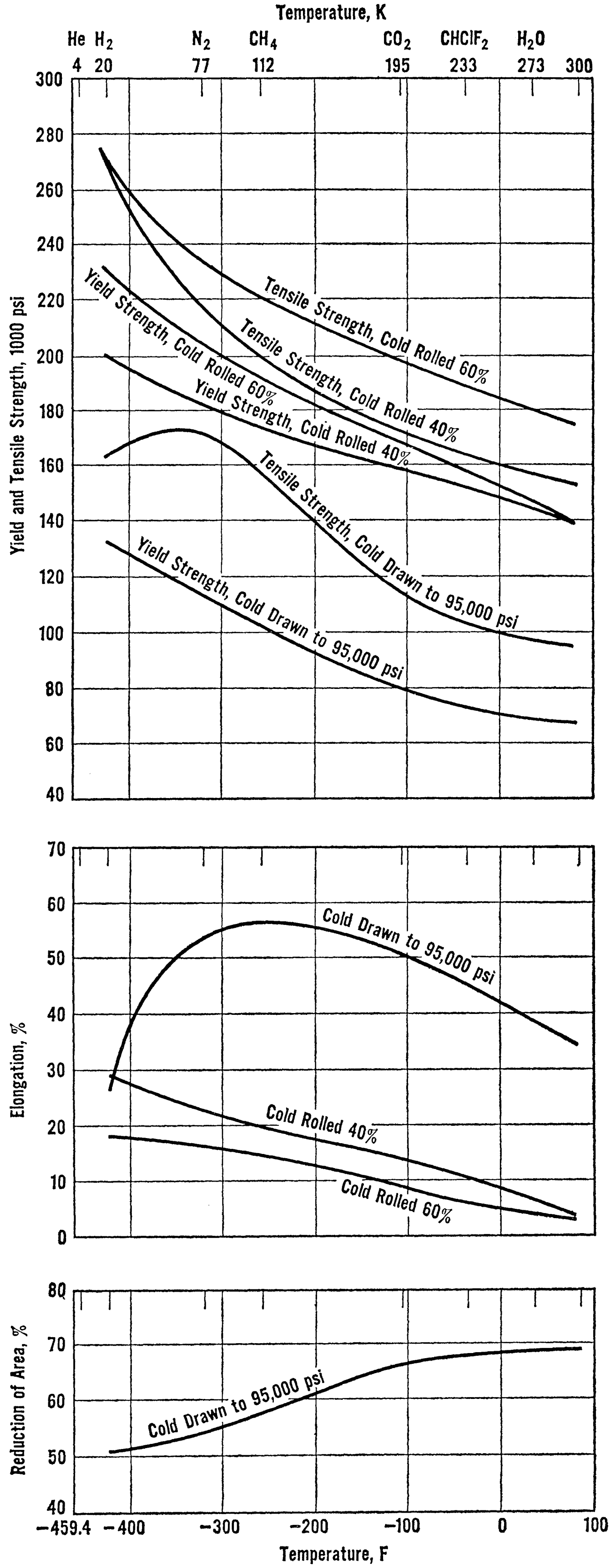

FIG. 10—Tensile Properties of cold worked Type 310 stainless steel[5, 39]

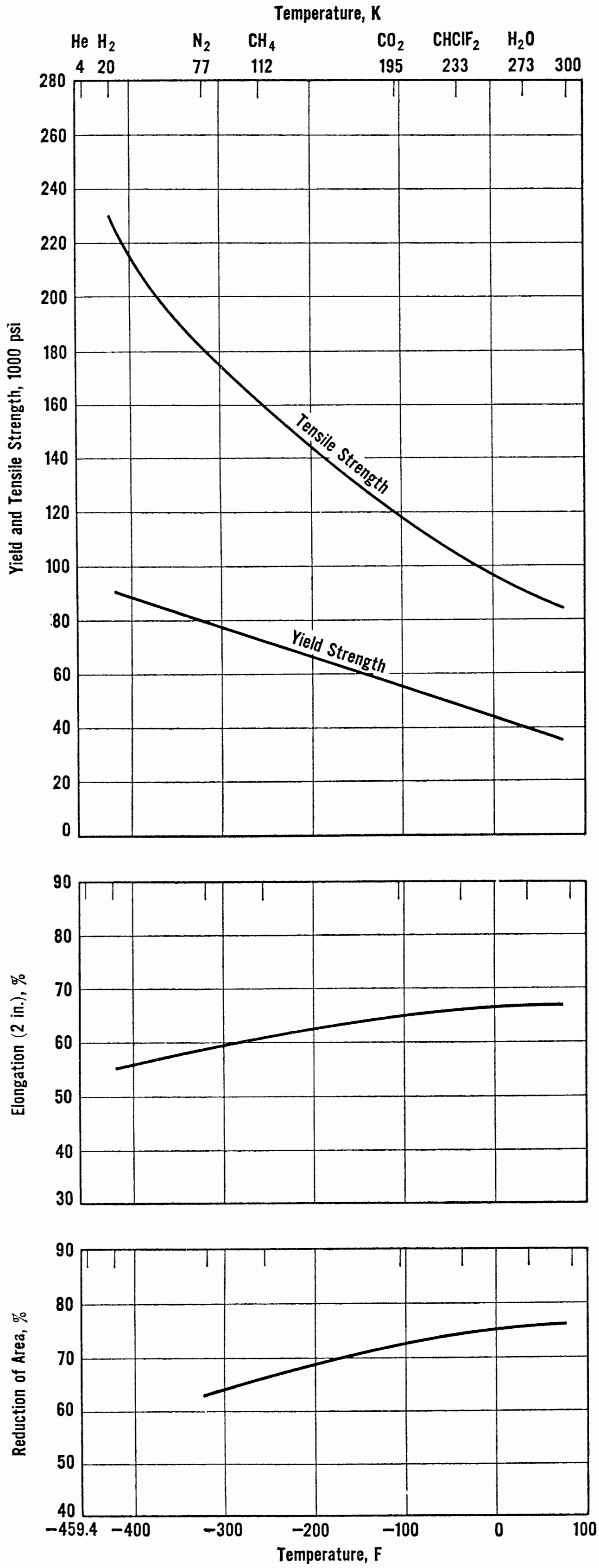

FIG. 11—Tensile properties of annealed Type 316 stainless steel[1,4]

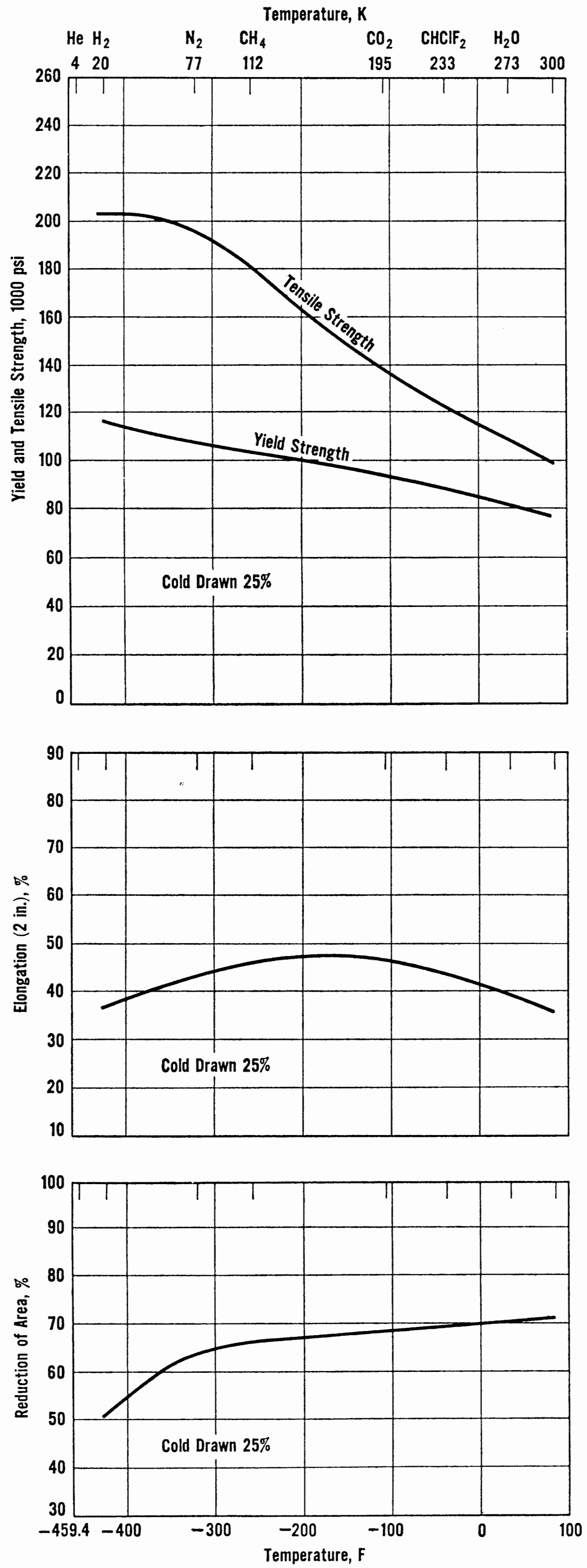

FIG. 12—Tensile properties of cold worked Type 316 stainless steel[5]

