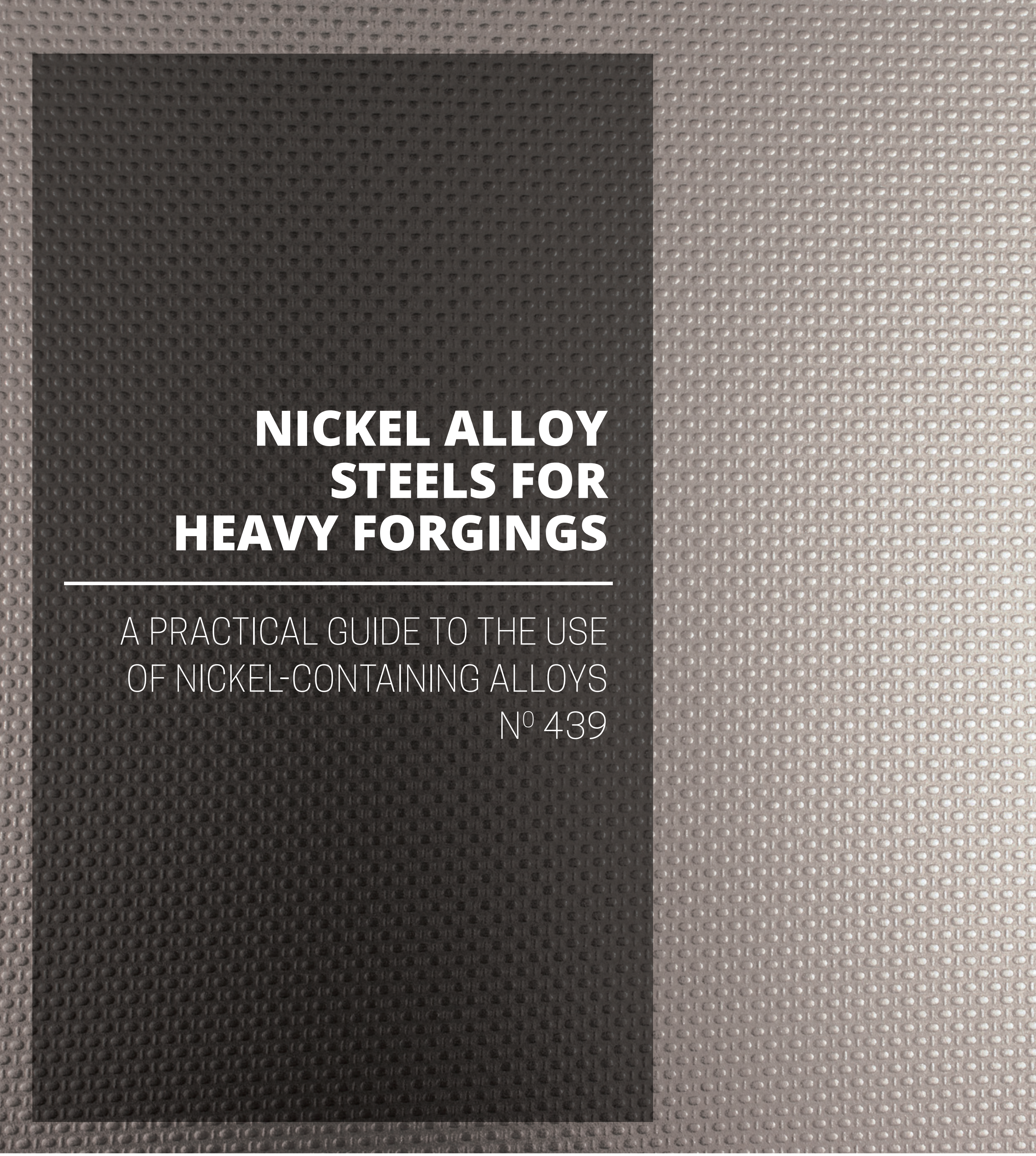

NICKEL ALLOY STEELS FOR HEAVY FORGINGS

A PRACTICAL GUIDE TO THE USE OF NICKEL-CONTAINING ALLOYS

Nº 439

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Nickel Institute

communications@nickelinstitute.org
www.nickelinstitute.org

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Nickel Alloy Steels for Heavy Forgings

INTRODUCTION

This bulletin provides information on specifications, properties and compositions of nickel alloy steels used for heavy forgings. The data pertain to massive components, usually more than four inches thick, normally forged or pressed from large ingots in open dies. Properties expected in forgings thinner than about four inches are given in other bulletins.* Alloy steels are used for heavy forgings to achieve higher strength, better fracture resistance, or improvements in other specific properties for a wide variety of applications. Examples are turbine and generator rotors and disks, large axles and shafts, large gears, ship forgings and pressure vessel components.

In the past heavy forgings were cooled relatively slowly as dictated by the massive sections and by the need to prevent hydrogen flaking. The alloy compositions that evolved, therefore, were designed to develop improved properties by normalizing and tempering, or even by furnace cooling at very slow rates.

In recent years, however, the demand for further increases in strength and fracture toughness in more and more massive sections has been met successfully by adopting compositions of higher hardenability and by heat treatments which involve quenching and tempering. The achievement of improved strength and toughness by these means was made possible largely by the advent of vacuum treating of liquid steel which markedly lessens susceptibility to hydrogen flaking,[1-8] even for the relatively rapid cooling rates associated with water quenching by immersion or spray.

Nickel-molybdenum and nickel-chromium-molybdenum alloy steels, usually also containing vanadium, are well suited to develop uniform strength and ductility and good toughness properties over wide ranges of section size and cooling rate. These compositions

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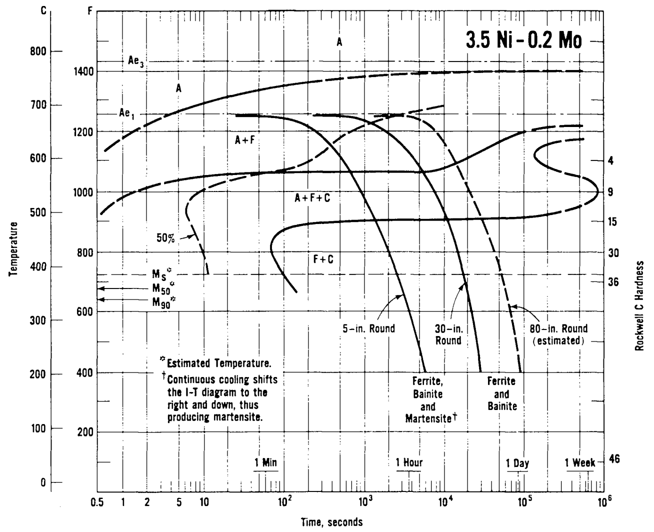
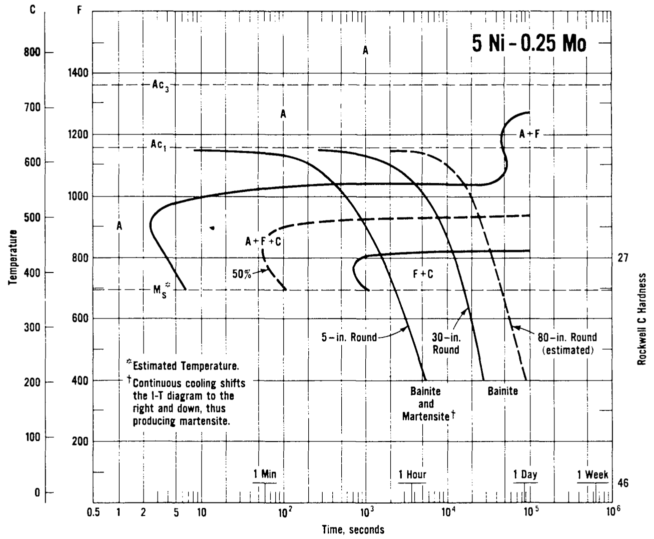
*Bulletin 2-A: "Quenched and Tempered Nickel Alloy Steels"
Bulletin 2-C: "Annealed, Hot Rolled and Normalized Nickel Alloy Steels"
Bulletin 6-C: "Annealing Characteristics of Nickel Alloy Steels"



C-0.16 Mn-0.52 Ni-3.36 Mo-0.19
Austenitized at 1650 F Grain Size: 8-9
Starting Criterion: 0.1% Transformation
A=Austenite F=Ferrite C=Carbide M=Martensite

Fig. 1. Isothermal transformation diagram of 3.5 per cent nickel-0.2 molybdenum steel with air-cooling curves for the center of 5-, 30- and 80-inch rounds. I-T Diagram from U.S. Steel.



C-0.17 Mn-0.49 Ni-5.07 Mo-0.24
Austenitized at 1700 F Grain Size: 5-6
Starting Criterion: 0.5% Transformation
A=Austenite F=Ferrite C=Carbide M=Martensite

Fig. 2. Isothermal transformation diagram of 5 per cent nickel-0.25 molybdenum steel with air-cooling curves for the center of 5-, 30- and 80-inch rounds. I-T Diagram from International Nickel Limited.

suppress the pearlite transformation and promote transformation to tougher bainitic structures, even at the low cooling rates typical of large forgings. The isothermal transformation diagrams in Figures 1 and 2 illustrate the ability of two nickel-molybdenum steels to suppress the pearlite transformation in section sizes ranging from 5 to 80 inches in diameter. Figure 1 shows that the austenite of a low-carbon 3.5 nickel-0.2 molybdenum steel (numbers are weight per cent) transforms to structures containing mixtures of ferrite, bainite and

TABLE I

Mechanical Properties of Nickel-Chromium-Molybdenum and Nickel-Chromium-Molybdenum-Vanadium Steel Rotor Forgings 38 to 52-Inches in Diameter[a]

Body Diameter, in.	Weight, lb	Cool from Austenite	Composition,[b] %						Location[c]	Tensile Properties				Transition Temp[d] (FATT), (Charpy V-Notch), F
			C	Mn	Ni	Cr	Mo	V		Tensile Strength, psi	Yield Strength (.02% Offset), psi	Elongation, %	Reduction of Area, %	
39	73,000	Oil	0.31	0.44	1.94	1.31	0.41	.09	Surface	110,000	88,000	16	42	140
40	101,000	Water	0.22	0.45	1.95	1.35	0.66	0.12	Surface	98,000	72,000	21	59	25
									Center	100,000	80,000	20	55	85
43	50,000	Oil	0.30	0.44	2.00	1.37	0.45	0.12	Surface	105,000	77,000	21	64	145
									Center	101,000	66,000	20	38	125
50	62,000	Air	0.24	0.31	2.65	1.53	0.59	0.11	Surface	114,000	92,000	21	63	95
									Center	113,000	87,000	20	62	75
52	96,000	Air	0.27	0.32	2.65	1.47	0.56	0.12	Surface	126,000	105,000	19	59	125
									Center	124,000	103,000	21	59	140
42	32,000	Air	0.25	0.36	2.68	1.56	0.58	0.11	Surface	114,000	92,000	20	56	20
									Center	116,000	91,000	20	58	4
44	51,000	Air	0.20	0.37	2.68	1.56	0.58	0.11	Surface	95,000	74,000	24	62	55
									Center	93,000	74,000	25	61	60
46	45,000	Air	0.28	0.35	2.69	1.58	0.59	—	Surface	103,000	76,000	16	47	100
									Center	106,000	78,000	23	62	110
47	64,000	Air	0.28	0.45	2.70	2.16	0.73	0.10	Surface	103,000	81,000	20	57	110
									Center	100,000	80,000	16	40	90
47	62,000	Water	0.28	0.23	2.74	1.45	0.58	—	Surface	104,000	75,000	20	48	0
									Center	101,000	74,000	24	61	120
38	72,000	Air	0.28	0.32	2.74	1.60	0.54	—	Surface	101,000	75,000	18	41	65
									Center	103,000	76,000	20	45	115
50	62,000	Air	0.23	0.33	2.75	1.47	0.50	0.10	Surface	114,000	92,000	21	61	105
									Center	111,000	86,000	21	60	100
44	51,000	Fog	0.28	0.33	2.75	1.57	0.57	—	Surface	103,000	76,000	24	64	25
									Center	100,000	74,000	21	41	130
50	126,000	Air	0.31	0.40	2.75	1.40	0.58	0.11	Surface	113,000	88,000	22	58	95
									Center	118,000	85,000	20	51	120
40	107,000	Water	0.24	0.60	2.83	1.30	0.50	.08	Surface	100,000	72,000	19	38	65
									Center	108,000	82,000	18	35	115
50	72,000	Air	0.23	0.33	2.95	1.00	0.44	0.11	Surface	113,000	88,000	21	61	115
									Center	115,000	83,000	20	56	125
44	45,000	Air	0.24	0.30	3.16	1.64	0.56	0.10	Surface	116,000	89,000	20	59	43
									Center	123,000	95,000	21	57	58

[a] Boyle, Curran, DeForest and Newhouse.[6]

[b] Phosphorus .008 to .022, Sulfur .007 to .029, Silicon 0.19 to 0.39.

[c] Surface location comprises radial specimens near surface; specimens from center are longitudinal.

[d] Temperature of 50% shear — 50% cleavage appearing fracture.

martensite, or to ferrite and bainite. In the more highly alloyed 5 nickel-0.25 molybdenum steel of Figure 2, the ferrite transformation also is suppressed and the austenite transforms to a mixture of bainite and martensite or to bainite only.

