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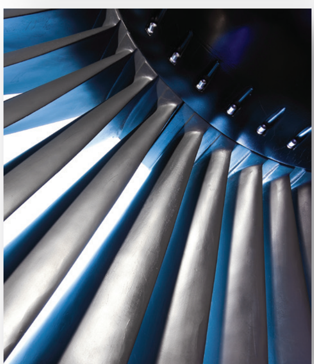
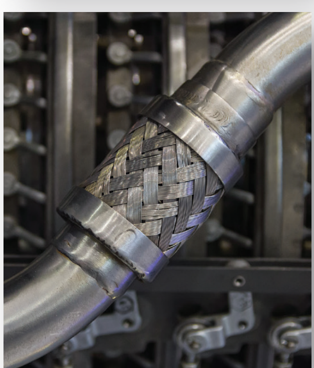
ARMCO® 15-5 PH® VAC CE

PRECIPITATION HARDENING STAINLESS STEEL PRODUCT DATA BULLETIN

- **Aircraft Components**
- **Forgings**
- **Plate Applications**
- **Pressure Transducers**
- **Pump and Valve Parts**





ARMCO® 15-5 PH® VAC CE STAINLESS STEEL is widely used in applications requiring high strength and toughness in all directions. Typical uses include forgings, pump and valve parts for high-pressure systems requiring good corrosion resistance, pressure transducers, aircraft components, and transversely loaded plate applications.

ARMCO® 15-5 PH® VAC CE STAINLESS STEEL

TABLE OF CONTENTS

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ARMCO® 15-5 PH® VAC CE STAINLESS STEEL

Product Description

ARMCO® 15-5 PH® VAC CE Stainless Steel is a martensitic precipitation hardening stainless steel that offers a unique combination of high strength and hardness, good corrosion resistance, excellent transverse toughness and good forgeability.

ARMCO 15-5 PH Stainless Steel is produced by consumable electrode vacuum arc remelting (designated VAC CE) to meet the stringent mechanical property and cleanliness requirements of the aerospace and nuclear industries. Besides lowering gas content, the VAC CE process reduces and disperses inclusions, and minimizes alloy segregation during solidification.

Composition		(wt %)
Carbon	(C)	0.07 max.
Manganese	(Mn)	1.0 max.
Phosphorus	(P)	0.04 max.
Sulfur	(S)	0.03 max.
Silicon	(Si)	1.00 max.
Chromium	(Cr)	14.00 – 15.50
Nickel	(Ni)	3.50 –5.50
Copper	(Cu)	2.50 –4.50
Niobium	(Nb)	0.15 –0.45

ARMCO 15-5 PH is also available in Electro Slag Remelted (ESR) form and as a combined ARMCO 17-4/15-5 PH dual grade.

Mechanical Properties

ARMCO® 15-5 PH® Stainless Steel is covered by the following specifications. It is suggested that the issuing agency be contacted for the latest revision of the specification. ARMCO 15-5 PH Stainless Steel is listed as Grade XM-12 (UNS S15500) in:

- ASTM A564 Hot-Finished or Cold-Finished Age Hardening Stainless and Heat-Resisting Steel Bars and Shapes.
- ASTM A693 Plate, Sheet, and Strip.
- ASTM A705 Age Hardening and Heat-Resisting Steel Forgings.
- AMS 5659 Consumable Electrode Melted Bars, Forgings, and Rings.
- AMS 5862 Sheet, Strip and Plate.

Contact your Cliffs AK Steel International sales representative for additional information.

CONDITIONS AVAILABLE FROM MILL

1) Condition A (Solution Annealed)	Material for fabrication and heat treatment by the user. If severe forming is required, use Condition H 1150 or H 1150-M.
2) Condition H 1075	Precipitation hardened condition. Machines as well as Condition A.
3) Condition H 1150	Precipitation hardened condition. More readily fabricated than Condition A. No further heat treatment necessary where no severe cold working is involved.
4) Overage for forging	Allows hot-sawing of sections without cracking.
5) Overage for heading	Maximum softness for cold heading. Materials in this condition will not respond to aging treatments without first solution treating.
6) Other Conditions	Inquire for availability.