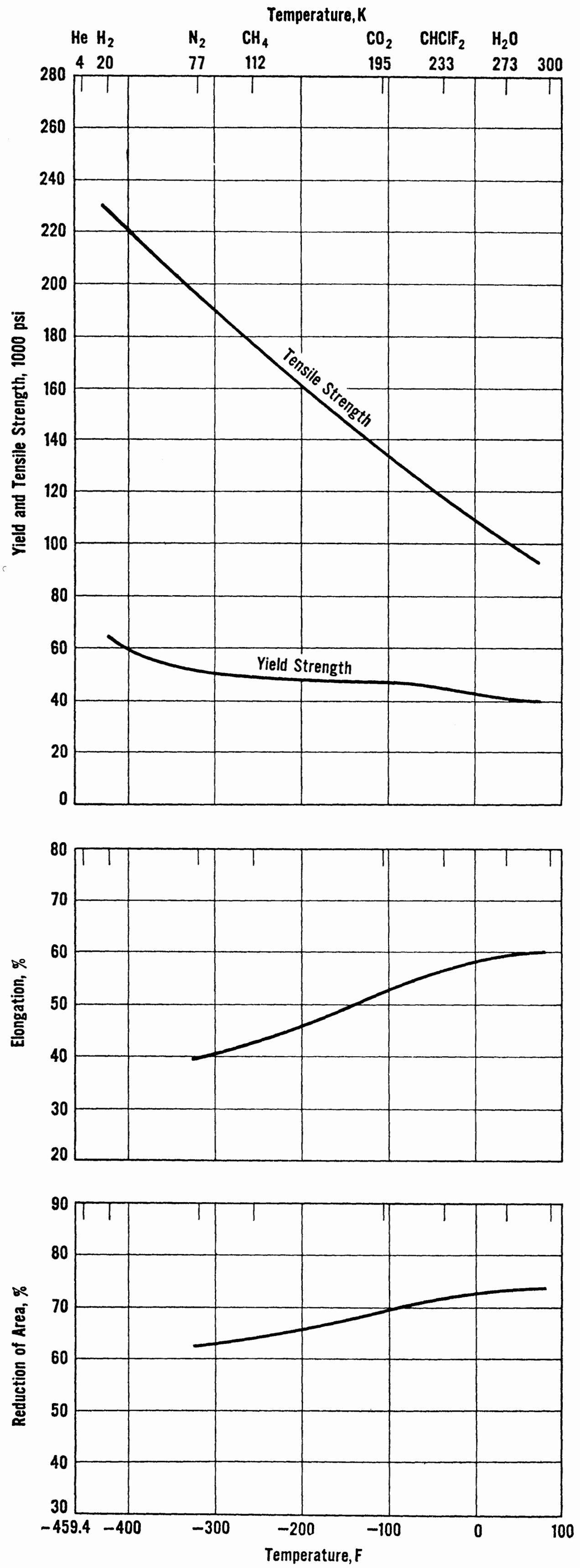

FIG. 13 — Tensile properties of annealed Type 347 stainless steel[1, 2, 3]

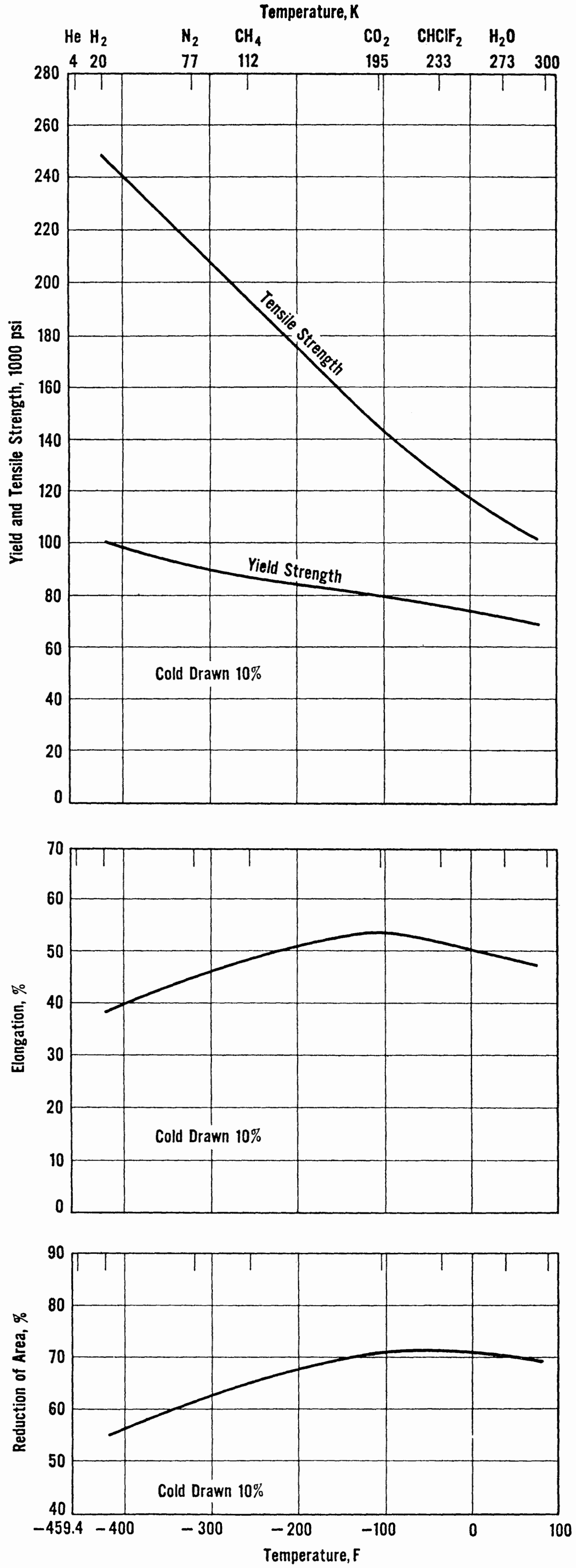

FIG. 14—Tensile properties of cold worked Type 347 stainless steel[7]

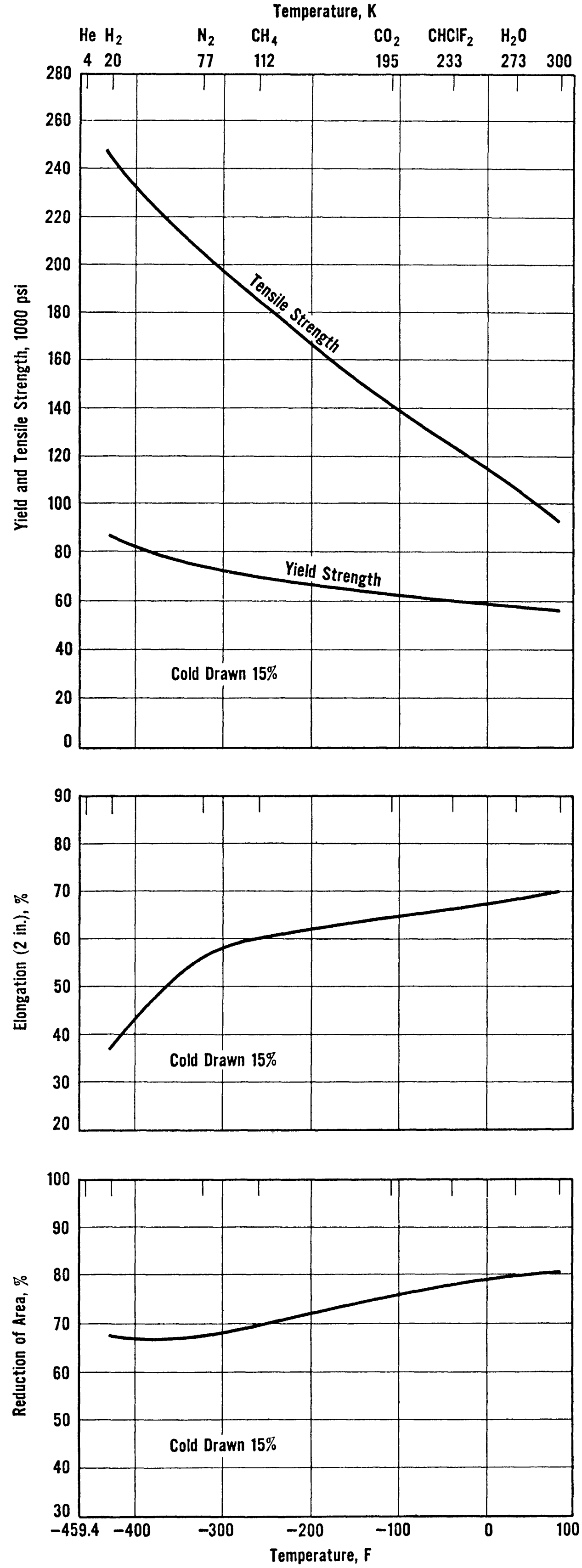

FIG. 15—Tensile properties of cold worked Type 308 stainless steel[7]

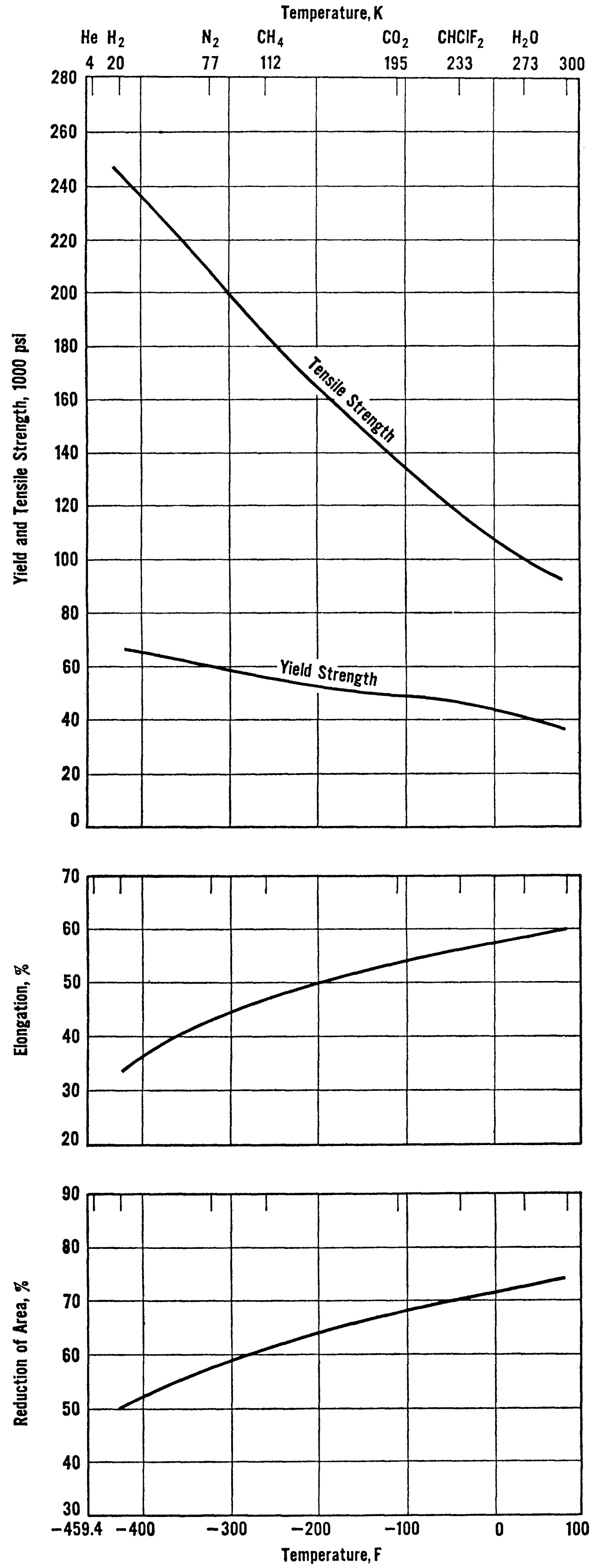

FIG. 16—Tensile properties of annealed Type 321 stainless steel[1,10,11,40]