The relatively high levels of strength and ductility and the low transition temperature* that can be realized by alloying and heat treatment are illustrated in Table I and Figure 3. Yield strengths of 70,000 to 100,000 psi were obtained in generator and turbine rotor forgings ranging from 38 to 52 inches in diameter and 32,000 to 126,000 pounds in weight. The uniformity of properties from surface to center obtained with these nickel-chromium-molybdenum steels also should be noted.

Tables I and II and Figures 4 and 5 illustrate how composition and treatment can be modified to develop desired combinations of properties in heavy forgings. The effectiveness of spray quenching is evident in Figure 4 and the advantages of compositions of higher hardenability are apparent in Figure 5. The improvements in fracture toughness are particularly significant, as indicated by the lowering of transition temperature.

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*In this bulletin the transition temperature is the fracture-appearance transition temperature (FATT), defined as the temperature of 50% shear — 50% cleavage appearing fracture on broken Charpy V-notch specimens.

TABLE II

Mechanical Properties of Nickel-Molybdenum-Vanadium and Nickel-Chromium-Molybdenum-Vanadium Steel Rotor Forgings

		Tensile Properties				Charpy Impact (V-Notch)	
Heat Treatment	Location of Test	Tensile Strength, psi	Yield Strength (.02% offset), psi	Elongation, %	Reduction of Area, %	Transition Temp^{a} (FATT), F	Impact, ft-lb
	Ni-Mo-V^{b} Generator Rotor, 37-in. Body Dia (52,000 lb)						
1470 F, accelerated air cool; Temper 1130 F, FC to 392 F	Radial, 3-in. from surface	85,000	67,000^{c}	25	64	40	57-71 (at 75 F)
1470 F, water spray cool; Temper 1060 F, FC to 392 F	Radial, 3-in. from surface	98,000	81,000^{c}	24	64	0	68-71 (at 75 F)
	Longitudinal bore bar	94,000	73,000^{c}	24	63	15	92 (at 75 F)
	Ni-Cr-Mo-V^{b} Generator Rotor, 39-in. Body Dia (77,000 lb)						
1500 F, water spray cool; Double temper 1110 and 1140 F	Radial, 3-in. from surface	111,000	91,000	22	68	—	82 (at 0° F)
	Longitudinal bore bar	111,000	91,000	24	71	−75	—
	Ni-Cr-Mo-V^{b} Turbine Rotor, 53-in. Body Dia (87,000 lb)						
1500 F, water spray cool; Double temper 1110 and 1140 F	Radial, 3-in. from surface	120,000	101,000	21	64	−80	77 (at 0° F)
	Longitudinal bore bar	121,000	101,000	22	69	−45	—

a Temperature of 50% shear — 50% cleavage appearing fracture.

b

	Composition, %								
Rotor	C	Mn	P	S	Si	Ni	Cr	Mo	V
Ni-Mo-V Generator	0.20	0.33	.010	.016	.01	3.48	.06	0.30	.07
Ni-Cr-Mo-V Generator	0.24	0.34	.007	.013	.02	3.42	1.86	0.34	0.10
Ni-Cr-Mo-V Turbine	0.25	0.28	.008	.010	0.25	3.40	1.73	0.47	0.11

c 0.2% offset.

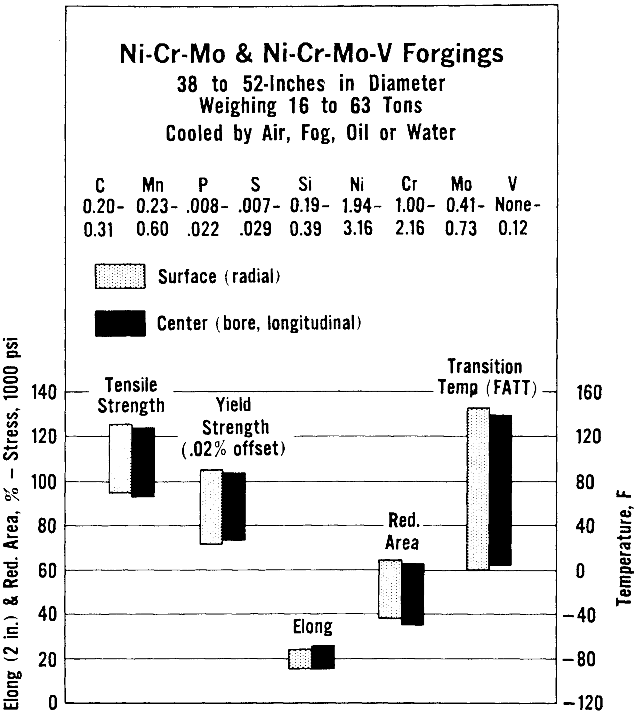

Fig. 3. Range of tensile properties and transition temperature of 17 forgings of nickel-chromium-molybdenum and nickel-chromium-molybdenum-vanadium steels for generator and low-pressure steam turbine rotors. See Table I for details. Boyle, Curran, DeForest and Newhouse.[6]

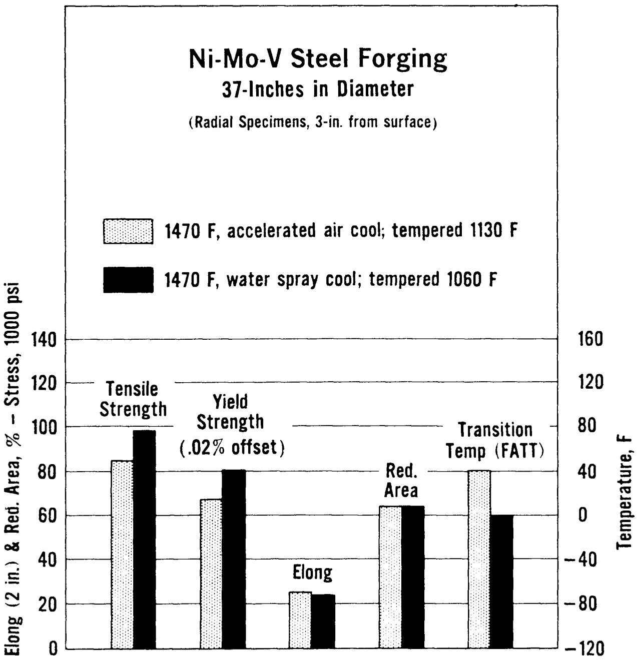

Fig. 4. Effect of air cooling vs water-spray quenching on tensile properties and transition temperature of a 3.5 per cent nickel-molybdenum-vanadium generator rotor forging. See Table II for details.

The sections that follow provide detailed information on the properties of nickel-chromium-molybdenum, nickel-molybdenum, nickel-chromium, and straight nickel steel forgings. Properties are related to section size, method of heat treatment, and requirements of standard specifications.

Information is available elsewhere on the following four subjects:

1. Manufacturing Practices
   (References 1-25)
2. Metallurgical Phenomena
   (References 1-15, 17, 18, 21-36)
3. Testing and Inspection Methods
   (References 1, 2, 6, 9-15, 18, 22-28, 30-34, 37-42)
4. Conditions Affecting Service Life
   (References 1, 2, 6, 8-15, 22-25, 42)

The "*Manual of Open Die Forgings*"[9] also contains much information on manufacture, treatment and testing of heavy forgings.

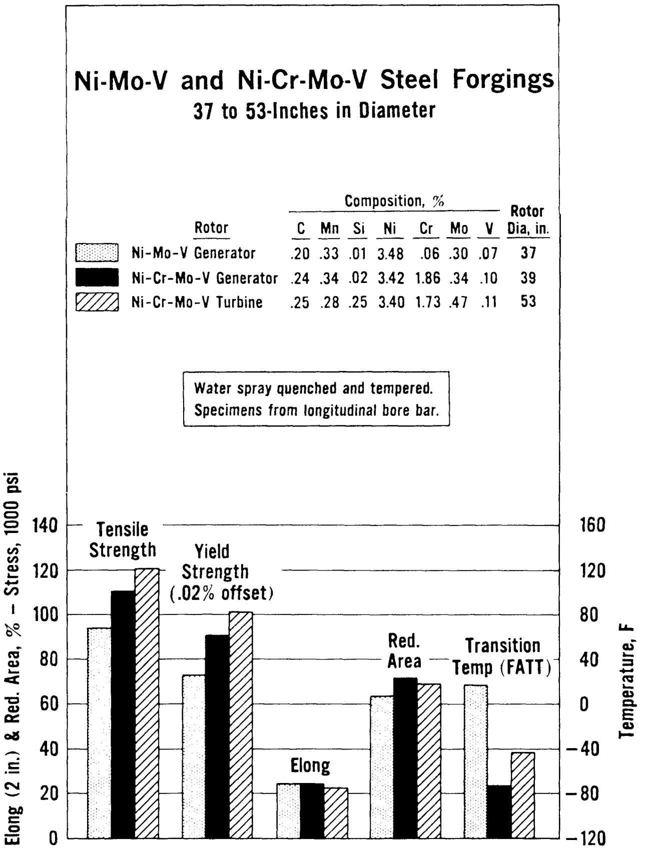

Fig. 5. Effect of composition on tensile properties and transition temperature of generator and turbine rotor forgings. See Table II for details.

STANDARD SPECIFICATIONS FOR FORGINGS

The mechanical properties shown in this bulletin are illustrative and *should not be used in specifications as minimum test requirements.* They are intended only to indicate the ability of the different classes of steel to meet the mechanical property requirements of standard specifications.

Published specifications which deal with alloy steel forgings include the following:

American Society for Testing and Materials

A 182	Forged or Rolled Alloy-Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service.
A 237	Alloy Steel Forgings for General Industrial Use.
A 238	Alloy Steel Forgings for Railway Use.
A 243	Carbon and Alloy Steel Ring, Hollow Cylinder and Disk Forgings for General Industrial Use.
A 288	Carbon and Alloy Steel Forgings for Magnetic Retaining Rings for Turbine Generators.
A 290	Carbon and Alloy Steel Forgings for Rings for Reduction Gears.
A 291	Carbon and Alloy Steel Forgings for Pinions and Gears for Reduction Gears.
A 292	Carbon and Alloy Steel Forgings for Turbine Generator Rotors and Shafts.
A 293	Carbon and Alloy Steel Forgings for Turbine Rotors and Shafts.
A 294	Heat-Treated Alloy Steel Forgings for Turbine Wheels and Disks.
A 320	Alloy Steel Bolting Materials for Low-Temperature Service.
A 336	Alloy Steel Seamless Drum Forgings.
A 350	Forged or Rolled Carbon and Alloy Steel Flanges, Forged Fittings, and Valves and Parts for Low-Temperature Service.
A 372	Carbon and Alloy Steel Forgings for Pressure Vessel Shells.
A 469	Vacuum Treated Steel Forgings for Generator Rotors.
A 470	Vacuum Treated Carbon and Alloy Steel Forgings for Turbine Rotors and Shafts.
A 471	Vacuum Treated Alloy Steel Forgings for Turbine Rotor Disks and Wheels.
A 508	Quenched and Tempered Vacuum Treated Carbon and Alloy Steel Forgings for Pressure Vessels.
A 521	Steel, Closed-Impression Die Forgings for General Industrial Use.
A 522	Forged or Rolled 9 per cent Nickel Alloy Steel Flanges, Fittings, Valves, and Parts for Low-Temperature Service.
A 541	Quenched and Tempered Carbon and Alloy Steel Forgings for Pressure Vessel Components.

Association of American Railroads

M-127	Alloy Steel Forgings (Classes and mechanical requirements identical with those of ASTM A 238).

Government

MIL-S-860 (Ships) Steel Forgings for Steam Turbine Rotors.

MIL-S-869 (Ships) Steel Bars, Billets and Forgings — Alloy Nitriding Application.

MIL-S-890 (Ships) Steel Forgings and Bars for Hulls, Engines and Ordnance.

MIL-S-19434 (Ships) Steel Gear and Pinion Forgings, Carbon and Alloy, Heat Treated, Naval Shipboard Propulsion Unit and Auxiliary Turbine.

MIL-S-23194 (Ships) Steel Forgings, Carbon and Low Alloy, for Pressure Vessels.

MIL-S-23284 (Ships) Steel Forgings, Carbon and Alloy, for Shafts, Sleeves, Couplings and Stocks (Rudders and Diving Planes).

MIL-S-23966 (Ships) Steel Bars, Billets and Forgings — Alloy Nitriding Application.

MIL-T-10458 (MR) Steel Forging for Tubular Parts for Cannons over 30 mm.

Specifications ASTM A 237, A 238 (AAR M-127) and A 243 and Specification MIL-S-890 are not restricted to specific compositions* or applications. The basic mechanical property requirements of these specifications are given in Table III. The properties apply to the smallest section sizes covered by the respective specifications and, therefore, *the specifications should be consulted* for the variation of properties with size, as illustrated in Table IV.

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*This is in contrast to other specifications, such as those in Tables V and VII, which cover both composition and mechanical properties.