EXCELLENT TRANSVERSE PROPERTIES

The VAC CE process, coupled with the elimination of delta ferrite, give ARMCO 15-5 PH VAC CE Stainless Steel excellent transverse mechanical properties in any test location. Consequently, it provides good transverse notch toughness and forgeability. ARMCO 15-5 PH VAC CE Stainless Steel offers valuable advantages in severe upset-forging or hot-flattening operations where splitting or rupturing are encountered with high-strength steels. Its forgeability is superior to ARMCO 17-4 PH® Stainless Steel.

READILY FABRICATED

Fabrication practices for ARMCO 15-5 PH VAC CE Stainless Steel are generally the same as those established for ARMCO 17-4 PH Stainless Steel. Most techniques are similar to those recommended for regular grades of stainless steel. Hardening heat treatments require temperatures of only 482 – 621 °C (900 – 1150 °F), depending on the properties desired. The first of the double heat treatments of the H 1150-M condition is at 760 °C (1400 °F). As a result, scaling and distortion difficulties are virtually eliminated. ARMCO 15-5 PH VAC CE Stainless Steel has good machining properties. Excellent surface finish can be produced with conventional tooling.

Standard Heat Treatments

ARMCO® 15-5 PH® VAC CE Stainless Steel can be heat treated at different temperatures to develop a wide range of properties. Fully hardened 15-5 PH VAC CE Stainless Steel, Condition H 900, will have a minimum ultimate tensile strength of 1310 MPa (190 ksi) and minimum yield strength of 1172 MPa (170 ksi). Typical properties for the standard conditions are shown in Tables 4 and 5.

TABLE 1 – ARMCO 15-5 PH VAC CE TREATMENTS

Condition A Solution Annealed 1036 ± 14 °C (1900 ± 25 °F) Oil or Air Cool below 32 °C (90 °F)

ARMCO 15-5 PH VAC CE Treatments			
Condition	Heat to ±9 °C (±15 °F)	Hold for Hours	Cool
H 900	482 °C (900 °F)	1	Air
H 925	495 °C (925 °F)	4	Air
H 1025	552 °C (1025 °F)	4	Air
H 1075	579 °C (1075 °F)	4	Air
H 1100	593 °C (1100 °F)	4	Air
H 1150	621 °C (1150 °F)	4	Air
H 1150-M (Double Overaged)	760 °C (1400 °F) 621 °C (1150 °F)	2 Followed by 4	Air Air

ARMCO 15-5 PH VAC CE Stainless Steel exhibits useful mechanical properties in Condition A, and tests in an exposed marine atmosphere for more than fourteen years show excellent stress corrosion cracking resistance. Condition A material can be used successfully in numerous applications without subsequent heat treating.

However, in critical applications, ARMCO 15-5 PH VAC CE Stainless Steel should be used in the precipitation hardened condition, rather than Condition A. Heat treating to the hardened conditions, especially at the higher end of the temperature range, stress relieves the structure and may provide more reliable resistance to stress corrosion cracking than Condition A.

HEAT-TREATING CYCLE FOR FORGING

If ARMCO 15-5 PH VAC CE stainless is to be forged, it is supplied "overaged for forging." Overaging consists of heat treatment at the mill in the temperature range of 621 – 648 °C (1150 – 1200 °F). Such treatment eliminates cracking during abrasive sawing. Material in this condition will not respond to hardening treatments without first solution treating.

ARMCO® 15-5 PH® VAC CE STAINLESS STEEL

Mechanical Properties

ORIENTATION AND LOCATION OF TEST SPECIMENS

ARMCO® 15-PH 5® VAC CE Stainless Steel is needed in many applications requiring excellent mechanical properties in the long and short transverse directions, as well as in the longitudinal direction (direction of rolling). Orientation and location of the test specimen and product section are receiving more emphasis in the determination of design values. The data included in this bulletin are identified regarding (1) orientation of specimen, (2) specimen location, and (3) section size from which the test specimens were taken. Orientation and location of test specimens are shown in figures 1A and 1B. Unless otherwise stated, data represents longitudinal direction – intermediate location.

Sketches showing the orientation and location of test specimens in a typical bar section. Figure 1A shows specimens located at the center or along the axes of the respective bar dimensions. Figure 1B illustrates the location of test specimens to determine properties at intermediate locations.