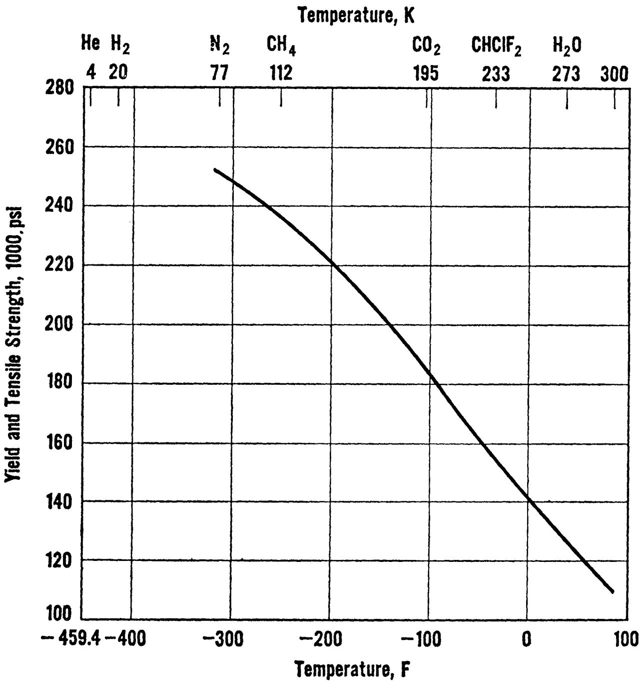

FIG. 17 — Tensile strength of cold worked Type 321 stainless steel[12]

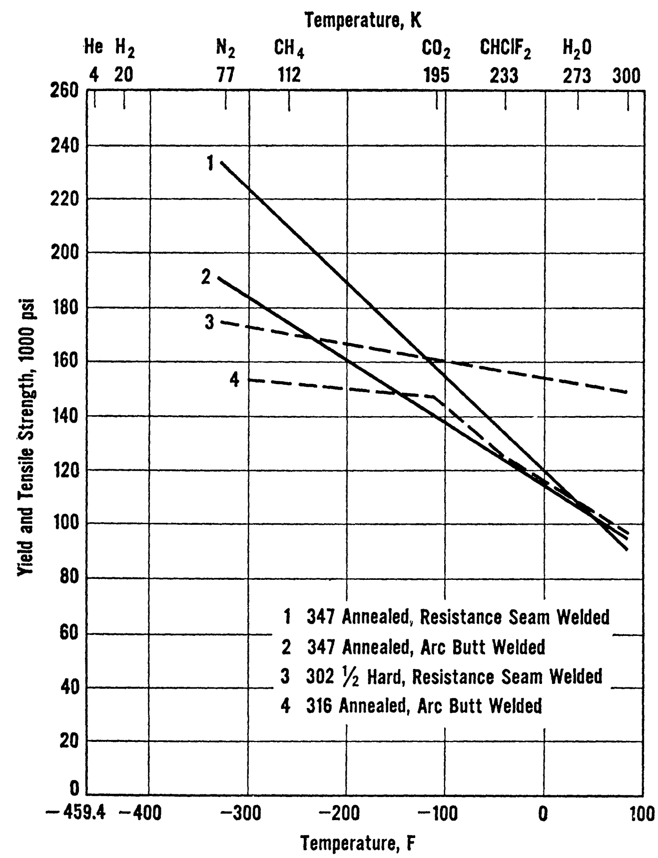

FIG. 18—Tensile strength of stainless steel weld joints[23, 24]

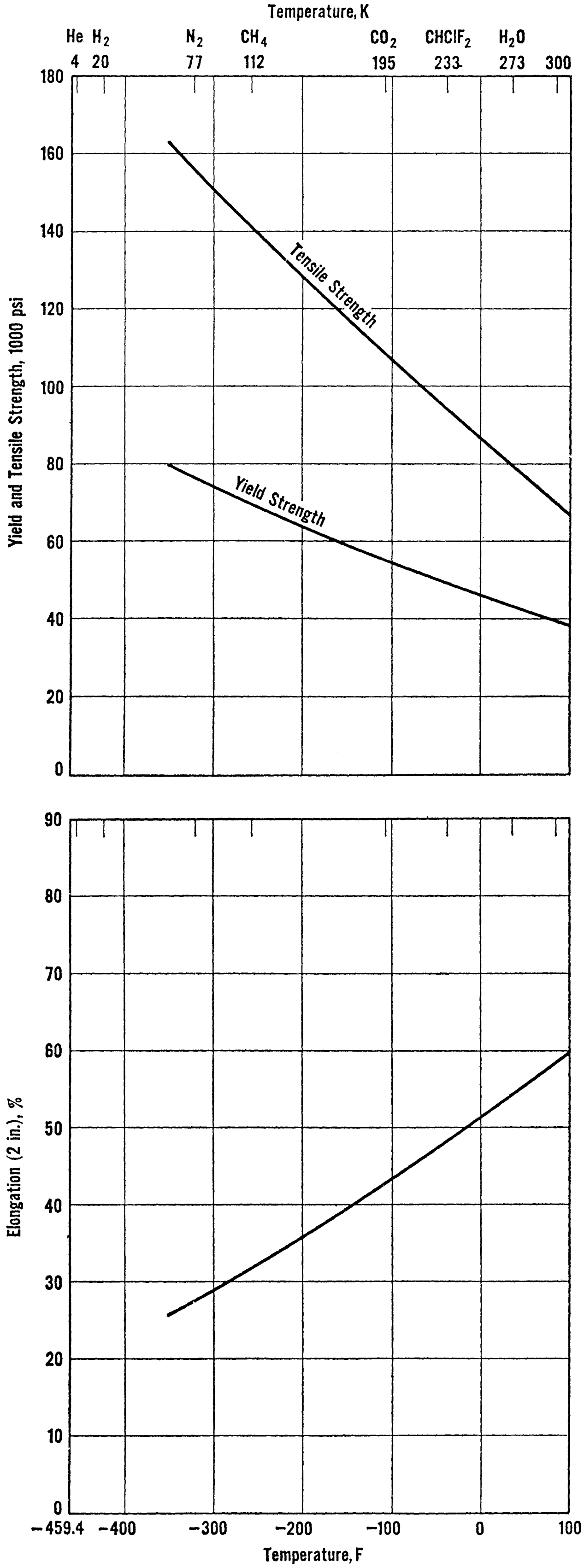

FIG. 19—Tensile strength of cast Type CF-8 stainless steel[37]

IMPACT PROPERTIES

The chromium-nickel stainless steels have good ductility and notch toughness down to at least –320 F. Figures 20 through 28 show that the annealed and cold worked alloys vary in their impact properties but all retain substantial toughness. In general, the cast stainless grades also retain adequate toughness, as shown in Figures 29 and 30.

Weldments of the chromium-nickel stainless steels have good properties at low temperatures. Table II shows that welded joints retain substantial toughness down to at least –320 F in the as-welded condition. The weld metal deposits vary considerably in their low temperature impact properties, as shown in Table III.

Carbide precipitation can have a pronounced effect on the low temperature impact properties. As shown in Figure 31, Type 302 is severely affected, Type 304 is affected more moderately, and Type 304L is practically unaffected. Carbide precipitation has little effect on the low temperature impact properties of low carbon Type 316 or Type 347 as shown in Figure 32.

Sigma phase markedly reduces the impact properties of austenitic stainless steels at ambient and low temperatures. Data on Types 316, 318 and 347 are presented graphically in Figure 33.

COMPRESSION PROPERTIES

Compressive strengths, like tensile strengths, increase with decrease in temperature. Compressive yield strengths and elastic limits are given in Figure 34 for Types 303 and 304.

FATIGUE PROPERTIES

Only limited data are available on the fatigue properties of the chromium-nickel stainless steels at low temperatures. Data indicate that the endurance limit

TABLE II

Charpy Impact Properties of Stainless Steel Weld Joints

(Values in ft-lb)

AISI Type	Condition	Notch in Weld			Notch in Heat Affected Zone			Notch in Unaffected Zone			Charpy Specimen
		85 F	–320 F	–440 F	85 F	–320 F	–440 F	85 F	–320 F	–440 F	
304	As welded	33	21	—	—	—	—	—	—	—	Keyhole
304	As welded	59	20	—	—	—	—	—	—	—	V-notch
304	Annealed	61	31	—	—	—	—	—	—	—	V-notch
304	As welded	16*	16*	—	50*	53*	—	—	—	—	Keyhole
304 L	As welded	32	16	19	70	65	60	76	71	70	Keyhole
304 L	As welded	—	—	25	—	—	69	—	—	109	V-notch
309	As welded	33	18	—	—	—	—	—	—	—	Keyhole
310	As welded	34	21	—	—	—	—	—	—	—	Keyhole
310	As welded	25	28	—	—	—	—	—	—	—	Keyhole
316	As welded	26	26	—	—	—	—	—	—	—	Keyhole
316	As welded	43	22	—	—	—	—	—	—	—	Keyhole
316 L	As welded	31	23	—	45	37	—	54	51	—	Keyhole
347	As welded	28	16	—	—	—	—	—	—	—	Keyhole
347	Annealed	30	21	—	—	—	—	—	—	—	Keyhole

* Subsize Specimens—0.200 in. thick.
Krivobok[2]; McClintock and Gibbons[10]; Henke [15]; Armstrong and Miller[19]; Mounce, Crossett, and Armstrong[21]; Watertown Arsenal[22]; J. Am. Welding Soc[23].