TABLE III

Basic Tensile Requirements of Standard Specifications for Alloy Steel Forgings[a]

Class in Specifications				Minimum Tensile Properties[b]				
ASTM A 237	ASTM A 238 and AAR M-127	ASTM A 243	MIL-S-890	Tensile Strength, psi	Yield Strength[c] (0.2% offset), psi	Elongation (2 in.), %	Reduction of Area, %	Heat Treatment[d]
—	—	—	An	80,000	45,000	25	45	e
A	—	H	—	80,000	50,000	24	40	A, N, NT
B	—	I	—	80,000	55,000	26	52	NT
—	A	—	—	80,000	55,000	28	60	NT
C	—	J	—	90,000	60,000	22	44	NT
—	B	—	—	90,000	60,000	24	48	NT
—	C	—	—	95,000	72,000	23	55	NT
C1	—	—	—	110,000	85,000	16	40	NT, NNT
—	—	—	HG	95,000	65,000	21	45	e
D	—	K	—	95,000	70,000	20	50	NQT
—	D	—	—	95,000	70,000	23	54	NQT
E	E	L	Alloy No. 3	105,000	80,000	20	50	NQTe
—	—	—	Alloy No. 4	120,000	100,000	15	40	e
—	—	—	Alloy No. 2	120,000	105,000	18	50	e
F	F	M	—	125,000	105,000	16	50	NQT
G	—	N	—	145,000	120,000	15	45	NQT
—	—	—	Alloy No. 1	170,000	140,000	10	35	e
H	—	O	—	170,000	140,000	13	40	NQT

[a] As determined on longitudinal specimens taken from prolongations at locations midway between surface and center of solid forgings and at the center of the wall of bored forgings.

[b] These values are for the smallest sizes covered. Strength and ductility requirements are lower for larger forgings; consult specifications for details.

[c] Yield point is specified for ASTM alloys that are annealed, normalized or normalized and tempered. Yield strength at .01% offset is specified for MIL-S-890.

[d] A=Annealed. N=Normalized. Q=Liquid Quenched. T=Tempered.

[e] No specific type of heat treatment required in MIL-S-890.

TABLE IV

Property Requirements of Several Standard Specifications for Alloy Steel Forgings of Various Sizes in Quenched and Tempered Condition[a]

Class in Specification			Size, in.		Minimum Tensile Properties			
ASTM A 237	ASTM A 238 and AAR M-127	ASTM A 243	Solid Diameter or Thickness	Bored Wall Thickness[b]	Tensile Strength, psi	Yield Strength (0.2% offset), psi	Elongation (2 in.), %	Reduction of Area, %
E	—	—	up to 8	up to 4	105,000	80,000	20	50
E	—	—	8 to 12	4 to 6	100,000	75,000	19	50
E	—	—	12 to 20	6 to 10	95,000	70,000	19	50
—	E	L	up to 7	up to 3½	105,000	80,000	20	50
—	E	L	7 to 10	3½ to 5	100,000	75,000	19	50
—	E	—	—	5 to 8	95,000	70,000	19	50
F	F	M	up to 4	up to 2	125,000	105,000	16	50
F	F	M	4 to 7	2 to 3½	115,000	95,000	16	45
F	F	M	7 to 10	3½ to 5	110,000	85,000	16	45

[a] As determined on longitudinal specimens taken from prolongations at locations midway between surface and center of solid forgings and at the center of the wall of bored forgings.

[b] Not included in ASTM A 243.

TABLE V

Summary of Composition and Mechanical Property Requirements of ASTM Specifications for Nickel Alloy Steel Heavy Forgings

											Charpy Impact (V-Notch)[a]	
	Composition, %						Minimum Tensile Properties[a]					
Specification	C	Mn	Ni	Cr	Mo	V	Tensile Strength, psi	Yield Strength (.02% offset), psi	Elongation (2 in.), %	Reduction of Area, %	Max Transition Temp,[b] F	Min Impact at 75 F, ft-lb
ASTM A 288	**Magnetic Retaining Rings for Turbine Generators (Vacuum Treated) — AQT or NQT[c]**											
Class 3	0.45 max	0.60-1.00	0.85-2.00[d]	0.70-1.25	0.15 min	Optional	110,000T	80,000T	18T	50T	—	20T[e]
Class 4	0.45 max	1.00 max	1.65-3.50	0.70-1.25	0.20 min	.07-0.12	120,000T	95,000T	18T	45T	—	35T[e]
Class 5	0.45 max	1.00 max	1.65-3.50	0.70-1.25	0.20 min	.07-0.12	130,000T	110,000T	16T	40T	—	30T[e]
Class 6	0.45 max	1.00 max	1.65-3.50	0.70-1.25	0.20 min	.07-0.12	140,000T	125,000T	14T	40T	—	30T[e]
Class 7	0.45 max	1.00 max	1.65-3.50	0.70-1.25	0.20 min	.07-0.12	150,000T	135,000T	13T	35T	—	25T[e]
Class 8	0.45 max	1.00 max	1.65-3.50	0.70-1.25	0.20 min	.07-0.12	165,000T	150,000T	12T	35T	—	25T[e]
ASTM A 290	**Rings for Reduction Gears — QT[c]**											
Class E	0.30-0.40	0.55-0.90	1.65-2.00	0.60-0.90	0.20-0.30	—	135,000T	110,000T[f]	16T	40T	—	—
Class F	0.30-0.40	0.55-0.90	1.65-2.00	0.60-0.90	0.20-0.30	—	145,000T	120,000T[f]	13T	37T	—	—
Class G	0.30-0.40	0.55-0.90	1.65-2.00	0.60-0.90	0.20-0.30	—	165,000T	135,000T[f]	11T	27T	—	—
ASTM A 291	**Pinions for Reduction Gears — QT[c] (Class 3 is NT)**											
Class 3	0.45 max	—	3.00 max	1.25 max	0.15 min	0.10 max	105,000[g]	80,000[f,g]	19L[g], 16T[g]	45L[g], 30T[g]	—	—
Class 4	0.35-0.45	—	1.65 min	0.60 min	0.20 min	0.10 max	117,000[g]	92,000[f,g]	14L[g], 12T[g]	35L[g], 30T[g]	—	—
Class 5	0.35-0.45	—	1.65 min	0.60 min	0.20 min	0.10 max	135,000[g]	110,000[f,g]	14L[g], 12T[g]	35L[g], 30T[g]	—	—
Class 6	0.35-0.45	—	1.65 min	0.60 min	0.20 min	0.10 max	140,000[g]	115,000[f,g]	14L[g], 12T[g]	35L[g], 30T[g]	—	—
Class 7	0.40-0.50	—	1.65 min	0.60 min	0.20 min	0.10 max	165,000[g]	135,000[f,g]	12L[g], 10T[g]	30L[g], 25T[g]	—	—
ASTM A 292	**Turbine Generator Rotors and Shafts — AS, NTS or NNTS[c,h]**											
Class 2	0.30 max	0.70 max	2.00 min	0.50 max	0.20 min	.03-0.12	75,000	55,000	22L, 18R	45L, 40R	175R[n]	15R[n]
Class 3	0.30 max	0.70 max	2.00 min	0.50 max	0.20 min	.03-0.12	90,000	70,000	20L, 16R	40L, 35R	175R[n]	12R[n]
Class 4	0.35 max	0.70 max	2.50 min	0.70 max	0.20 min	.03-0.12	105,000	80,000	18L, 14R	38L, 30R	175R[n]	10R[n]
Class 5	0.35 max	0.70 min	2.50 min	0.70 max	0.20 min	.03-0.12	115,000	90,000	16L, 12R	32L, 25R	p	p
ASTM A 293	**Turbine Rotors and Shafts — NTS or NNTS[c,h]**											
Class 2	0.30 max	0.70 max	2.00 min	0.75 max	0.25 min[k]	.03-0.12	80,000	55,000	22L, 18R	45L, 40R	175R[n]	15R[n]
Class 3	0.30 max	0.70 max	2.00 min	0.75 max	0.25 min[k]	.03-0.12	95,000	70,000	20L, 16R	40L, 35R	175R[n]	12R[n]
Class 4	0.35 max	0.70 max	2.50 min	0.75 max	0.25 min[k]	.03-0.12	105,000	80,000	18L, 15R	40L, 30R	175R[n]	10R[n]
Class 5	0.35 max	0.70 max	2.50 min	1.25 max	0.25 min[k]	.03 min	120,000	95,000	17L, 14R	40L, 30R	p	p
ASTM A 294	**Turbine Wheels and Disks — NT or QT[c]**											
Class B1	0.45 max	0.60-1.00	1.65-3.50	0.50-1.25	0.20 min	Optional	90,000T	65,000T	20T	50T	—	15T
Class B2	0.45 max	0.60-1.00	1.65-3.50	0.50-1.25	0.20 min	Optional	100,000T	75,000T	20T	50T	—	15T
Class B3	0.45 max	0.60-1.00	1.65-3.50	0.50-1.25	0.20 min	Optional	110,000T	85,000T	19T	48T	—	15T
Class B4	0.45 max	0.60-1.00	1.65-3.50	0.50-1.25	0.20 min	Optional	120,000T	95,000T	18T	46T	—	15T
Class B5	0.45 max	0.60-1.00	1.65-3.50	0.50-1.25	0.20 min	Optional	125,000T	105,000T	18T	45T	—	15T
Class B6	0.45 max	0.60-1.00	1.65-3.50	0.50-1.25	0.20 min	Optional	130,000T	115,000T	16T	42T	—	p
Class B7	0.45 max	0.60-1.00	1.65-3.50	0.50-1.25	0.20 min	Optional	140,000T	125,000T	15T	40T	—	p
Class C1	0.35 max	0.60-0.90	1.50-3.50	0.70 max	0.20 min	.03-0.12	90,000T	65,000T	20T	50T	—	15
Class C2	0.35 max	0.60-0.90	1.50-3.50	0.70 max	0.20 min	.03-0.12	100,000T	75,000T	20T	50T	—	15
Class C3	0.35 max	0.60-0.90	1.50-3.50	0.70 max	0.20 min	.03-0.12	110,000T	85,000T	19T	48T	—	15
Class C4	0.35 max	0.60-0.90	1.50-3.50	0.70 max	0.20 min	.03-0.12	120,000T	95,000T	18T	46T	—	15
Class C5	0.35 max	0.60-0.90	1.50-3.50	0.70 max	0.20 min	.03-0.12	125,000T	105,000T	18T	45T	—	15
Class C6	0.35 max	0.60-0.90	1.50-3.50	0.70 max	0.20 min	.03-0.12	130,000T	115,000T	16T	42T	—	p
Class C7	0.35 max	0.60-0.90	1.50-3.50	0.70 max	0.20 min	.03-0.12	140,000T	125,000T	15T	40T	—	p
ASTM A 336	**Seamless Drums and Other Pressure Vessel Components — A or NT[c]**											
Class F31	0.35 max	0.50-0.90	2.25-3.00	—	0.20-0.50	0.15 max	95,000	70,000[f]	18T	35T	—	—
Class F32	0.35 max	0.50-0.90	0.50-1.00	3.00-3.60	0.30-0.50	.05-0.15	100,000	60,000[f]	18T	35T	—	—

TABLE V (Continued)

Summary of Composition and Mechanical Property Requirements of ASTM Specifications for Nickel Alloy Steel Heavy Forgings

	Composition, %						Minimum Tensile Properties[a]				Charpy Impact (V-Notch)[a]	
Specification	C	Mn	Ni	Cr	Mo	V	Tensile Strength, psi	Yield Strength (.02% offset), psi	Elongation (2 in.), %	Reduction of Area, %	Max Transition Temp,[b] F	Min Impact at 75 F, ft-lb
ASTM A 469	**Vacuum Treated Generator Rotors — NTS or QTS[c]**											
Class 2	0.25 max	0.60 max	2.50 min	0.50 max	0.20-0.50	.03 min	80,000	55,000	20	50	100R[n]	30R[n]
Class 3	0.27 max	0.60 max	2.50 min	0.50 max	0.20-0.50	.03 min	90,000	70,000	20	50	100R[n]	30R[n]
Class 4	0.27 max	0.70 max	3.00 min	0.50 max	0.20-0.60	.03 min	100,000	80,000	17	45	120R[n]	25R[n]
Class 5	0.31 max	0.70 max	3.00 min	0.50 max	0.20-0.70	.05-0.15	110,000	90,000	15	40	175R[n]	15R[n]
Class 6	0.28 max	0.60 max	3.25-4.00	1.25-2.00	0.30-0.60	.05-0.15	115,000	95,000	17	45	50R[n]	40R[n]
ASTM A 470	**Vacuum Treated Turbine Rotors and Shafts — NNTS[h] for Classes 2 to 4; NQTS for Classes 5 to 7[c]**											
Class 2	0.25 max	0.20-0.60	2.50 min	0.75 max	0.25 min	.03 min	80,000	55,000	22L, 20R	50L, 50R	100R[n]	28R[n]
Class 3	0.28 max	0.20-0.60	2.50 min	0.75 max	0.25 min	.03 min	90,000	70,000	20L, 17R	48L, 45R	110R[n]	25R[n]
Class 4	0.28 max	0.20-0.60	2.50 min	0.75 max	0.25 min	.03 min	105,000	85,000	17L, 16R	45L, 40R	140R[n]	20R[n]
Class 5	0.28 max	0.20-0.60	3.25-4.00	1.25-2.00	0.30-0.60	.05-0.15	90,000	70,000	20L, 18R	52L, 50R	30R[n]	50R[n]
Class 6	0.28 max	0.20-0.60	3.25-4.00	1.25-2.00	0.30-0.60	.05-0.15	105,000	85,000	18L, 17R	52L, 50R	40R[n]	45R[n]
Class 7	0.28 max	0.20-0.60	3.25-4.00	1.25-2.00	0.30-0.60	.05-0.15	120,000	95,000	18L, 17R	52L, 50R	50R[n]	40R[n]
ASTM A 471	**Vacuum Treated Turbine Rotor Disks and Wheels — QT[c]**											
Class 1	0.40 max	0.70 max	2.00-4.00	2.00 max	0.20-0.70	.05 min	100,000	75,000- 95,000	20	50	0	40
Class 2	0.40 max	0.70 max	2.00-4.00	2.00 max	0.20-0.70	.05 min	105,000	85-000,-105,000	19	48	0	40
Class 3	0.40 max	0.70 max	2.00-4.00	2.00 max	0.20-0.70	.05 min	110,000	95,000-115,000	18	45	0	37
Class 4	0.40 max	0.70 max	2.00-4.00	2.00 max	0.20-0.70	.05 min	120,000	105,000-125,000	17	43	0	37
Class 5	0.40 max	0.70 max	2.00-4.00	2.00 max	0.20-0.70	.05 min	130,000	115,000-135,000	16	40	15	35
Class 6	0.40 max	0.70 max	2.00-4.00	2.00 max	0.20-0.70	.05 min	140,000	125,000-145,000	15	40	15	35
ASTM A 508	**Vacuum Treated Forgings for Pressure Vessels — QT[c]**											
Class 2	0.27 max	0.50-0.80	0.50-0.90	0.25-0.45	0.55-0.70	.05 max	80,000L	50,000L[f]	18L	38L	—	30L[m] (40 F)
Class 3	0.15-0.25	1.20-1.50	0.40-0.80	—	0.45-0.60	.05 max	80,000L	50,000L[f]	18L	38L	—	30L[m] (40 F)
Class 4	0.25 max	0.20-0.40	2.75-3.90	1.50-2.00	0.40-0.60	.03 max	105,000L	85,000L[f]	18L	45L	—	35L[m] (−20 F)
Class 5	0.25 max	0.20-0.40	2.75-3.90	1.50-2.00	0.40-0.60	.05-0.15	105,000L	85,000L[f]	18L	45L	—	35L[m] (−20 F)
ASTM A 541	**Forgings for Pressure Vessel Components — QT[c]**											
Class 2	0.27 max	0.50-0.80	0.50-0.90	0.25-0.45	0.55-0.70	.06 max	80,000L	50,000L[f]	18L	38L	—	30L[m] (40 F)
Class 3	0.15-0.25	1.20-1.50	0.40-0.80	—	0.45-0.60	.06 max	80,000L	50,000L[f]	18L	38L	—	30L[m] (40 F)
Class 7	0.23 max	0.20-0.40	2.75-3.90	1.25-2.00	0.40-0.60	.03 max	105,000L	85,000L[f]	18L	48L	—	35L[m] (40 F)
Class 8	0.23 max	0.20-0.40	2.75-3.90	1.25-2.00	0.40-0.60	.05-0.15	105,000L	85,000L[f]	18L	48L	—	35L[m] (40 F)