1. Transverse properties cannot be determined if bar dimensions are under 76.2 mm (3 in.) in the test direction.
2. In rounds, squares, and hexagon bars, no short transverse direction exists.

FIGURE 1A

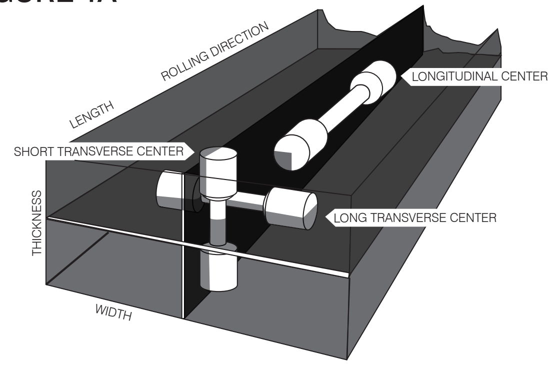
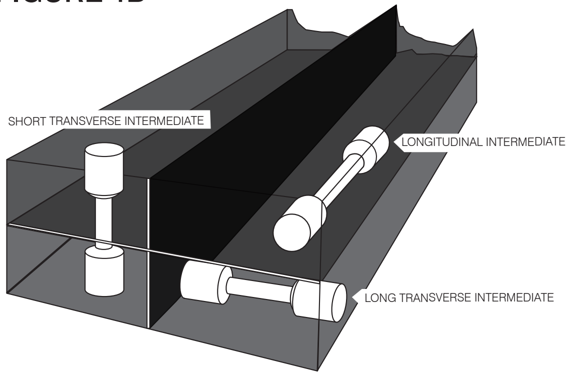


FIGURE 1B



PROPERTIES ACCEPTABLE FOR MATERIAL SPECIFICATIONS

TABLE 1 – MAXIMUM HARDNESS OR TENSILE STRENGTH IN CONDITION A

Rounds, Hexagons and Squares			Flats
3.18 mm (0.125 in.) and smaller	Over 3.18 – 12.7 mm Incl. (0.125 – 0.5 in Incl.)	Over 12.7 mm (0.5 in.)	Over 12.7 mm (0.5 in.)
1207 MPa (175 ksi) max.	HB 363 max.	HB 363	HB 363

TABLE 2 – MINIMUM PROPERTIES (SUITABLE FOR SPECIFICATIONS) LONGITUDINAL DIRECTION — INTERMEDIATE LOCATION UP TO 304.8 mm (12 in.) SECTION

Property	Condition						
	H 900	H 925	H 1025	H 1075	H 1100	H 1150	H 1150-M
Ultimate Tensile Strength, MPa (ksi)	1310 (190)	1172 (170)	1069 (155)	1000 (145)	965 (140)	931 (135)	793 (115)
0.2% Yield Strength, MPa (ksi)	1172 (170)	1069 (155)	1000 (145)	862 (125)	793 (115)	724 (105)	517 (75)
Elongation % in $4D_0$	10	10	12	13	14	16	18
Reduction of Area, %	35	38	45	45	45	50	55
Hardness Brinell Rockwell	388/448 C40/47	375/438 C38/45	331/401 C35/42	302/375 C32/39	294/364 C31/38	277/352 C28/37	255/293 C24/30
Impact, Charpy V-Notch, J (ft•lbs)	–	6.8 (5)	20 (15)	27 (20)	34 (25)	41 (30)	75 (55)

**Please note that, in the metric version of the ASTM A564, some required values are rounded to the nearest multiple of 5.*