TABLE III

Impact Properties of Weld Metal

Test No.	Type of Plate	Type of Electrode	Heat Treatment*	Per Cent** Ferrite	Charpy Impact (Keyhole Notch), ft-lb		
					Room Temp	−105 F	−320 F
1	301	301	As welded	—	35–39	20–22	5–6
			Annealed		41–42	30–31	24
2	302	302	As welded	—	32–34	26–28	9–10
			Annealed		37–40	31–35	25–28
3	304	304	As welded	—	32–37	24–28	18–23
			Annealed		41–49	39–42	32–42
4	304	308	As welded	—	31–33	21–25	14–20
			Annealed		36–38	30	30–31
5	310	310	As welded	—	35–38	26–32	24
			Annealed		30–34	28–29	18–20
6	316	316	As welded	0.5%	27–35	25–28	14–21
			Stress relieved		30–34	25–27	13–14
			Stabilized		26–30	21–22	11–15
			Annealed		32–36	28–30	22
7	316	316	As welded	8.0%	31–32	28–29	18–20
			Stress relieved		25–27	17–18	7–8
			Stabilized		11–12	7–8	3
			Annealed		32–41	28–33	24–28
8	317	317	As welded	2.0%	21–23	16–17	9–14
			Annealed		21	16–17	11–17
9	317	317	As welded	5.5%	10–15	7–8	4–4
			Annealed		10–12	5–7	3
10	318	318	As welded	None	28	23	9–18
			Stress relieved		23–30	23–26	9–18
			Stabilized		21–22	15–16	13
			Annealed		30–33	21–30	19–22
11	318	318	As welded	0.5%	15–23	15–18	11–12
			Stress relieved		17–22	14–16	7–10
			Stabilized	None	8–10	6–9	5–6
			Annealed		25–26	19–23	10–18
12	321	347	As welded	***	32	24–27	18–26
			Annealed		29–32	28–36	23–27
13	347	347	As welded	None	26–29	19–27	18–20
			Stress relieved		25–27	20	13–14
			Stabilized		22	14–17	14–16
			Annealed		24–26	25–26	16–20
14	347	347	As welded	3.5%	27–33	21–29	16–22
			Stress relieved		24–27	15–16	9–13
			Stabilized		19–22	15–18	7–20
			Annealed		25–27	20–30	23–26
15	347	347[a]	As welded	—	25–28	18–23	13–27
			Annealed		28–31	20–27	21–23

* Heat treatments were as follows: As welded
Stress relieved 1200 F 2 hr
Stabilized 1550 F 2 hr
Annealed 1950 F ½ hr water quenched

** Ferrite was determined by use of an Aminco-Brenner Magne-Gage, as outlined in "Detection of Ferrite by its Magnetism," by T. V. Simpkinson & M. J. Lagne, METAL PROGRESS, Feb. 1949, p 164.

*** Not measured but probably the same as test No. 14 since the same electrode was used.

[a] Titania type coating. All other electrodes had lime type coating.

Krivobok and Thomas[14]

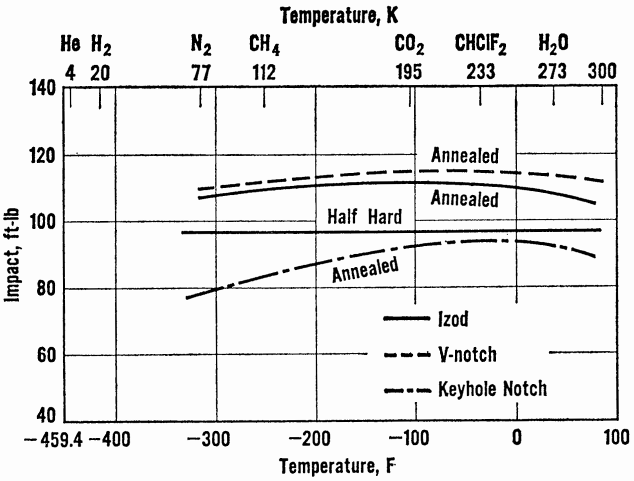

FIG. 20—Impact properties of Type 301[1, 14, 15, 18]

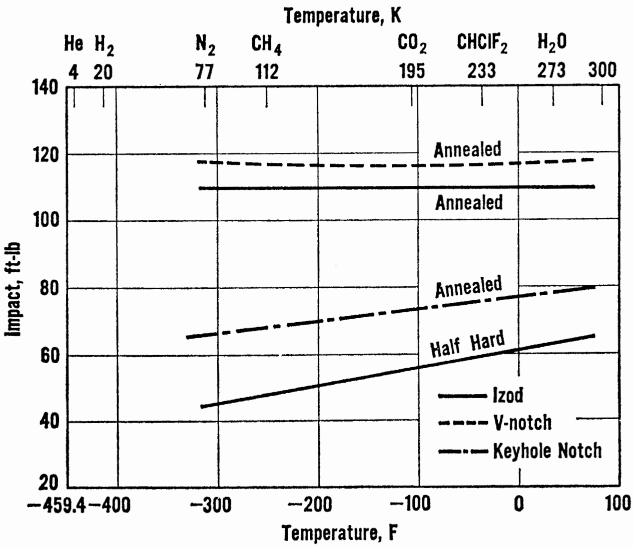

FIG. 21—Impact properties of Type 302[2, 15, 18, 25]

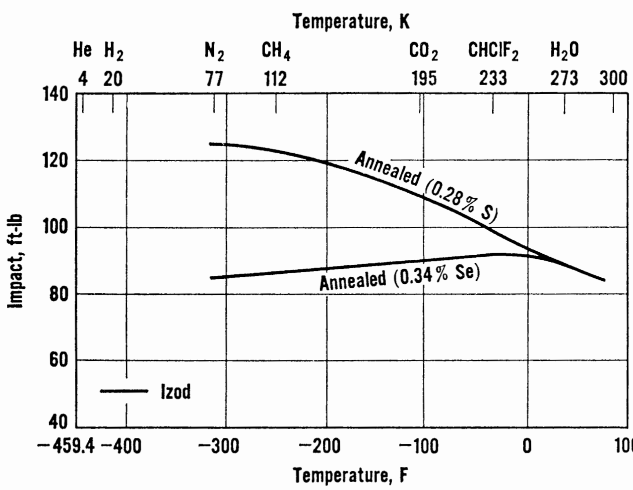

FIG. 22—Impact properties of Type 303[1]

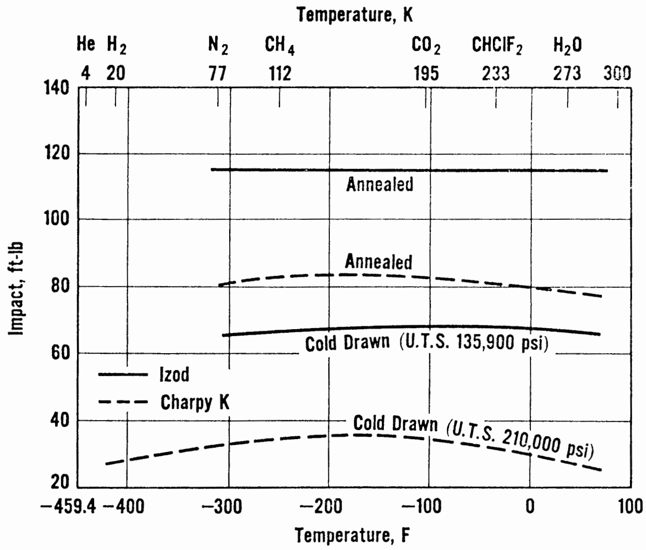

FIG. 23—Impact properties of Type 304[1, 8, 13, 18, 20, 25]

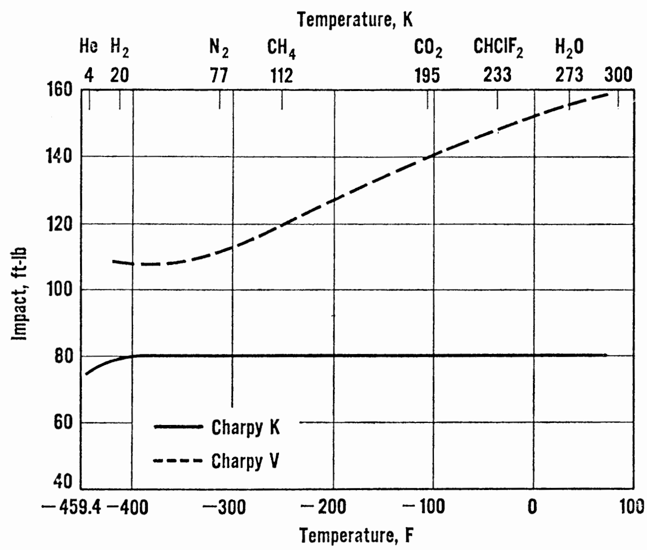

FIG. 24—Impact properties of Type 304L[21, 22]

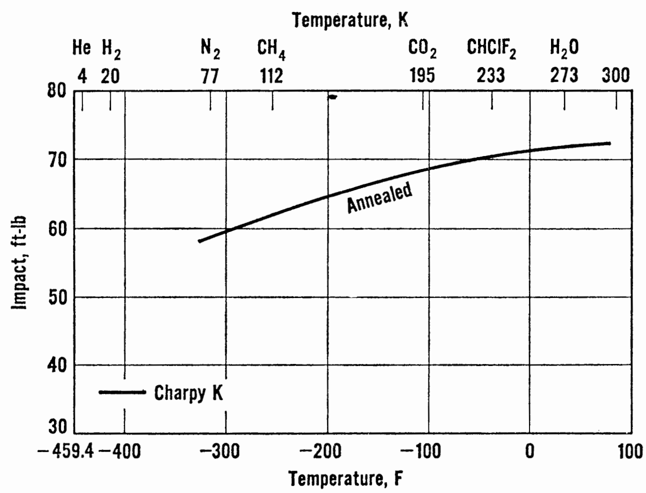

FIG. 25—Impact properties of Type 310[2, 14, 19]

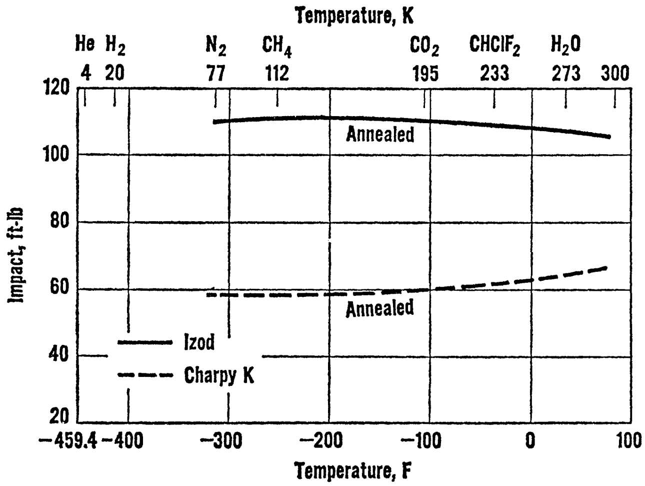

FIG. 26—Impact properties of Type 316[1,2,18,19]