[a] L Longitudinal. T Tangential (Transverse). R = Radial.

[b] Temperature of 50% shear — 50% cleavage appearing fracture (FATT).

[c] A = Annealed. N Normalized. Q Quenched. T = Tempered. S Stress Relieved.

[d] For sizes over 2.5-inch diameter or thickness.

[e] Notch-axis direction is radial.

[f] 0.2% offset.

[g] Solid diameter or wall thickness from 10 to 20 inches. Required strength and ductility are higher for smaller forgings and lower for larger ones; consult specification for details.

[h] Liquid quenching and/or other cooling faster than in air (normalizing) are permissible, if agreed upon by manufacturer and purchaser.

[k] When specified by the purchaser, the molybdenum content may be 0.40% min.

[m] Notch-axis direction is to be normal to nearest heat-treated surface.

[n] Notch-axis direction is tangential.

[p] Should be determined for each forging for information. Specification to be set later.

NICKEL-CHROMIUM-MOLYBDENUM STEEL FORGINGS

Nickel-chromium-molybdenum alloy steels, frequently also containing vanadium, are used widely for large, thick-section forgings requiring high strength. Figure 6 shows that yield strengths† of 90,000 to 100,000 psi can be achieved with a nominal composition, in per cent, of 3.50 nickel, 1.75 chromium, 0.50 molybdenum, 0.10 vanadium and 0.25 carbon in water-quenched forgings 65 inches in diameter and weighing as much as 110,000 pounds.

Normalized and Tempered

The properties of representative normalized and tempered 1.8 to 2.5 per cent nickel-chromium-molybdenum forgings ranging from 4 to 18 inches in diameter are shown in Figures 7a and 7b. Figure 7a shows data for 1.8 per cent nickel-chromium-molybdenum compositions at the nominal 0.40 per cent carbon level, whereas 7b covers 2.5 per cent nickel-chromium-molybdenum steels with nominally 0.30 per cent carbon. Such compositions provide yield strengths from 60,000 to 90,000 psi in a wide range of section sizes. They meet the requirements of many of the standard specifications (Table III), some of which for easy comparison are superimposed on the tensile property charts of Figures 7a and 7b.

An examination of the ASTM specifications in Table V shows that the normalized and tempered nickel-chromium-molybdenum steels of Figures 7a and 7b can be used for Classes B1, B2, C1 and C2 of ASTM Specification A 294 and Class F31 of ASTM A 336. Table V also shows that other normalized and tempered nickel-chromium-molybdenum steels, with or without vanadium, are used for classes in the following ASTM Specifications: A 291, A 292, A 293, A 294, A 336, A 469 and A 470.

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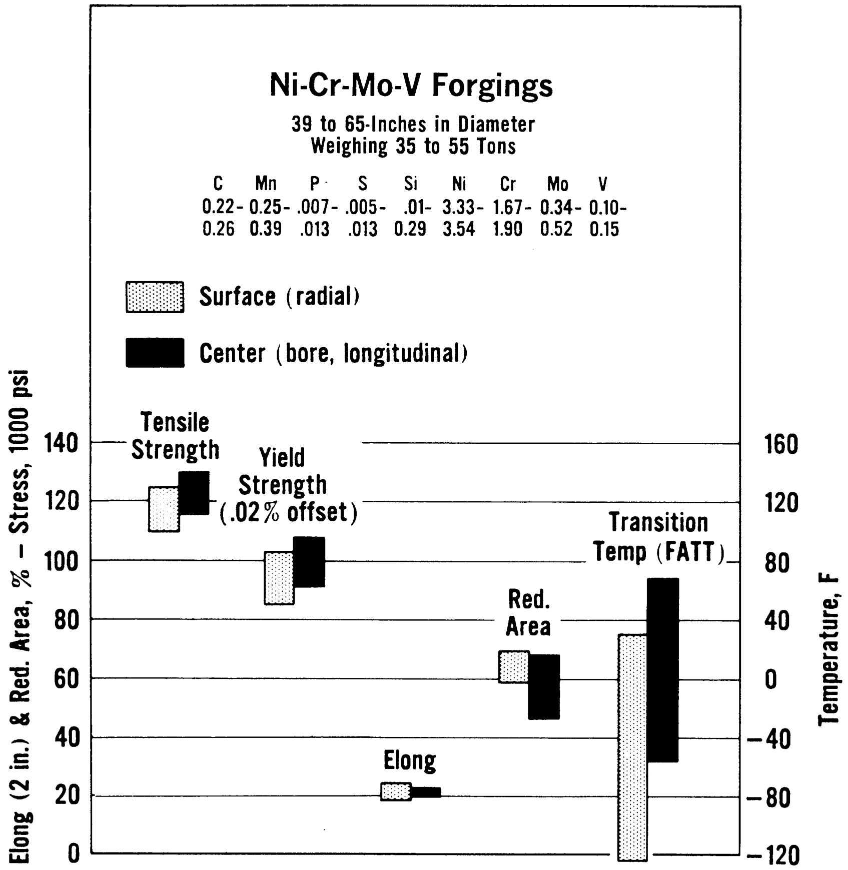
†Unless otherwise noted, tensile properties reported in this bulletin refer to longitudinal specimens taken from locations —1. Midway between surface and center of prolongations of solid forgings (the "half-radius" or "one-quarter thickness") or —2. Midway between the outer and inner wall surfaces of prolongations of bored forgings.



C	Mn	P	S	Si	Ni	Cr	Mo	V
0.22-0.26	0.25-0.39	.007-.013	.005-.013	.01-0.29	3.33-3.54	1.67-1.90	0.34-0.52	0.10-0.15

Fig. 6. Range of tensile properties and transition temperatures of 15 water-quenched and tempered forgings of 3.5 per cent nickel-chromium-molybdenum-vanadium steel for generator and low-pressure steam turbine rotors. Boyle, Curran, DeForest and Newhouse.[6]

Nickel-Chromium-Molybdenum Steel Forgings up to 18-Inch Sections

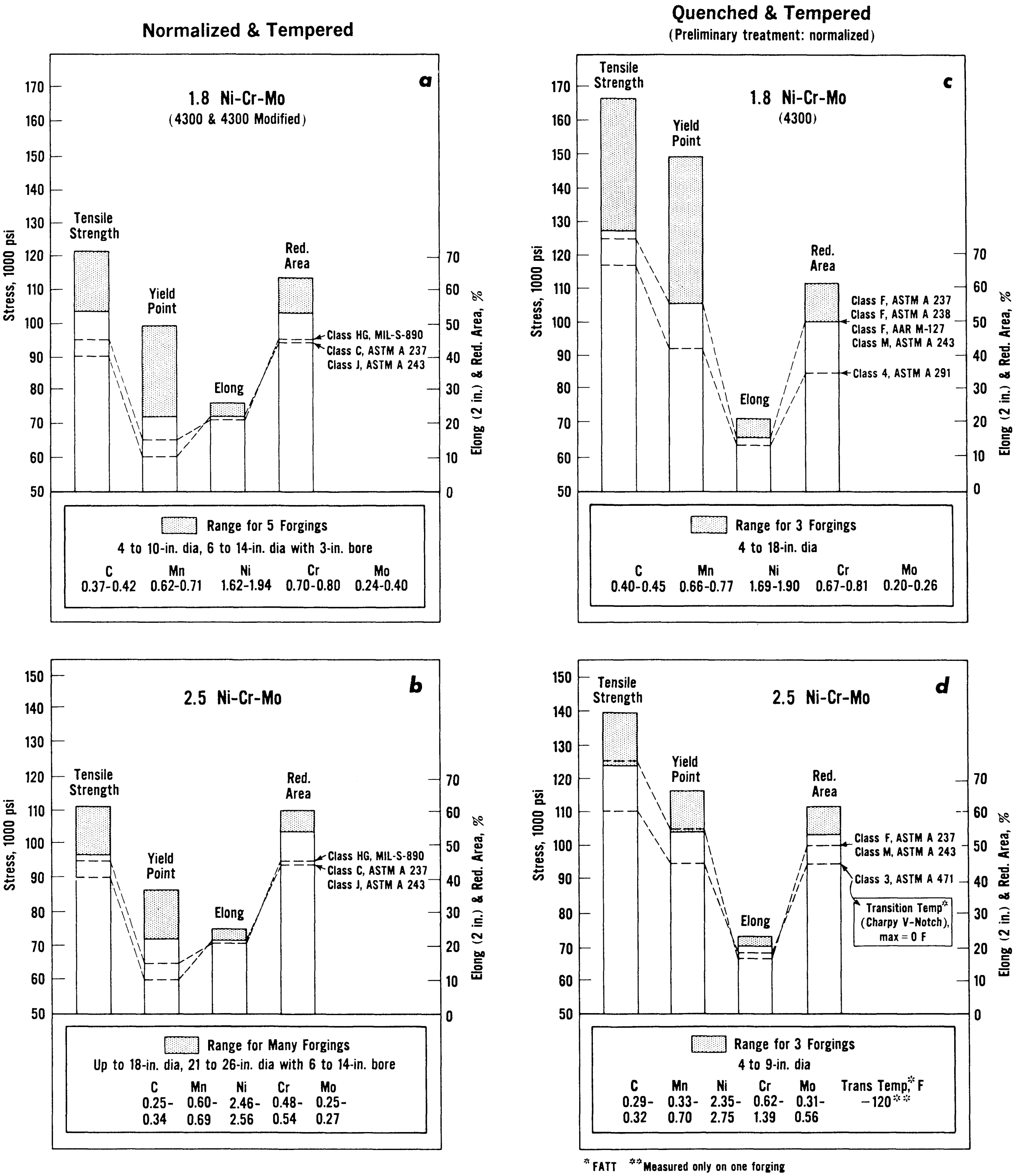


Fig. 7. Representative tensile properties of nickel-chromium-molybdenum steel forgings and how they compare with the minima in some standard specifications for alloy steel forgings. See Tables III and V for more details on specifications.

Quenched and Tempered

Light Section. Properties typical of quenched and tempered nickel-chromium-molybdenum steel forgings of relatively light section (18-inch maximum diameter) are shown in Figures 7c and 7d. These nickel-chromium-molybdenum steels contain nominally in per cent, 1.8 nickel with 0.40 carbon and 2.5 nickel with 0.30 carbon. In comparison with the normalized and tempered properties in Figures 7a and 7b, the more effective hardening, brought about by liquid quenching, increases the yield strengths to well above 100,000 psi and provides excellent fracture toughness.

Figure 8 and Table VI summarize properties obtained with low-carbon (0.16 to 0.19 per cent), 3 per cent nickel-chromium-molybdenum-vanadium steels in section sizes from 4 to 11 inches. The data were developed from quenched and tempered steels forged for a pressure vessel for nuclear applications. The good combination of strength and toughness exceeds the requirements for Class 4 of ASTM A 508, as shown by Figure 8.