ARMCO® 15-5 PH® VAC CE STAINLESS STEEL

Mechanical Properties

TABLE 3 – MINIMUM PROPERTIES (SUITABLE FOR SPECIFICATIONS) TRANSVERSE DIRECTION UP TO 304.8 mm (12 in.) SECTION

Property	Condition						
	H 900	H 925	H 1025	H 1075	H 1100	H 1150	H 1150-M
Ultimate Tensile Strength, MPa (ksi)	1310 (190)	1172 (170)	1069 (155)	1000 (145)	965 (140)	931 (135)	793 (115)
0.2% Yield Strength, MPa (ksi)	1172 (170)	1069 (155)	1000 (145)	862 (125)	793 (115)	724 (105)	517 (75)
Elongation % in $4D_0$	6	7	8	9	10	11	14
Reduction of Area, %	15	20	27	28	29	30	35
Hardness Brinell Rockwell	388/448 C40/47	375/438 C38/45	331/401 C35/42	302/375 C32/39	294/364 C31/38	277/352 C28/37	255/293 C24/30
Impact, Charpy V-Notch, J (ft•lbs) Intermediate Location	*	*	14 (10)	20 (15)	20 (15)	27 (20)	47 (35)

Minimum impact properties cannot be accepted in this condition. If toughness is a design criteria, this heat treatment should be used with caution.

TABLE 4 – TYPICAL MECHANICAL PROPERTIES** LONGITUDINAL DIRECTION – INTERMEDIATE LOCATION

Property	Condition						
	H 900	H 925	H 1025	H 1075	H 1100	H 1150	H 1150-M
Ultimate Tensile Strength, MPa (ksi)	1379 (200)	1310 (190)	1172 (170)	1138 (165)	1034 (150)	1000 (145)	862 (125)
0.2% Yield Strength, MPa (ksi)	1276* (185)	1207 (175)	1138 (165)	1034 (150)	931 (135)	862 (125)	586 (85)
Elongation % in $4D_0$	14	14	15	16	17	19	22
Reduction of Area, %	50	54	56	58	58	60	68
Hardness Brinell Rockwell	420 C44	409 C42	352 C38	341 C36	332 C34	311 C33	277 C27
Impact, Charpy V-Notch, J (ft•lbs)	20 (15)	34 (25)	47 (35)	54 (40)	61 (45)	68 (50)	136 (100)

Compressive yield strength for Condition H 900 is 1227 MPa (178 ksi).
***Typical data represent average values of qualification tests for production orders.*

Mechanical Properties

TABLE 5 – TYPICAL MECHANICAL PROPERTIES*
TRANSVERSE DIRECTION – INTERMEDIATE AND CENTER LOCATION

Property	Condition													
	H 900		H 925		H 1025		H 1075		H 1100		H 1150		H 1150-M	
Intermediate (I) Center (C)	I	C	I	C	I	C	I	C	I	C	I	C	I	C
Ultimate Tensile Strength, MPa (ksi)	1379 (200)	1379 (200)	1310 (190)	1310 (190)	1172 (170)	1172 (170)	1138 (165)	1138 (165)	1034 (150)	1034 (150)	1000 (145)	1000 (145)	862 (125)	862 (125)
0.2% Yield Strength, MPa (ksi)	1276 (185)	1276 (185)	1207 (175)	1207 (175)	1138 (165)	1138 (165)	1034 (150)	1034 (150)	931 (135)	931 (135)	862 (125)	862 (125)	586 (85)	586 (85)
Elongation % in $4D_0$	10	10	11	11	12	12	13	13	14	14	15	15	18	18
Reduction of Area, %	30	30	35	35	42	42	43	43	44	44	45	45	50	50
Hardness														
Brinell	420	420	409	409	352	352	341	341	332	332	311	311	277	277
Rockwell	C44	C44	C42	C42	C38	C38	C36	C36	C34	C34	C33	C33	C27	C27
Impact, Charpy V-Notch, J (ft•lbs)														
Notch Axis Longitudinal	9.5 (7)	–	23 (17)	–	37 (27)	–	41 (30)	–	41 (30)	–	68 (50)	–	136 (100)	–
Notch Axis Transverse	11 (8)	–	16 (12)	–	34 (25)	–	34 (25)	–	34 (25)	–	61 (45)	–	95 (70)	–

**Typical data represent average values of qualification tests for production orders.*

TABLE 6 – ULTIMATE SHEAR STRENGTH IN DOUBLE SHEAR

Condition	UTS, MPa (ksi)	Shear Strength, MPa (ksi)	Shear/Tensile Ratio %
H 900	1418 (205.6)	855 (124.0)	60.7
H 925	1304 (189.1)	800 (116.0)	61.8
H 1025	1136 (164.7)	718 (104.2)	63.2
H 1100	1067 (154.7)	683 (99.1)	63.0
H 1150-M	930 (134.9)	616 (89.3)	66.2

Data developed on 6.35 mm (0.25 in.) round wire. Average of five tests on one heat.