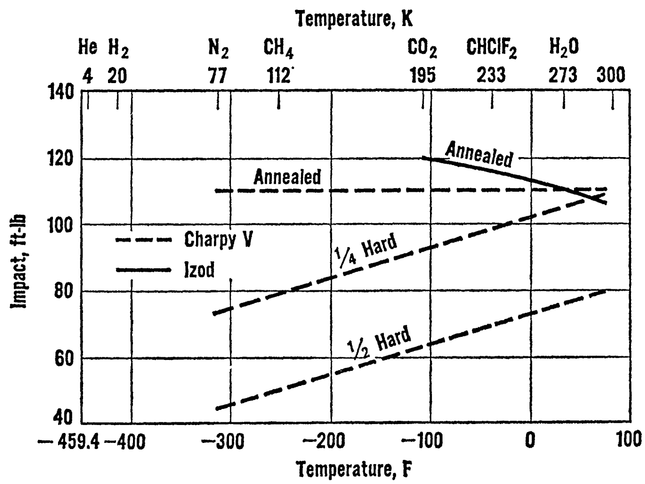

FIG. 27—Impact properties of Type 321[1,15,16]

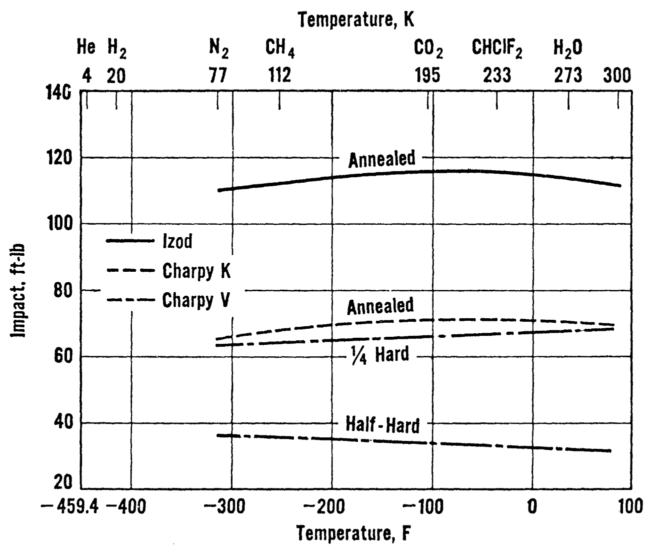

FIG. 28—Impact properties of Type 347[1,15,18]

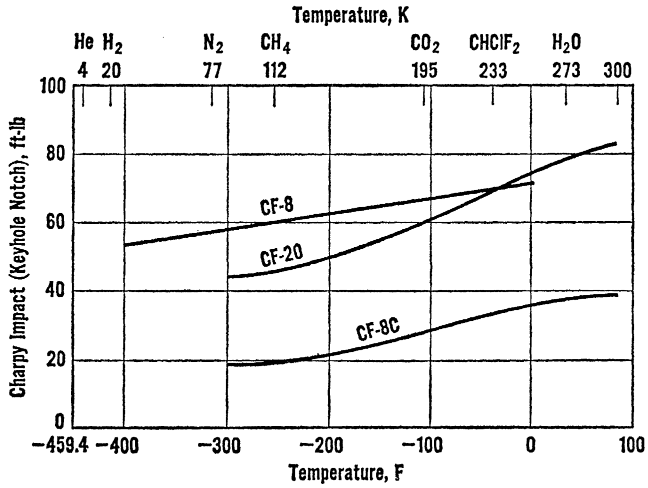

FIG. 29—Impact properties of cast Types CF-8, CF-20 and CF-8C stainless steels[37,38]

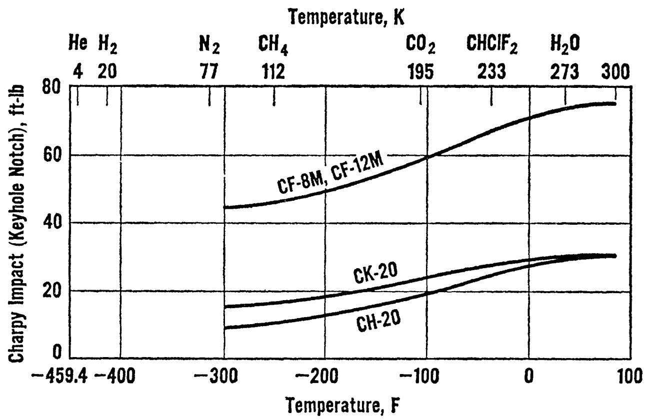

FIG. 30—Impact properties of cast Types CF-8M, CF-12M, CH-20, and CK-20 stainless steels[37,38]

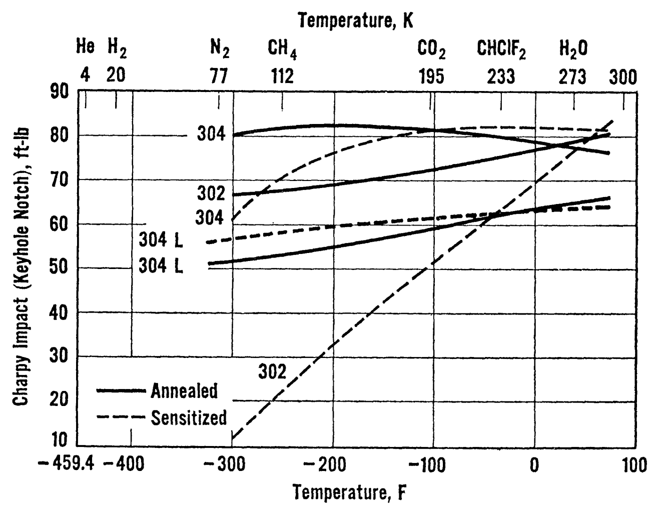

FIG. 31—Effect of sensitization (1200 F for 2 hr) and carbon content on impact properties of annealed Types 302 (0.14C) 304 (.07C) and 304L (.03 max C) stainless steels[2,25]

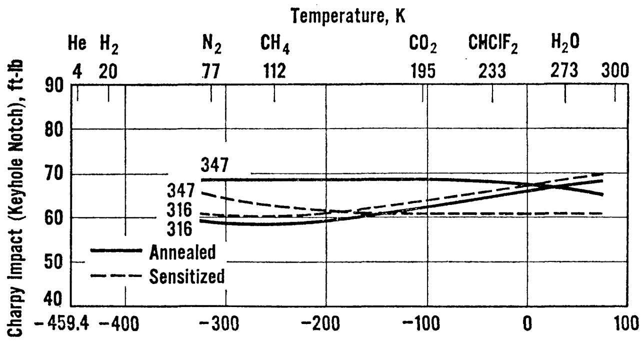

FIG. 32—Effect of sensitization (1200 F for 2 hr) on impact properties of annealed Types 316 (.03 max C) and 347 (.03 max C) stainless steels[2]

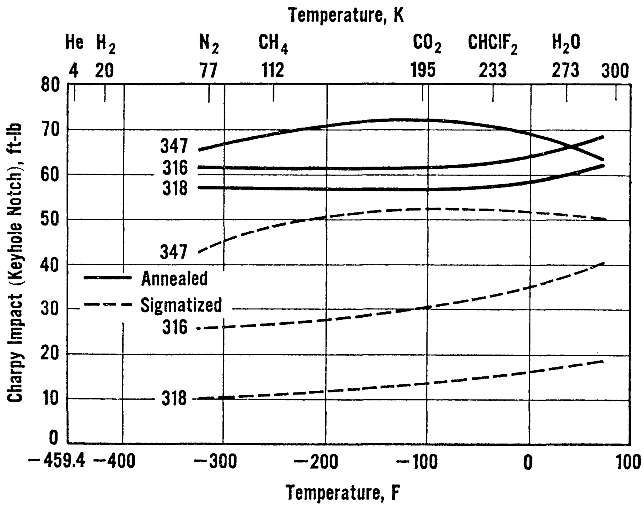

FIG. 33—Effect of sigmatizing (1350—1650 F) on impact properties of Types 316 (.02 C), 318 (.02 C) and 347 (.02 C) stainless steels[2]

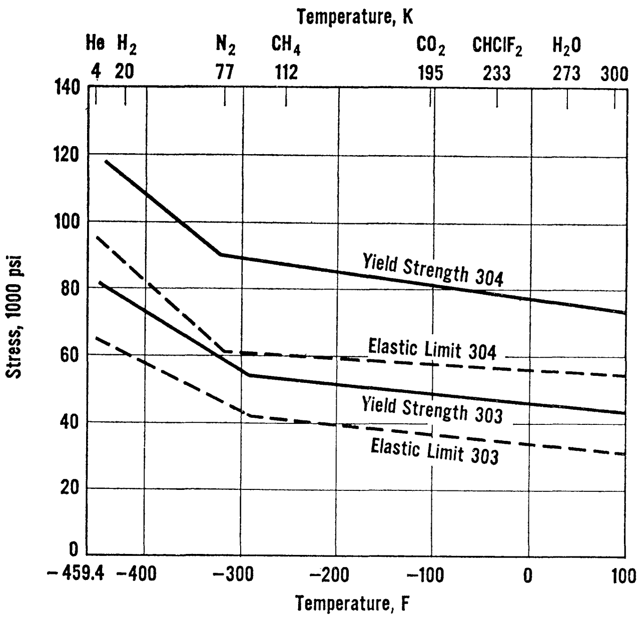

FIG. 34—Compressive yield strengths and elastic limits of Types 303 and 304 stainless steels[26]

increases as the temperature decreases. Figure 35 shows the fatigue properties of cold worked Type 304 at several temperatures. Both smooth and notched bars show increasing strength with falling temperatures, although the improvement in notched bars is less pronounced than in the smooth bars. Figures 36 and 37 indicate that the fatigue strengths of both annealed and cold worked Type 302 are considerably higher at —40 F than they are at room temperature.

TOUGHNESS

In addition to the other properties, notched to unnotched tensile ratios are included in Figures 38 to 42 for 301, 302, 304L, 310 and 301N as a basis for evaluation of fracture toughness.

PHYSICAL PROPERTIES

The effect of temperature on the physical properties of the chromium-nickel stainless steels varies, depending upon the property under consideration.