Several ASTM specifications for even lighter sections, up to 4- or 5-inch thicknesses, are presented in Table VII. In general, such thin sections are considered to be outside the scope of this bulletin but Table VII is included here for the convenience of the reader.

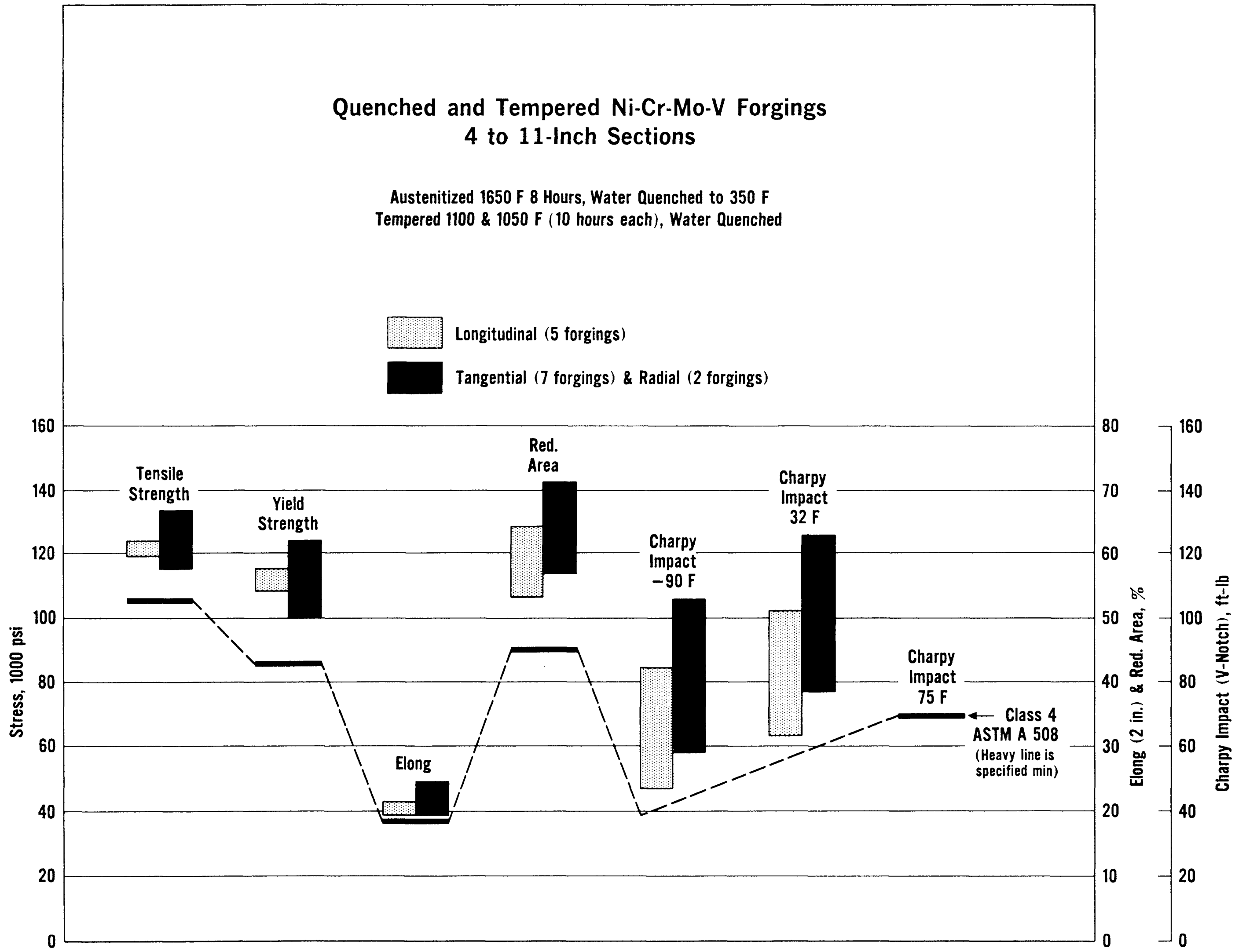


Fig. 8. Range of average mechanical properties for quenched and tempered 3 per cent nickel-chromium-molybdenum-vanadium steel forgings for a heavy-walled pressure vessel for nuclear reactor applications. For composition and other details, see Table VI. Greenberg.[25]

TABLE VI

Average Mechanical Properties for Quenched and Tempered Nickel-Chromium-Molybdenum-Vanadium Steel Forgings in 4 to 11-Inch Sections for Nuclear Reactor Applications[a]

Forging Number and Wall Thickness		Specimen Orientation[b]	Tensile Properties[c]				Charpy Impact (V-Notch)[c]			
							−90 F		32 F	
No.	In.		Tensile Strength, psi	Yield Strength (0.2% offset), psi	Elongation, %	Reduction of Area, %	Impact, ft-lb	Shear Fracture, %	Impact, ft-lb	Shear Fracture, %
1	5	L	127,000	115,000	21	64	66	85	101	100
		T	129,000	119,000	21	65	83	85	116	100
2	4	L	127,000	111,000	21	62	63	85	82	100
		T	126,000	108,000	24	70	63	85	101	100
3	5½	L	127,000	113,000	19	58	82	100	102	100
		T	124,000	110,000	22	71	106	100	126	100
4	6	L	119,000	109,000	19	53	46	90	63	100
		T	119,000	105,000	22	70	76	85	100	100
5	6	L	127,000	112,000	20	61	84	100	102	100
		T	126,000	113,000	22	69	89	95	122	100
6	11	R	115,000	101,000	21	61	69	90	89	100
		T	115,000	103,000	20	59	58	85	77	100
7	11	R	132,000	123,000	19	57	63	90	80	100
		T	133,000	124,000	20	64	68	95	77	100
ASTM A 508, Class 4			105,000 min	85,000 min	18 min	45 min	35 ft-lb min at 75 F			

[a] Greenberg.[25] Forgings were austenitized 1600 F for 8 hr, water quenched to 350 F, tempered 1100 and 1050 F, 10 hr each, and water quenched.

[b] L = Longitudinal. T = Tangential. R = Radial.

[c] Composition (Range for the 7 steel forgings and ASTM A 508, Class 4), %

	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu	Ti
Forgings	0.16-0.19	0.27-0.31	.009-.011	.006-.014	0.25-0.36	2.93-3.18	1.43-1.65	0.44-0.53	.01	.09-0.20	.005-.007
A 508, Class 4	0.25 max	0.20-0.40	.020 max	.020 max	0.30 max	2.75-3.90	1.5-2.0	0.40-0.60	.03 max	—	—

TABLE VII

Summary of ASTM Specifications for Nickel Alloy Steel Light Forgings

Specification	Composition, %						Minimum Tensile Properties[a]				Charpy Impact (V-Notch)	
	C	Mn	Ni	Cr	Mo	Other	Tensile Strength, psi	Yield Strength (0.2% offset), psi	Elongation (2 in.) %	Reduction of Area, %	Max Transition Temp,[b] F	Min Impact at −320 F, ft-lb
ASTM A 320 Bolting Materials for Low Temperature Service (Up to 4 in.) — QT[c] (Except Grade L10 is N)												
Grade L9	0.36-0.44	0.65-0.95	3.25-3.75	—	—	—	125,000[d]	105,000[d]	16[d]	50[d]	−225	—
							105,000[e]	80,000[e]	20[e]	50[e]	−225	—
Grade L10	0.15-0.20	0.40-0.60	3.25-3.75	—	—	—	70,000[f]	40,000[f]	25[f]	40[f]	−150	—
Grade L43	0.38-0.43	0.60-0.85	1.65-2.00	0.70-0.90	0.20-0.30	—	125,000[f]	105,000[f]	16[f]	50[f]	−150	—
ASTM A 350 Flanges, Forged Fittings, and Valves and Parts for Low Temperature Service (Up to 5 in.) — N, NT or QT[c]												
Grade LF3	0.20 max	0.90 max	3.25-3.75	—	—	—	70,000	40,000	25	50	−150	—
Grade LF4	0.12 max	0.55-1.00	0.50-0.95	0.50-0.95	—	0.40-0.75 Cu .04-0.30 Al	60,000	30,000	25	38	−150	—
ASTM A 372 Forgings for Pressure Vessel Shells (Relatively thin wall) — N, NT or QT[c]												
Class V-C	0.26-0.34	0.70-1.00	0.40-0.70	0.40-0.65	0.15-0.25	—	120,000	70,000	18	—	—	—
Class V-D	0.31-0.39	0.75-1.05	0.40-0.70	0.40-0.65	0.15-0.25	—	120,000	70,000	18	—	—	—
Class VI	0.18 max	0.10-0.40	2.00-3.25	1.00-1.80	0.20-0.60	—	100,000	80,000	20	—	—	—
Class VII	0.38-0.43	0.60-0.80	1.65-2.00	0.70-0.90	0.20-0.30	—	155,000	135,000	12	—	—	—
ASTM A 522 9% Nickel Alloy Steel Flanges, Fittings, Valves and Parts for Low Temperature Service (Up to 5 in.) — NNT[g] or QT[c]												
	0.13 max	0.90 max	8.50-9.50	—	—	—	100,000	75,000	22	45	—	25

[a] Longitudinal.

[b] 15 ft-lb Charpy, Keyhole-notch or U-notch specimens.

[c] N = Normalized. Q = Quenched. T = Tempered.

[d] 2½-inch diameter and under.

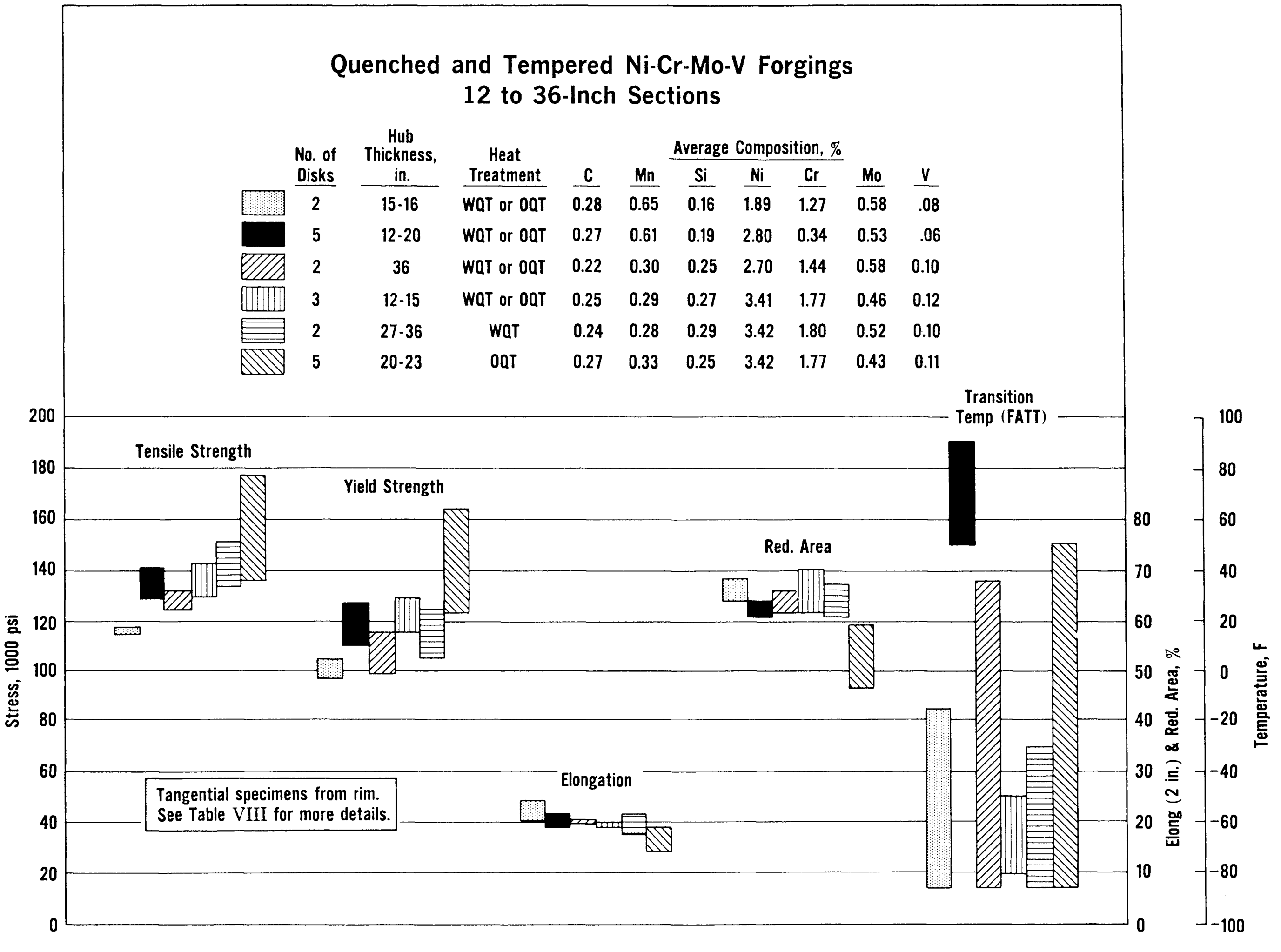
[e] 2½ to 4-inch diameter.

[f] 4-inch diameter and under.

[g] Up to 3-inch section thickness for NNT.