Fatigue Strength

TABLE 7 – FATIGUE STRENGTH — UNNOTCHED* TENSION — TENSION

Maximum Stress. MPa (ksi)	Cycles to Failure**				
	Condition A	Condition H 1025	Condition H 1025	Condition H 1150	Condition H 1150-M
1103 (160.0)	–	32 900	–	–	–
1069 (155.0)	–	322 800	–	–	–
1034 (150.0)	–	38 800	55 100	–	–
1034 (150.0)	–	99 200	–	130	–
1000 (145.0)	–	–	–	38 200	–
965 (140.0)	61 200	125 600	95 000	–	–
965 (140.0)	–	358 600	–	38 400	–
948 (137.5)	–	–	96 100	–	–
948 (137.5)	–	–	97 400	72 100	–
931 (135.0)	–	80 700	3 696 000	–	–
931 (135.0)	–	162 600	7 096 000	–	–
931 (135.0)	–	2 032 000	–	78 200	–
914 (132.5)	–	–	127 100	–	–
914 (132.5)	–	–	219 900	92 700	–
896 (130.0)	190 400	118 700	4 860 000	–	–
896 (130.0)	–	8 044 800	–	–	–
896 (130.0)	–	8 720 100	–	99 600	–
879 (127.5)	–	–	7 300 000	11 911 200	–
862 (125.0)		–	3 907 000	4 053 800 (Discontinued)	5000
862 (125.0)	–	–	6 031 000	9 877 100	–
827 (120.0)	214 900	–	–	–	64 500
793 (115.0)	4 792 000 (Discontinued)	–	–	–	124 600
758 (110.0)	3 433 600 (Discontinued)	–	–	–	138 900
724 (105.0)	–	–	–	–	4 453 600 (Discontinued)
707 (102.5)	–	–	–	–	381 700
690 (100.0)	–	–	–	–	399 200
690 (100.0)	–	–	–	–	4 910 900
672 (97.5)	–	–	–	–	898 000
655 (95.0)	–	–	–	–	8 265 400
621 (90.0)	5 152 200 (Discontinued)	–	–	–	10 982 700 (Discontinued)
621 (90.0)	10 100 000 (Discontinued)	–	–	–	4 453 600 (Discontinued)

*Transverse specimens prepared from 51 x 152 mm (2 x 6 in.) hot forged bar.
$R = \frac{\text{minimum stress}}{\text{maximum stress}} = 0.1$, speed = 30 Hz. uniaxial loading.