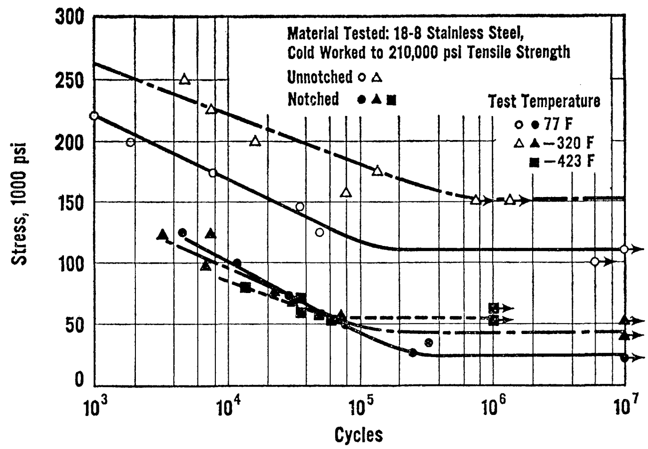

FIG. 35—Reciprocating beam fatigue strength of cold worked Type 304 stainless steels[9, 13]

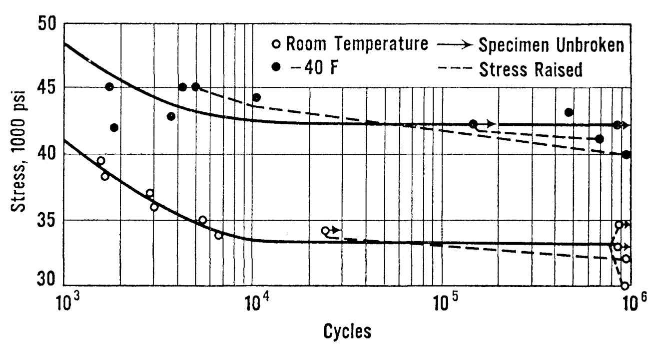

FIG. 36—Fatigue strength of annealed Type 302 stainless steel[15]

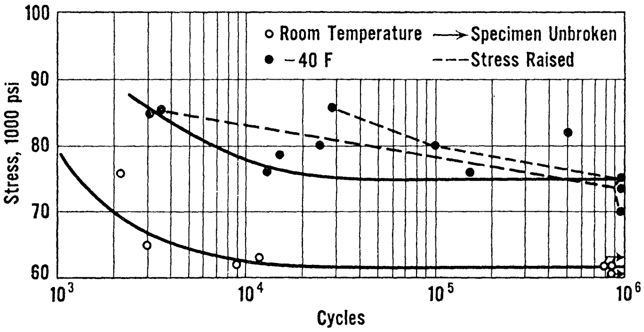

FIG. 37—Fatigue strength of cold worked Type 302 stainless steel[15]

As shown in Figure 43, density increases markedly as the temperature is reduced from ambient to −250 F. Thermal diffusivity varies. As shown in Figure 44, the thermal diffusivity of Types 316 and 347 increase with falling temperature; Type 301 remains relatively unaffected by changes in temperature down to −300 F.

On the other hand, specific heat, emissivity, electrical resistivity, thermal conductivity, and thermal expansion decrease with falling temperature. Data on specific heat are shown in Figures 45 and 46. The effects of surface finish and decreasing temperature

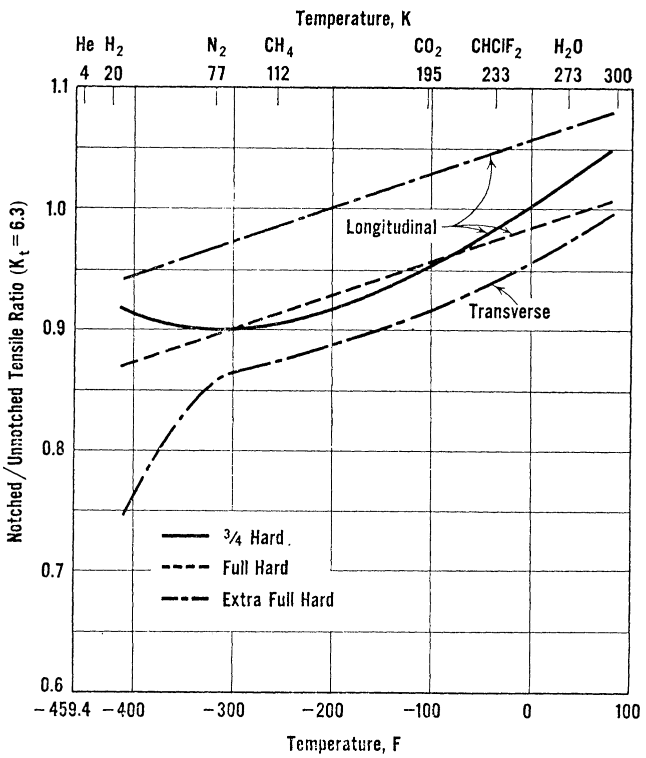

FIG. 38—Notched/unnotched tensile ratio for Type 301 cold rolled stainless steel[39]

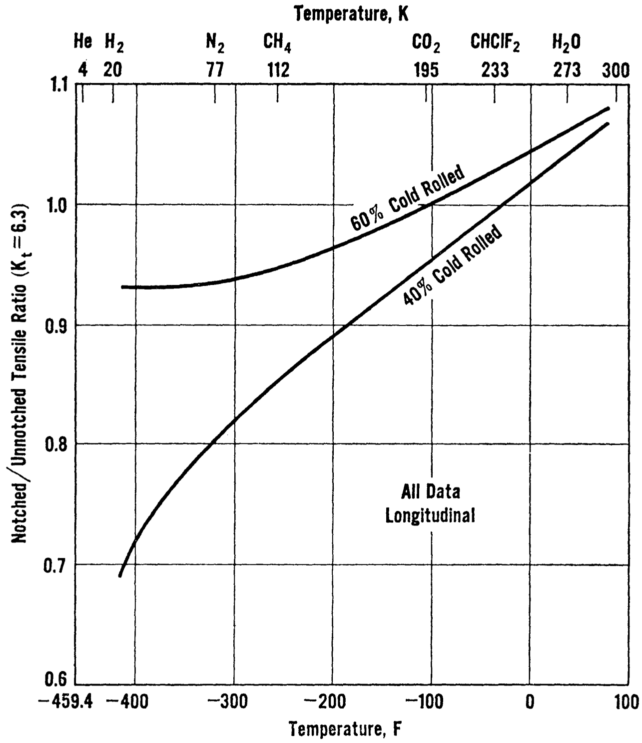

FIG. 39—Notched/unnotched tensile ratio for Type 302 cold rolled stainless steel[39]

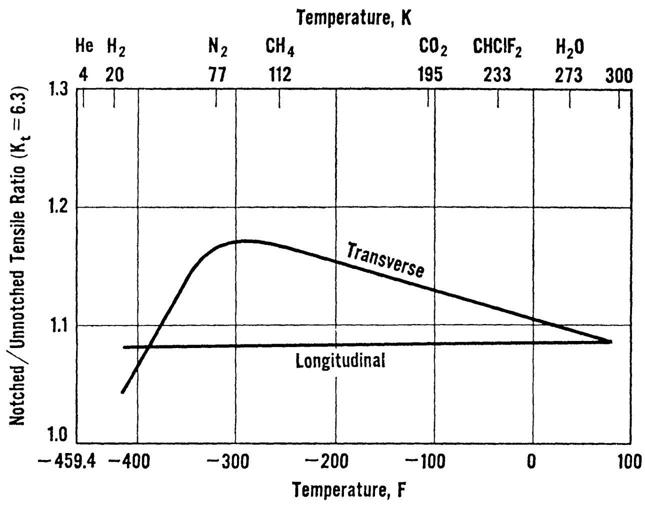

FIG. 40—Notched/unnotched tensile ratio for full hard Type 304L stainless steel[39]

on the emissivity are shown in Figure 47 for Types 316 and 321 stainless steels. Electrical resistivities of various grades are shown in Figure 48; thermal conductivities in Figures 49 and 50.

Thermal expansion is an important property in the design of structures for low temperature service and

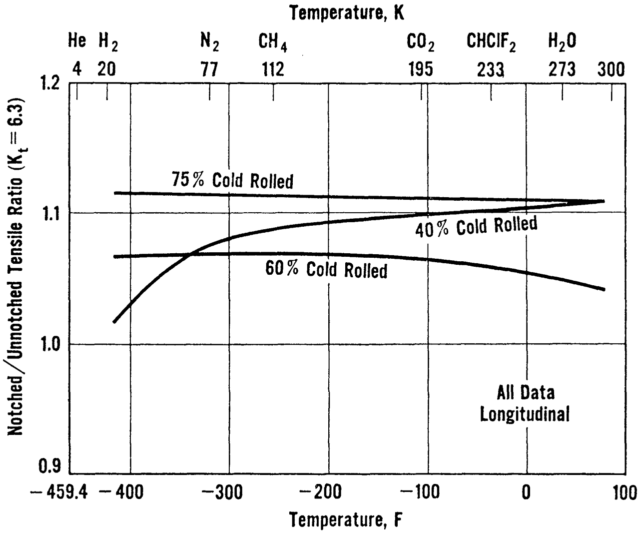

FIG. 41 — Notched/unnotched tensile ratio for Type 310 cold rolled stainless steel[39]

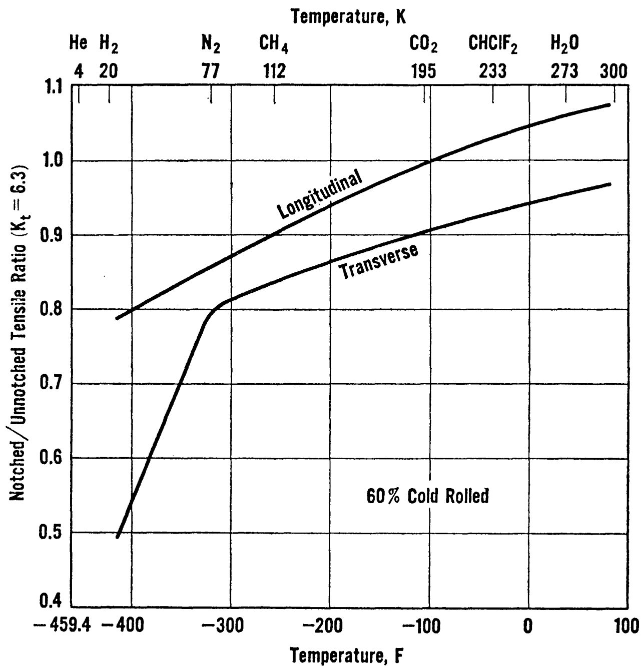

FIG. 42—Notched/unnotched tensile ratio for Type 301N cold rolled stainless steel[39]

therefore data are presented in two different forms. Table IV gives the mean linear coefficient for a series of steels between 70 F and several subzero temperatures. Figures 51, and 53 to 56, inclusive, show the actual expansion that will occur between any two temperatures from −300 F to room temperature per unit of length.

TABLE IV

Coefficients of Thermal Expansion of Stainless Steels[a]

AISI Type	−300 F to 70 F	−200 F to 70 F	−100 F to 70 F	0 F to 70 F
301	7.6 x 10^{-6}	7.8 x 10^{-6}	8.2 x 10^{-6}	8.7 x 10^{-6}
304	7.4	7.7	8.2	8.7
316	7.1	7.4	7.8	8.2
347	7.5	8.1	8.5	8.7
310	7.0	7.5	7.8	8.0
330	5.8	6.5	7.2	7.6

Furman[34]

[a] Mean coefficients.