Medium Section. Properties typical of forgings of intermediate section thickness, in the range 12 to 36 inches, are presented in Figure 9 and Table VIII. Yield strengths of 100,000 psi, and more, are attained along with excellent fracture toughness. Data are for liquid-quenched turbine rotor disk forgings of nickel-chromium-molybdenum-vanadium steels containing about 2 to 3.5 per cent nickel and less than 0.30 per cent carbon.

Heavy Section. Properties in large forgings of nickel-chromium-molybdenum-vanadium steels have been mentioned in the introduction and are shown in Tables I and II and in Figures 3, 5 and 6. The data in Table I and Figure 3 are from a program aimed at developing forgings with lower transition temperatures. They show that compositions with 2 to 3 per cent nickel provide yield strengths in the range 75,000 to 100,000 psi in rotor forgings 38 to 52 inches in diameter and weighing as much as 63 tons. Figure 6 shows data developed in 15 quenched and tempered nickel-chromium-molybdenum-vanadium generator and turbine rotors, up to 65 inches in diameter, containing nominally 0.25 per cent carbon and 3.5 per cent nickel. As in Figure 3, remarkably uniform tensile properties are developed with yield strength in the range of 90,000 to 105,000 psi. In addition, the compositions in Figure 6 show substantially improved fracture toughness over those in Figure 3 as indicated by the lower transition temperatures (FATT). Another indication of the excellent combinations of high yield strength and low transition temperature, which can be obtained with nickel-chromium-molybdenum-vanadium heavy forgings, is shown in Figure 10.



Quenched and Tempered Ni-Cr-Mo-V Forgings
12 to 36-Inch Sections

	No. of Disks	Hub Thickness, in.	Heat Treatment	C	Mn	Si	Ni	Cr	Mo	V
						Average Composition, %				
░	2	15-16	WQT or OQT	0.28	0.65	0.16	1.89	1.27	0.58	.08
■	5	12-20	WQT or OQT	0.27	0.61	0.19	2.80	0.34	0.53	.06
▨	2	36	WQT or OQT	0.22	0.30	0.25	2.70	1.44	0.58	0.10
▥	3	12-15	WQT or OQT	0.25	0.29	0.27	3.41	1.77	0.46	0.12
▤	2	27-36	WQT	0.24	0.28	0.29	3.42	1.80	0.52	0.10
▧	5	20-23	OQT	0.27	0.33	0.25	3.42	1.77	0.43	0.11

Tangential specimens from rim. See Table VIII for more details.

Fig. 9. Typical range of mechanical properties of liquid quenched and tempered nickel-chromium-molybdenum-vanadium steels in turbine rotor disk forgings.

Compliance with Standard Specifications

Quenched and tempered nickel-chromium-molybdenum steels can meet all the requirements of the standard specifications listed in Table III. Table V shows that these steels are required for Classes 3 to 8 of ASTM Specification A 288, Classes E to G of A 290, Classes 4 to 7 of A 291, Classes 5 to 7 of A 470, Classes 1 to 6 of A 471, Classes 2 to 5 of A 508 and Classes 2, 3, 7 and 8 of A 541. They can be used interchangeably with normalized and tempered steels for all classes of ASTM A 294 and for Classes 2 to 6 of A 469.

Elevated Temperature Properties

Nickel-chromium-molybdenum steels are used frequently in applications such as the low-temperature stage of steam turbine rotors, requiring strength retention to about 650 F. Rupture and creep properties at elevated temperatures and short-time tensile tests on some nickel alloy steels are given in another bulletin.*

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*Bulletin 4-D: "Elevated Temperature Properties of Nickel Alloy Steels."

TABLE VIII

Typical Mechanical Properties of Quenched and Tempered Forgings of Nickel-Chromium-Molybdenum-Vanadium Steels in Turbine Rotor Disks of 12 to 36-Inch Sections

Hub Thickness, in.	Composition, %							Heat Treatment[a]	Test Location[b]	Tensile Properties				Charpy Impact (V-Notch)	
	C	Mn	Si	Ni	Cr	Mo	V			Tensile Strength, psi	Yield Strength (0.2% offset), psi	Elongation, %	Reduction of Area, %	Transition Temp (FATT), F	Impact at 75 F, ft-lb
15-16 (2 disks)	0.28 0.28	0.63 0.67	0.14 0.18	1.93 1.85	1.27 1.27	0.62 0.54	.08 .09	WQT or OQT	Rim	116,000- 118,000	97,000- 104,000	21- 24	64- 68	−85 to 15	82- 103
									Bore	116,000- 122,000	94,000- 105,000	22- 24	60- 64	55 to 10	69- 90
12-20 (5 disks)	0.25- 0.29	0.59- 0.63	0.16- 0.24	2.59- 2.89	0.27- 0.40	0.50- 0.58	.06- .07	WQT or OQT	Rim	128,000- 141,000	110,000- 127,000	19- 22	61- 64	50 to 90[c]	38- 56[c]
									Bore	119,000- 156,000	103,000- 145,000	14- 23	54- 66		
36 (2 disks)	0.22 0.23	0.31 0.28	0.24 0.26	2.68 2.72	1.45 1.43	0.59 0.57	0.10 0.11	WQT or OQT	Rim	124,000- 132,000	99,000- 115,000	20- 21	62- 66	−85 to 35	69- 86
									Bore	122,000- 132,000	98,000- 108,000	20- 21	60- 69	−85 to 45	38- 95
12-15 (3 disks)	0.23- 0.26	0.26- 0.32	0.24- 0.33	3.37- 3.46	1.69- 1.85	0.45- 0.47	0.10- 0.14	WQT or OQT	Rim	129,000- 142,000	115,000- 128,000	18- 21	62- 70	−80 to 50[c]	48- 82[c]
									Bore	133,000- 146,000	118,000- 134,000	19- 20	61- 68		
27-36 (2 disks)	0.24 0.25	0.30 0.26	0.27 0.31	3.45 3.38	1.74 1.85	0.50 0.53	0.11 .09	WQT	Rim	134,000- 151,000	105,000- 124,000	20- 22	61- 67	−85 to 30	54- 69
									Bore	132,000- 156,000	104,000- 132,000	18- 22	50- 63	30 to 0	42- 53
20-23 (5 disks)	0.23- 0.34	0.28- 0.46	0.20- 0.31	3.21- 3.69	1.62- 1.84	0.32- 0.55	.06- 0.16	OQT	Rim	136,000- 177,000	123,000- 164,000	14- 19	47- 59	−85 to 50[c]	25- 77[c]
									Bore	139,000- 174,000	128,000- 166,000	14- 20	44- 65		

[a] No significant difference was observed between water and oil-quenched disks. W = Water. Q = Quench. O = Oil. T = Temper.

[b] Tangential test specimens were used.

[c] Impact specimens randomly selected from rim and bore.

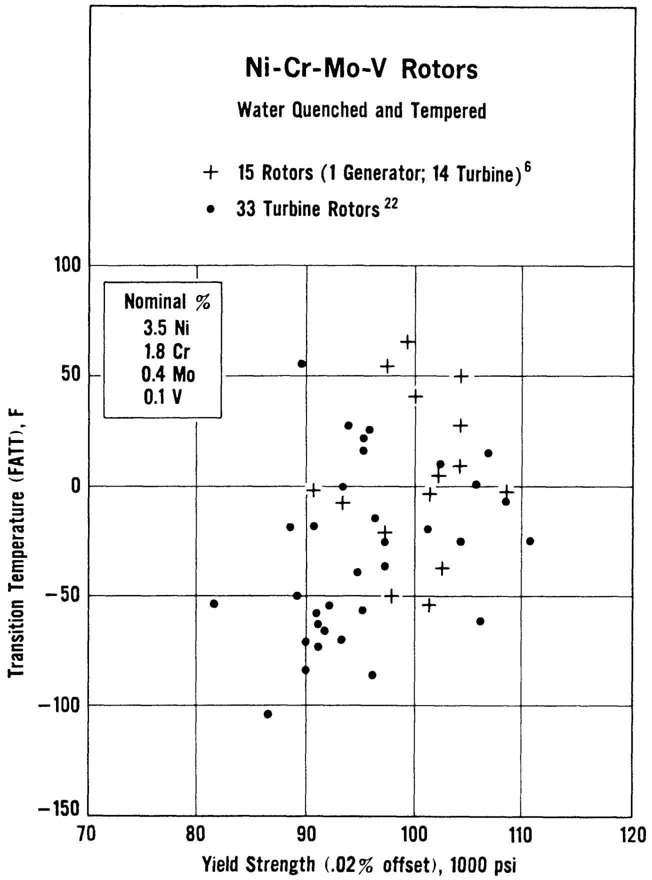

Fig. 10. Transition temperature (Charpy V-notch impact) vs yield strength at center of large generator and low-pressure steam turbine rotors of nickel-chromium-molybdenum-vanadium steels. Boyle, Curran, DeForest and Newhouse.[6,22]

NICKEL-MOLYBDENUM STEEL FORGINGS

Nickel-molybdenum steels, usually containing some vanadium, are employed frequently for heavy forgings such as generator rotors and large gears and shafts where moderate strengths and good toughness are required. Table II and Figure 4 illustrate the strength, ductility and toughness ranges developed in 37-inch diameter generator rotor forgings by accelerated air cooling and by water spray quenching heat treatments. Figure 11 shows the superiority of quenching and tempering over normalizing and tempering for developing a high impact level and a low transition temperature. Nickel-molybdenum compositions are preferred frequently for generator rotors when high magnetic permeability is of primary importance.

Calculation of Magnetic Flux Density from Composition

The following tabulation[43] presents factors indicating approximately the effect of steel composition on magnetic flux density near saturation:

Element	Factor
Cobalt	3.5
Nickel	–1.0
Tungsten	–3.2
Manganese	–8.2
Molybdenum	–8.2
Chromium	–11.3
Vanadium	–11.5
Silicon	–16
Aluminum	–20.3
Carbon	–44

The change which these elements produce in the near-saturation flux density of pure iron can be calculated by use of the following equation:

Flux Density, Gauss* =
21,250 + 30x(%C)x(-44) + 30x(%Mn)x(-8.2)
\+ . . . . . . (Repeat for each element)

It will be noted that the alloying elements which contribute hardenability, and therefore strength, adversely affect permeability. Cobalt enhances permeability but decreases hardenability and strength. Carbon has the strongest negative factor. Chromium and vanadium have strong negative factors, but vanadium is used ordinarily in relatively small amounts in heavy forgings. Manganese and molybdenum also are quite negative but a small amount of the latter contributes greatly to hardenability and strength. Nickel reduces magnetic permeability the least of the elements that provide hardenability and strength. Hence, for high magnetic permeability, nickel-molybdenum-vanadium compositions are preferable, although chromium is used judiciously for strengthening when the design situation allows for its effect in lowering magnetic flux density.

Normalized and Tempered

Properties representative of a wide range of nickel-molybdenum steel forgings are shown in Figure 12. The data in Figures 12a and 12b represent normalized and tempered forgings. Figure 12a provides data for comparing nickel-molybdenum steel forgings at the 1.8 and 2.5 per cent nickel levels with some standard specifications. Compositions designed to give improved fracture toughness and magnetic characteristics for generator rotors in 40- to 60-inch forgings are shown in Figure 12b. With carbon reduced to 0.21 to 0.23 per cent and nickel at 3.5 per cent, yield strengths of 90,000 psi are obtained along with low impact transition temperatures. Figure 12b also shows properties for 5.3 per cent nickel steels with even lower carbon (0.16 to 0.21 per cent) and low molybdenum (0.23 to 0.27 per cent) designed to combine maximum magnetic permeability, 75,000 to 95,000 psi yield strength, and good fracture toughness.

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*Lines of force per square inch = Gauss × 6.45.

Quenched and Tempered

Figures 12c and 12d present information on the properties of quenched and tempered nickel-molybdenum steel forgings. In Figure 12c yield strengths of about 90,000 psi are reached in 4-inch sections with the 1.8 per cent nickel grade. The nominal 2.5 per cent nickel composition in Figure 12d provides higher strength with good ductility in 6-inch sections. Judging from the transition temperature data in Figure 12b, it is likely that the steels in 12d would have transition temperatures low enough for the three specifications superimposed on 12d. The advantage of water quenching over normalizing for large generator rotor forgings of nickel-molybdenum-vanadium steels is shown in Figure 13. Data on yield strength and transition temperature of large generator rotors are presented in Figure 14.