Of the alloys included, Type 301 is the least stable, the instability being attributed to the partial transformation of austenite to ferrite. However, the instability of Type 301 has a negligible effect on expansion characteristics.

The effects of low temperature on the magnetic permeabilities of annealed chromium-nickel stainless steels are shown in Figure 57. Since stability depends on composition, it is necessary to select a stable composition to predict the permeability at low temperatures.

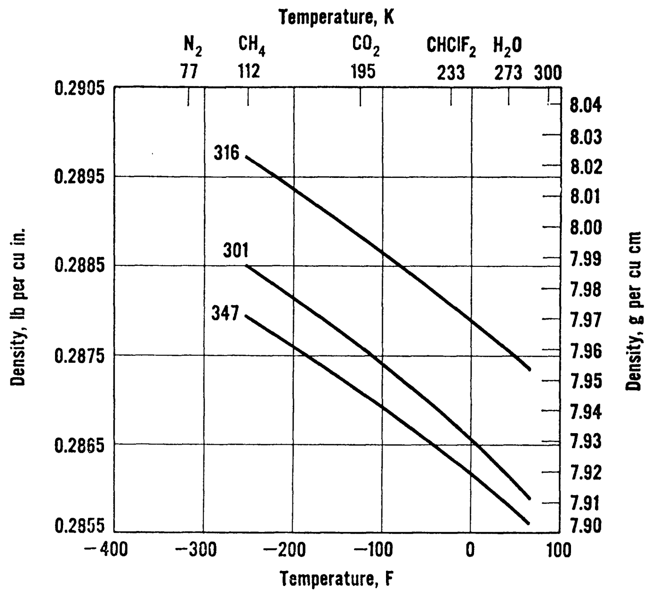

FIG. 43—Densities of Types 301, 316, and 347 stainless steels[36]

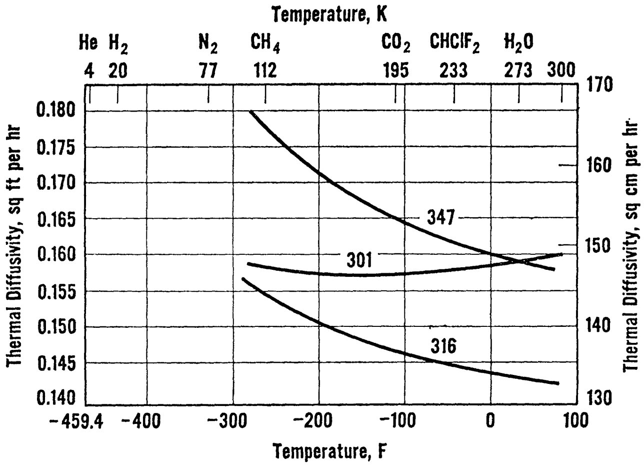

FIG. 44—Thermal diffusivity of Types 301, 316 and 347 stainless steels[36]

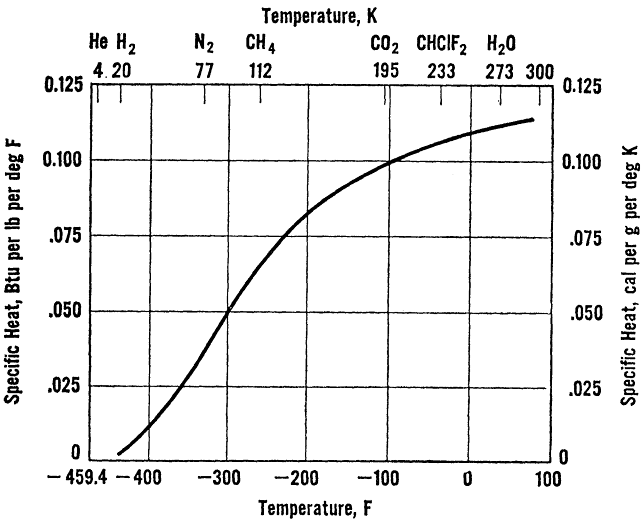

FIG. 45—Specific heat of Type 304 stainless steel[27]

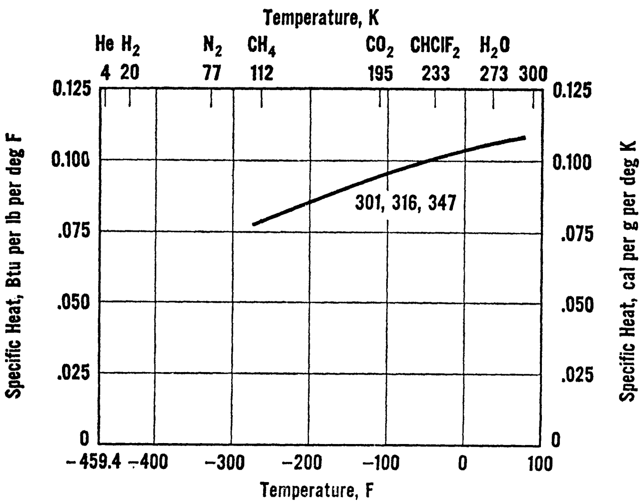

FIG. 46—Specific heat of Types 301, 316 and 347 stainless steels[36]

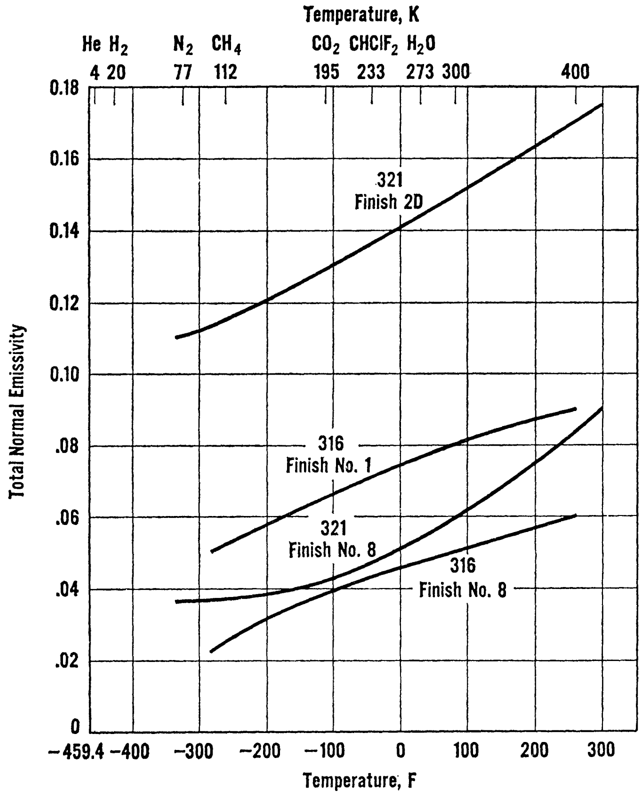

FIG. 47—Effect of surface finish on the total normal emissivity of Types 316 and 321 stainless steels[31]

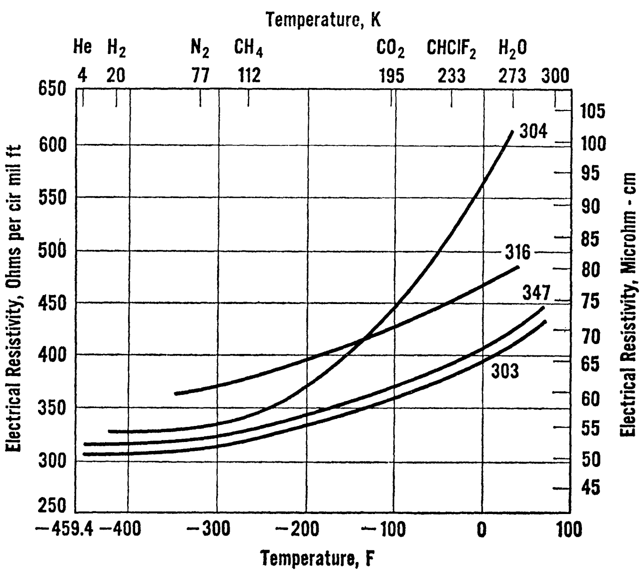

FIG. 48—Electrical resistivities of various stainless steels[28, 29, 30]

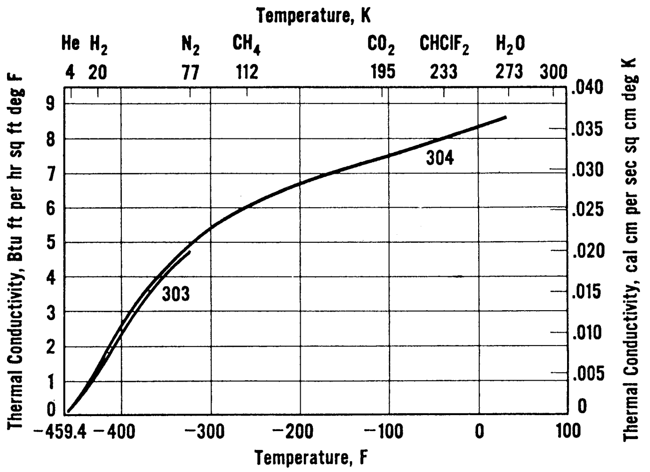

FIG. 49—Thermal conductivities of Types 303 and 304 stainless steels[29, 32]

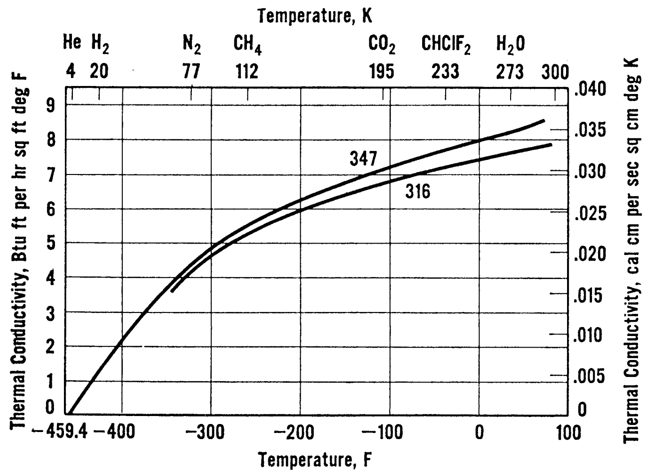

FIG. 50—Thermal conductivities of Types 316 and 347 stainless steels[29, 30, 32]