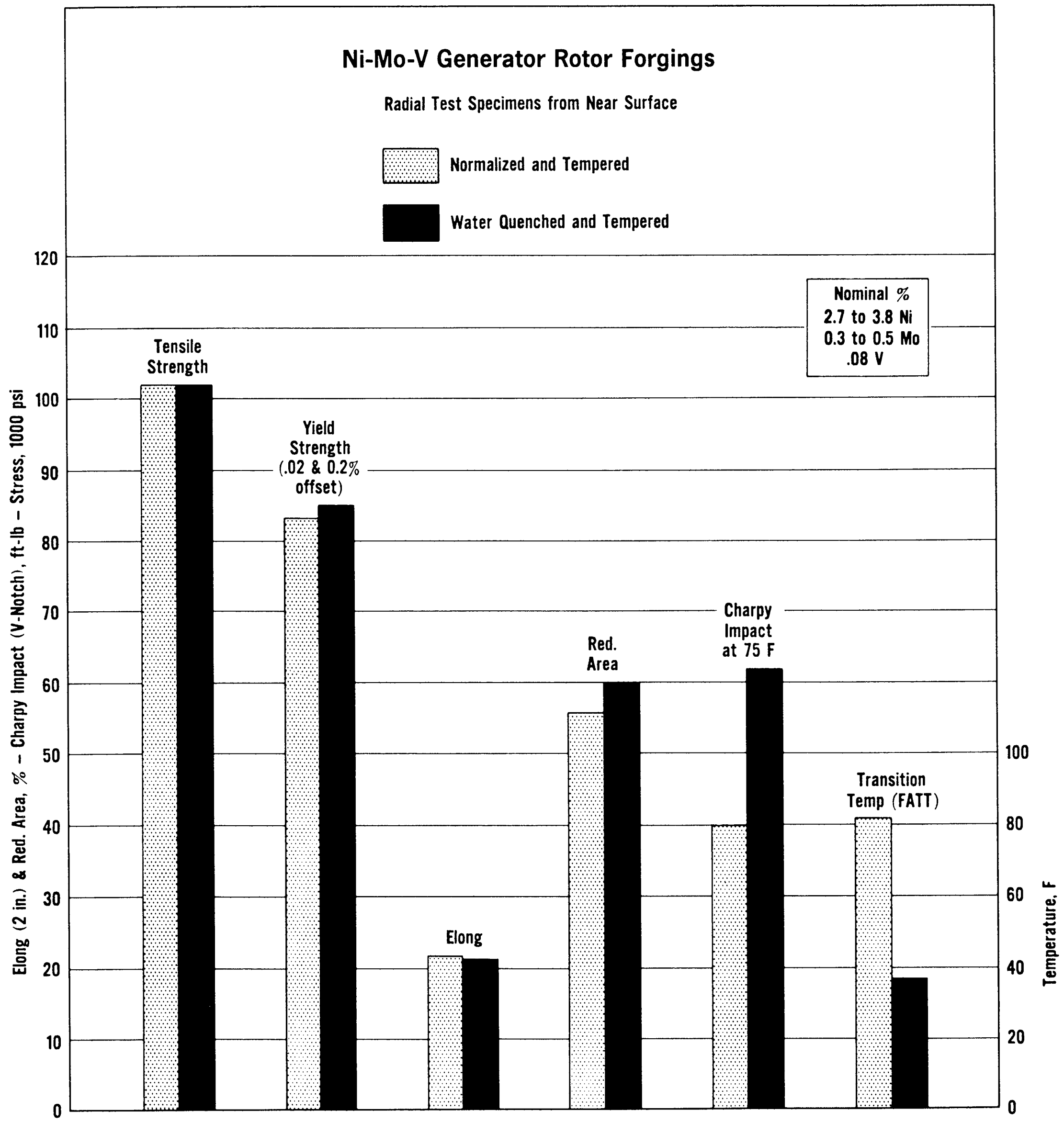
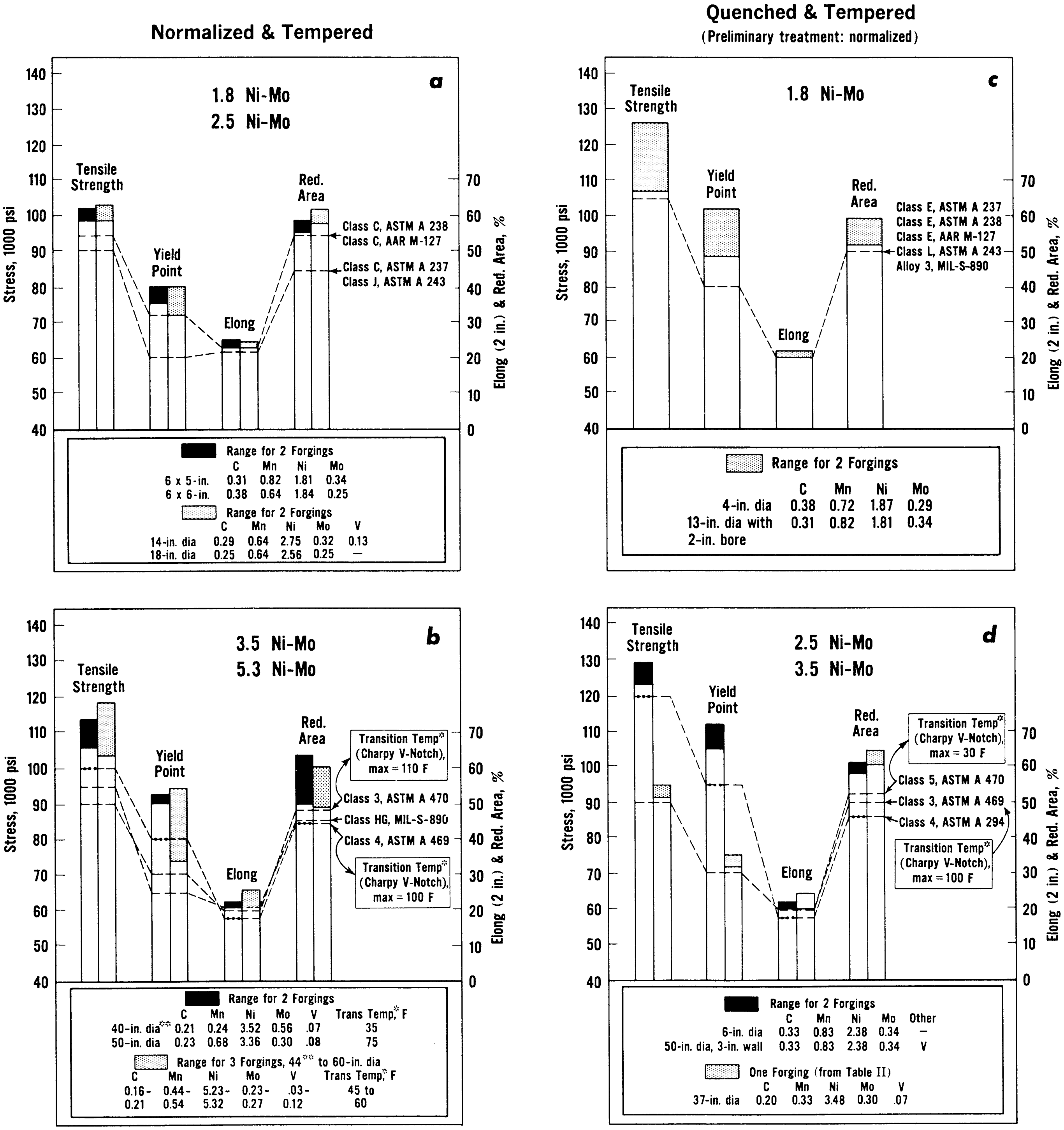


Fig. 11. Average radial mechanical properties near surface of 197 normalized and 60 water-quenched large generator rotor forgings of nickel-molybdenum-vanadium steels. Boyle, Curran, DeForest and Newhouse[22] and Greenberg.[23]

Nickel-Molybdenum Steel Forgings



a

■ Range for 2 Forgings

	C	Mn	Ni	Mo
6 x 5-in.	0.31	0.82	1.81	0.34
6 x 6-in.	0.38	0.64	1.84	0.25

▨ Range for 2 Forgings

	C	Mn	Ni	Mo	V
14-in. dia	0.29	0.64	2.75	0.32	0.13
18-in. dia	0.25	0.64	2.56	0.25	—

c

▨ Range for 2 Forgings

	C	Mn	Ni	Mo
4-in. dia	0.38	0.72	1.87	0.29
13-in. dia with 2-in. bore	0.31	0.82	1.81	0.34

b

■ Range for 2 Forgings

	C	Mn	Ni	Mo	V	Trans Temp,* F
40-in. dia**	0.21	0.24	3.52	0.56	.07	35
50-in. dia	0.23	0.68	3.36	0.30	.08	75

▨ Range for 3 Forgings, 44** to 60-in. dia

C	Mn	Ni	Mo	V	Trans Temp,* F
0.16- 0.21	0.44- 0.54	5.23- 5.32	0.23- 0.27	.03- 0.12	45 to 60

*FATT **Small bar cooled to simulate this size

d

■ Range for 2 Forgings

	C	Mn	Ni	Mo	Other
6-in. dia	0.33	0.83	2.38	0.34	–
50-in. dia, 3-in. wall	0.33	0.83	2.38	0.34	V

▨ One Forging (from Table II)

	C	Mn	Ni	Mo	V
37-in. dia	0.20	0.33	3.48	0.30	.07

Fig. 12. Representative tensile properties of nickel-molybdenum steel forgings and how they compare with the minima in some standard specifications for alloy steel forgings. See Tables III and V for more details on specifications.

Ni-Mo-V Generator Rotor Forgings

Normalized or Water Quenched
Radial Test Specimens from Near Surface

Specified Yield Strength (0.2% offset) (min), psi	Number of Rotors		Average Composition, % C	Mn	P	S	Si	Ni	Cr	Mo	V
░ 55,000	40	N	0.22	0.51	.009	.012	0.20	3.01	0.15	0.32	.08
	1	WQ	0.22	0.36	.009	.010	0.23	3.48	0.10	0.29	.08
▨ 75,000	26	N	0.24	0.51	.009	.012	0.18	3.30	0.19	0.33	.08
	4	WQ	0.24	0.32	.009	.008	0.17	3.38	0.12	0.31	.08
▩ 85,000	43	N	0.26	0.53	.008	.011	0.21	3.37	0.24	0.39	.08
	7	WQ	0.26	0.44	.008	.012	.08	3.55	0.22	0.39	.08
▧ 95,000	9	N	0.28	0.44	.008	.010	0.22	3.46	0.16	0.43	.08
	3	WQ	0.27	0.46	.008	.010	0.14	3.47	0.41	0.39	.09

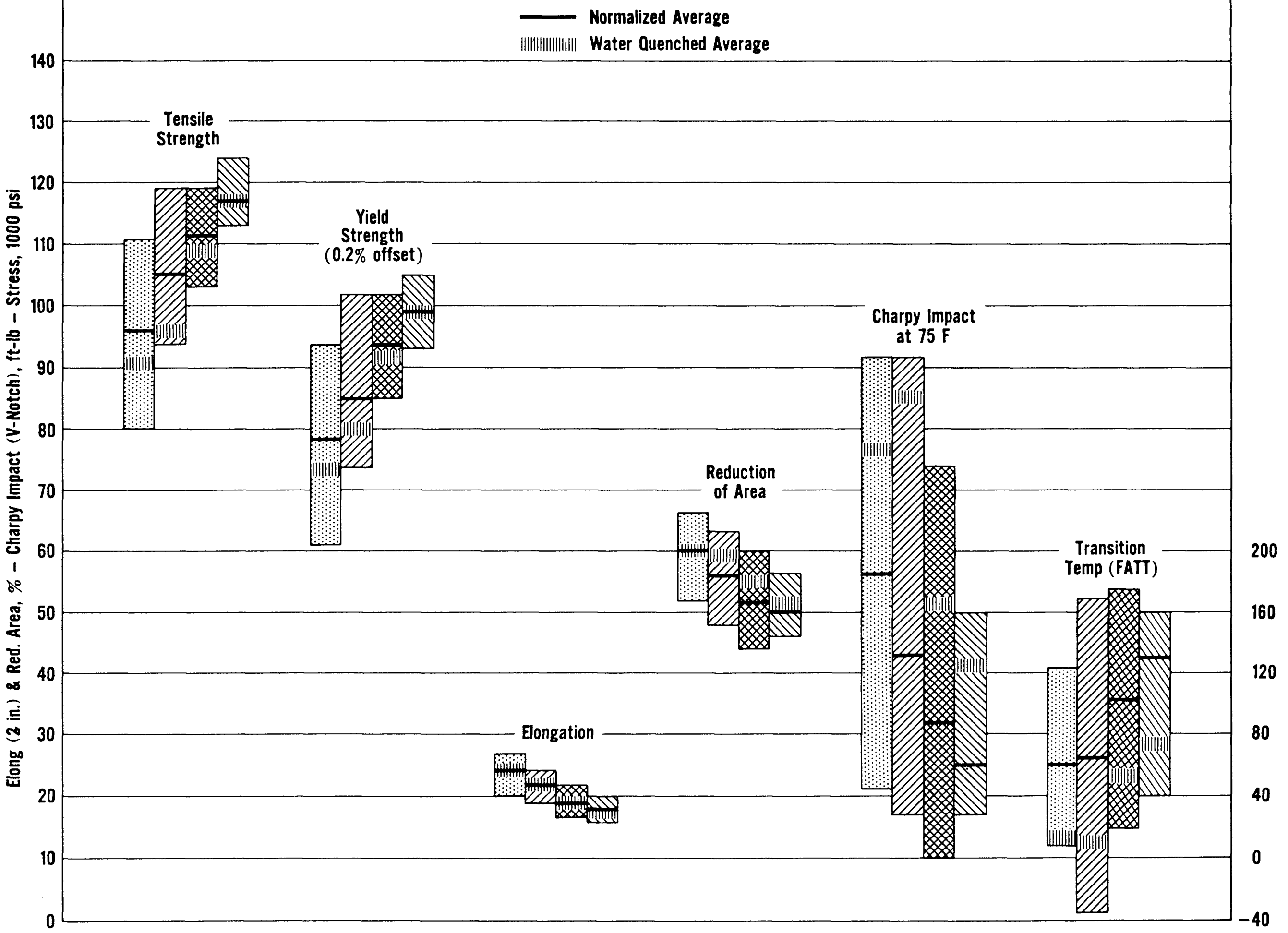


Fig. 13. Effect of normalizing vs water quenching on range and average mechanical properties of large nickel-molybdenum-vanadium generator rotor forgings at four yield strength levels. Greenberg.[23]

Compliance with Standard Specifications

The nickel-molybdenum steels, with vanadium added, meet the requirements of Classes 2 to 5 of ASTM Specification A 469 for generator rotors and Classes 2 to 4 of A 470 for turbine rotors and shafts, Table V. Such forgings are quite heavy, the main body being sometimes as large as 68 inches in diameter. The most commonly used treatment for these rotors has been double normalizing and tempering (ASTM A 292 and A 293, Table V); however, liquid quenching is on the increase since the advent of commercial vacuum treating of liquid steel and the consequent lower hydrogen content of such heavy forgings (ASTM A 469 and A 470, Table V).