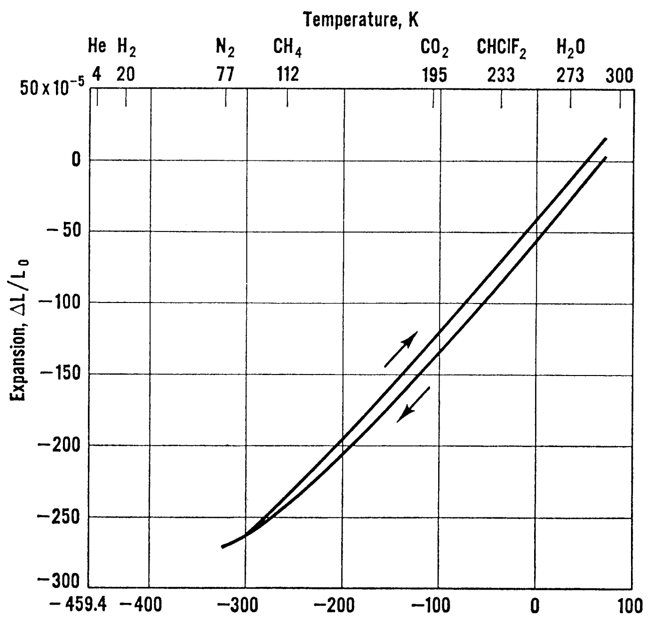

FIG. 51—Expansion characteristics of Type 301 stainless steel[34]

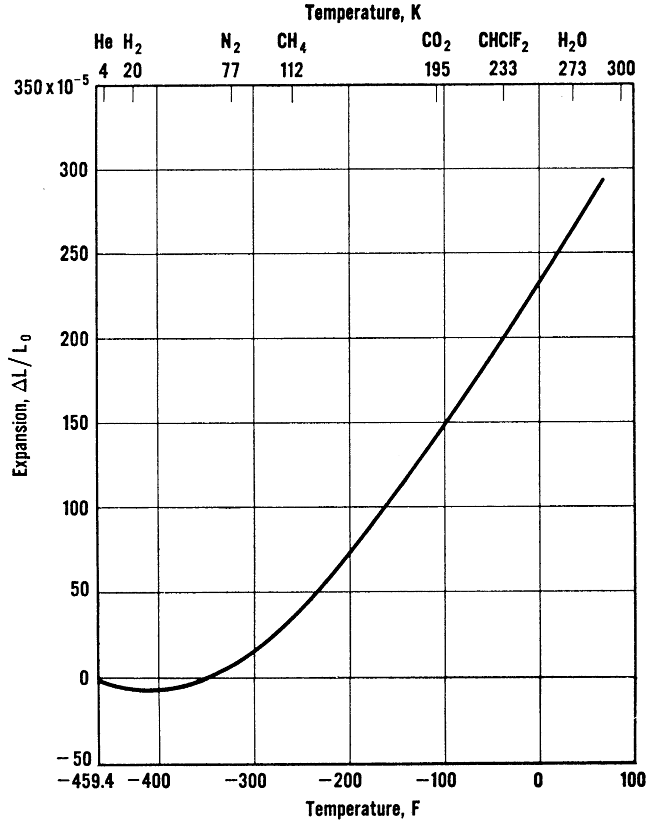

FIG. 52—Mean linear thermal expansion of Type 304 stainless steel[27, 34]

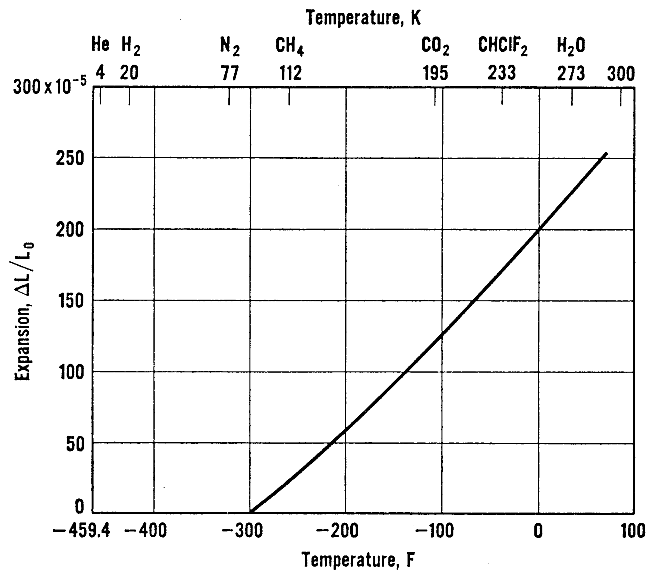

FIG. 53—Expansion characteristics of Type 310 stainless steel[34]

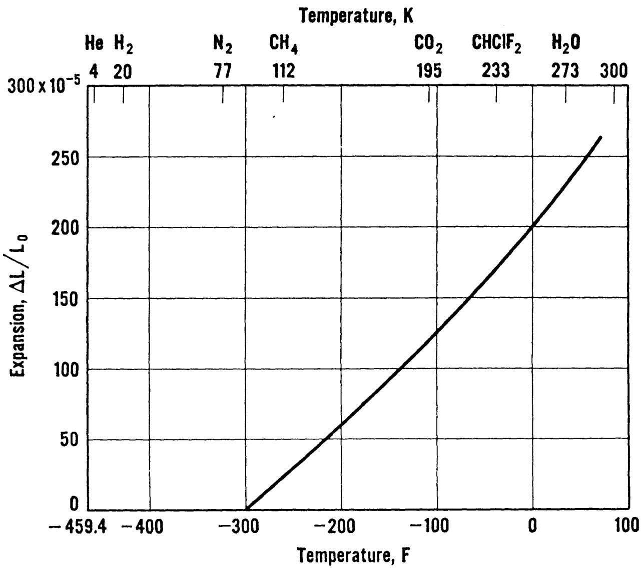

FIG. 54—Expansion characteristics of Type 316 stainless steel[34]

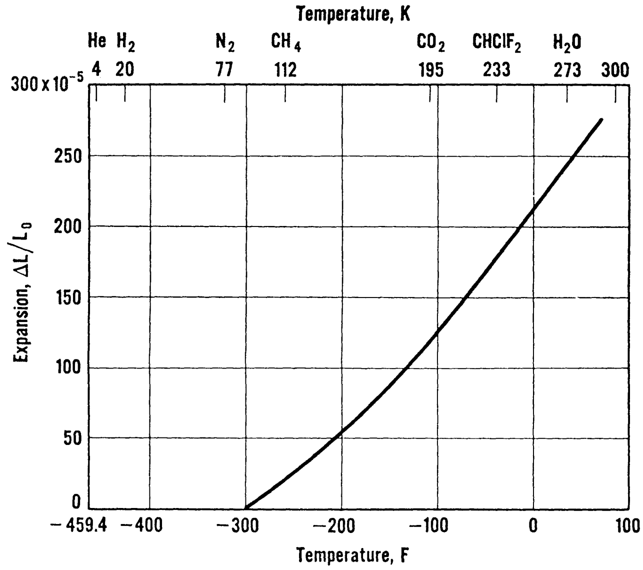

FIG. 56—Expansion characteristics of Type 347 stainless steel[34]

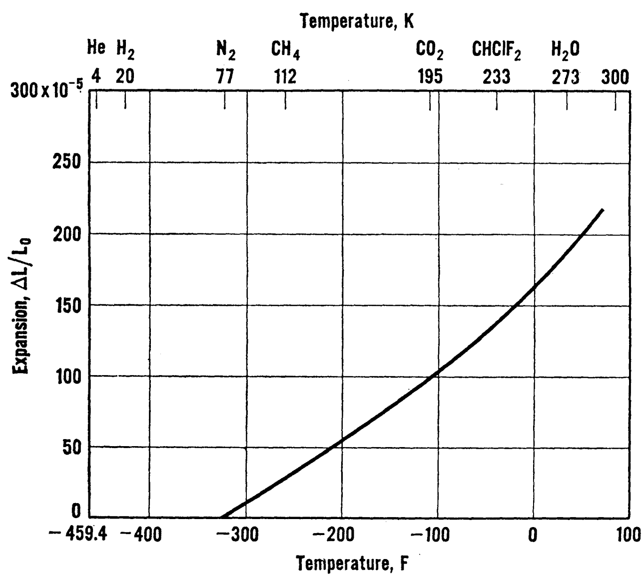

FIG. 55—Expansion characteristics of Type 330 stainless steel[34]

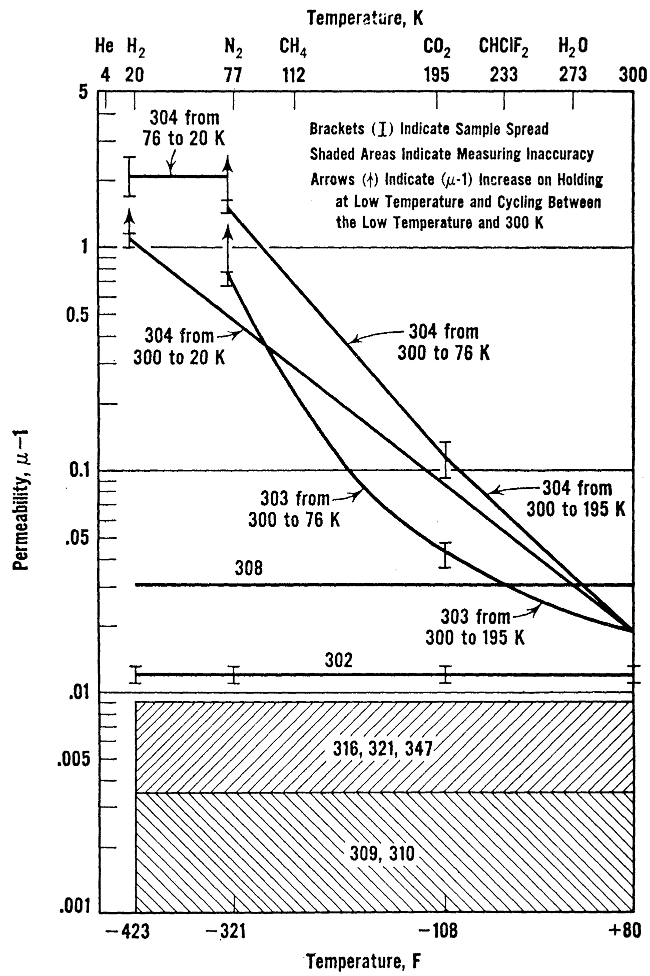

FIG. 57—Permeabilities of some austenitic stainless steels[35]

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