The nickel-molybdenum steels also are capable of meeting many of the standard specifications of Table III, as shown in Figure 12. Normalized and tempered nickel-molybdenum steels meet the requirements of Class 3 of ASTM Specification A 291 covering forgings for pinions and gears and Class F31 of A 336 for pressure vessel components. Composition and mechanical property requirements of these specifications are listed in Table V.

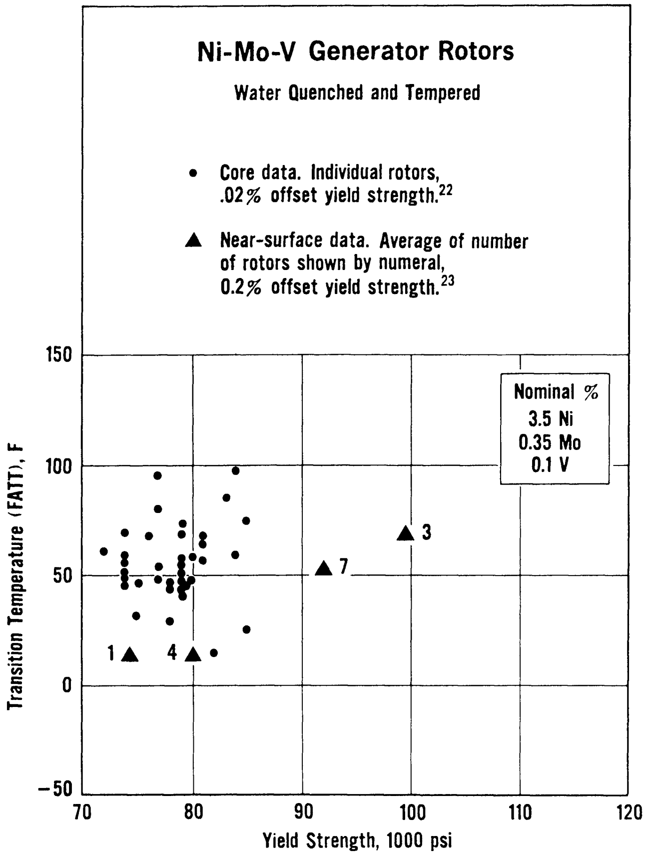


Fig. 14. Transition temperature (Charpy V-notch impact) vs yield strength of large generator rotors of nickel-molybdenum-vanadium steel water quenched and tempered. Boyle, Curran, DeForest and Newhouse[22] and Greenberg.[23]

Nickel-molybdenum-vanadium steels meet the requirements of Classes C1 to C7 of ASTM Specification A 294, Table V, for turbine wheels and disks; the specified values for Class C4 are superimposed on Figure 12d. They also are capable of meeting the requirements of Classes 1 to 6 of ASTM A 471, Table V.

NICKEL-CHROMIUM STEEL FORGINGS

Nickel-chromium steels have been used extensively in the past for large forgings, although now the nickel-molybdenum or nickel-chromium-molybdenum grades covered in the preceding two sections are more popular. The properties of representative nickel-chromium steel forgings of various sizes are given in Figure 15 which also shows how they meet some of the standard specifications of Table III.

NICKEL STEEL FORGINGS

Plain nickel steels were among the earliest alloy compositions used for heavy forgings, offering substantial improvement in strength and toughness over ordinary carbon steels. Heavy shafts for the first *Ferris* wheel, propeller shafts for naval vessels, hammer and press rods, bridge components and locomotive forgings were made of nickel steels before the turn of the century, and some are still in service.[44] The plain nickel steels continue to be used in heavy forgings for some appplications: for example, in heavy crane hooks, ship drive and propeller shafts, lumbering and oil well tools, and rolling mill drives.

Figure 16 gives typical tensile values that can be expected for 2.8 and 3.5 per cent nickel steel forgings in different sizes and shows how they meet some standard specifications.

Low-Temperature Uses

The excellent low-temperature properties of the nickel steels have led to their frequent use for machinery or structural components in localities subject to low atmospheric temperatures. Large forgings of 0.15 per cent carbon, 3.5 per cent nickel steel are used particularly for applications involving service temperatures below 0° F. Shafts of this composition have given excellent service in gyratory crushers operating in northern United States and in Canada. Forgings of low-carbon 3.5 per cent nickel steels, covered in ASTM Specifications A 320 and A 350, Table VII, are in common use down to −150 F. Forgings of 9 per cent nickel steel, ASTM Specification A 522, Table VII, are used down to −320 F. Further data on the use of nickel steels at low temperatures are given in another bulletin.*

A 0.40 per cent carbon, 3.5 per cent nickel steel forged bolting material may be used as low as −225 F, ASTM Specification A 320, Table VII.

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*Bulletin 4-C: "Low Temperature Properties of Nickel Alloy Steels."

Nickel-Chromium Steel Forgings

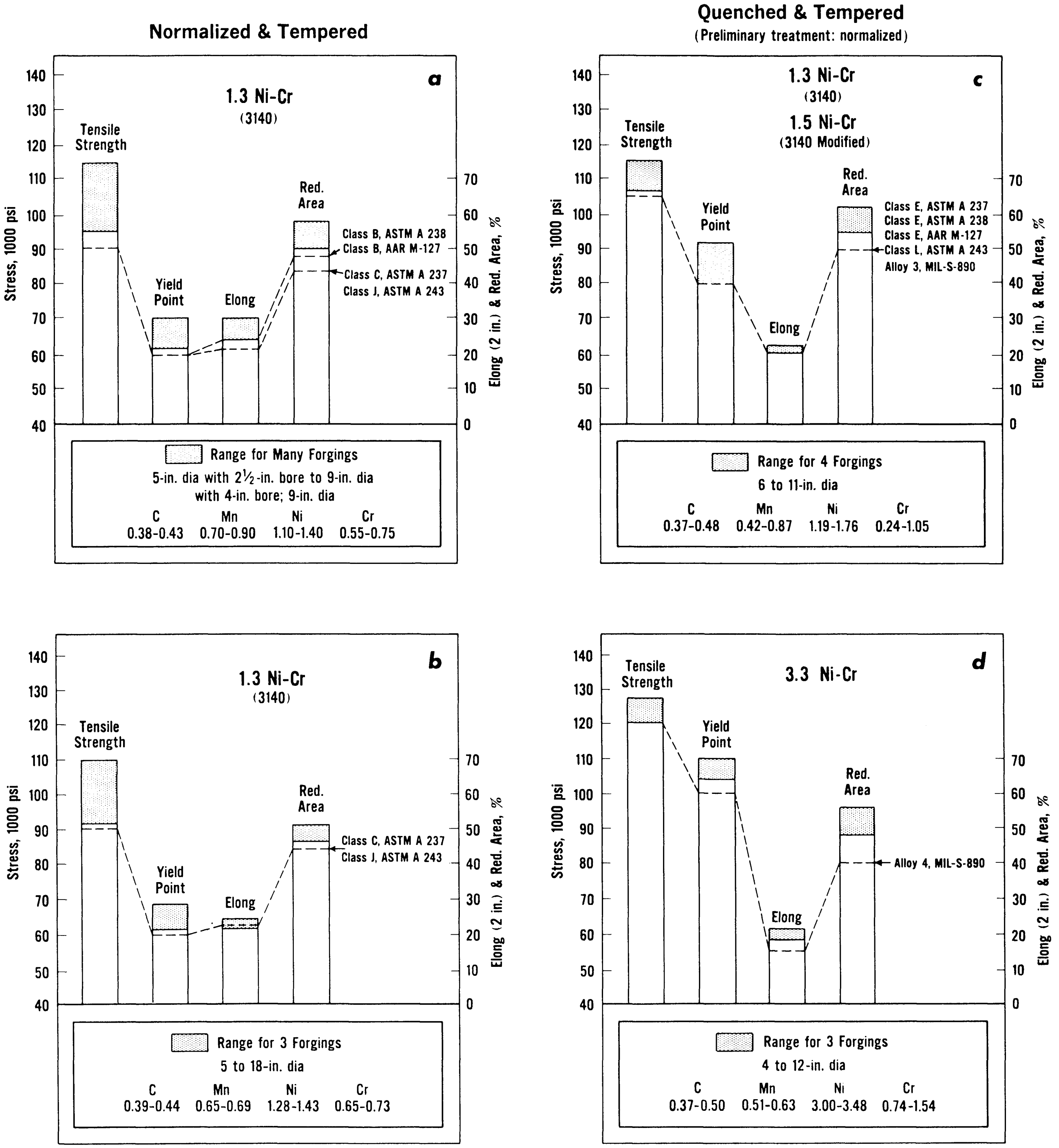

Fig. 15. Representative tensile properties of nickel-chromium steel forgings and how they compare with the minima in some standard specifications for alloy steel forgings. See Table III for more details on specifications.

Nickel Steel Forgings

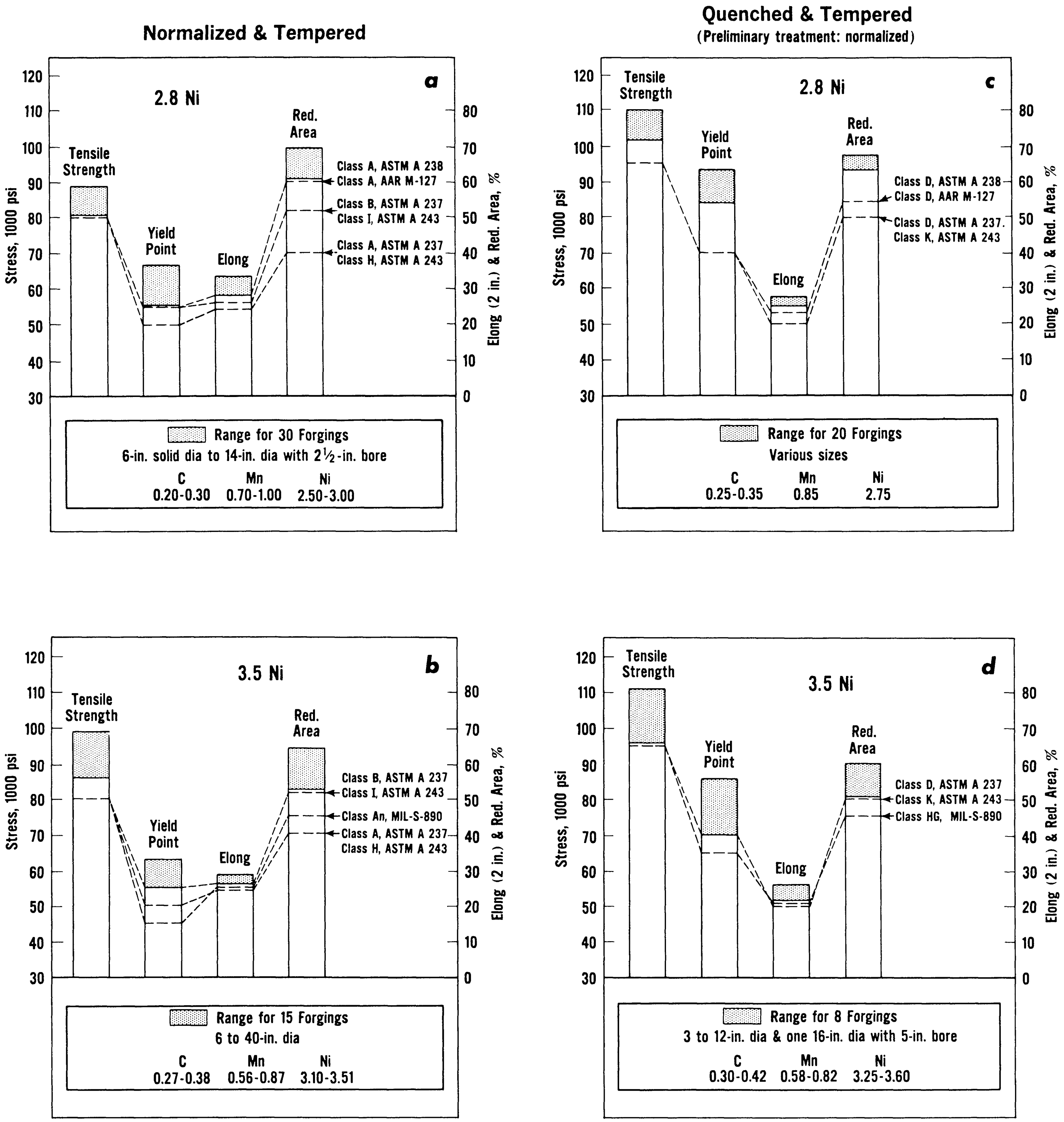

Fig. 16. Representative tensile properties of nickel steel forgings and how they compare with the minima in some standard specifications for alloy steel forgings. See Table III for more details on specifications.

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