**Data represent individual tests from one heat.

Fatigue Strength

TABLE 8 – FATIGUE STRENGTH — NOTCHED (k_t = 3.0) TENSION — TENSION*

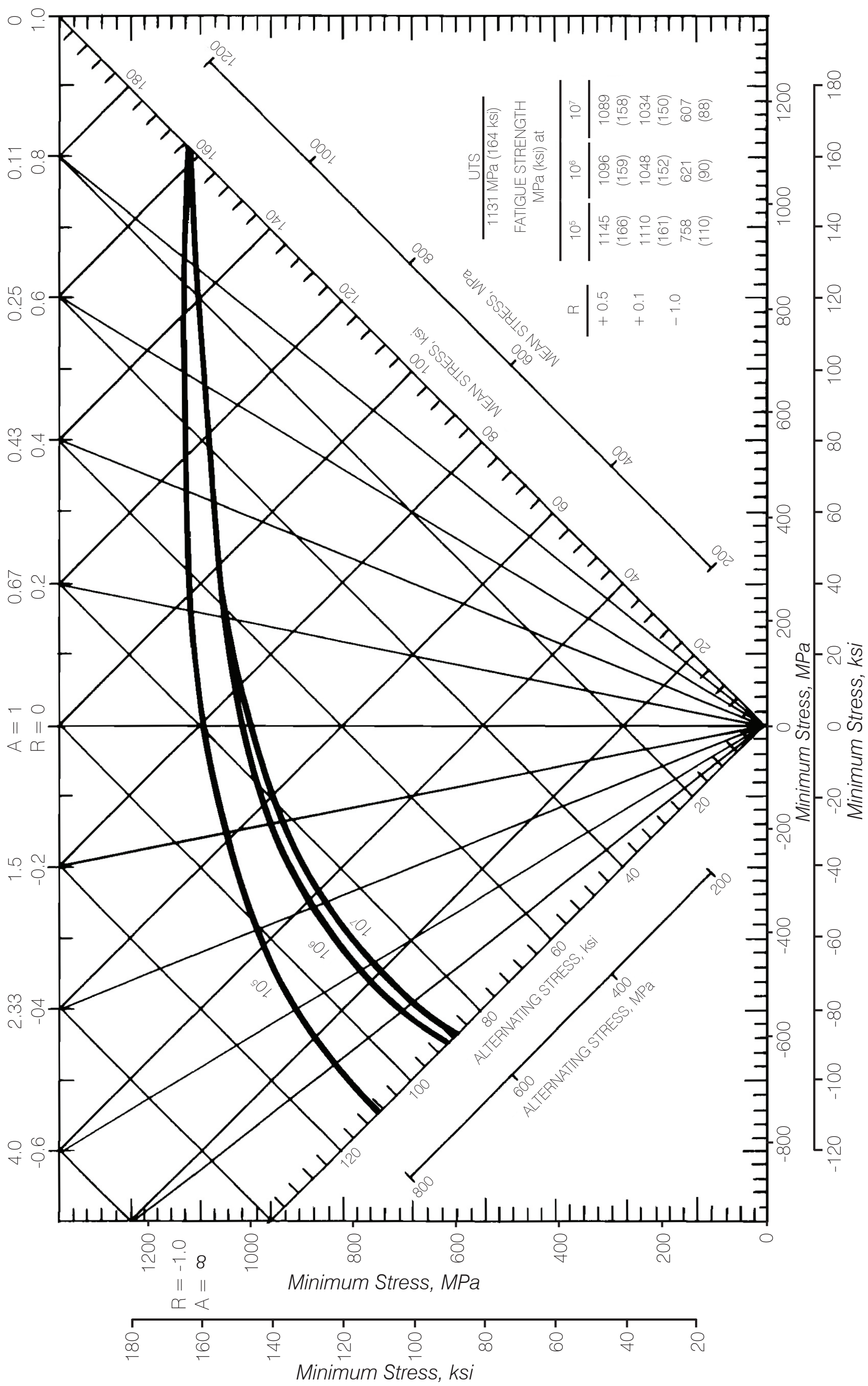
Maximum Stress. MPa (ksi)	Cycles to Failure**			
	Condition A	Condition H 1025	Condition H 1100	Condition H 1150
483 (70.0)	–	–	–	128 100
448 (65.0)	–	–	107 000	113 500
431 (62.5)	–	111 500	–	305 200
414 (60.0)	–	105 200	–	–
414 (60.0)	–	150 400	232 600	225 000
396 (57.5)	–	262 200	–	–
396 (57.5)	–	6 966 400	–	131 100
379 (55.0)	–	225 700	332 000	–
379 (55.0)	–	1 678 300	332 000	–
379 (55.0)	–	3 004 000	5 529 400	439 300
362 (52.5)	–	–	23 300 000 (Discontinued)	2 608 900
362 (52.5)	–	10 164 000 (Discontinued)	10 000 000 (Discontinued)	10 516 800 (Discontinued)
345 (50.0)	88 200	–	10 017 000 (Discontinued)	10 183 900 (Discontinued)
345 (50.0)	299 200	–	–	–
310 (45.0)	350 000	–	–	–
310 (45.0)	10 826 000 (Discontinued)	–	–	–
293 (42.5)	255 500	–	–	–
293 (42.5)	10 110 500 (Discontinued)	–	–	–
276 (40.0)	10 563 800 (Discontinued)	–	10 200 000 (Discontinued)	–
276 (40.0)	10 565 000 (Discontinued)	–	–	–

*Transverse specimens prepared from 51 x 152 mm (2 x 6 in.) hot forged bar.
$R = \frac{\text{minimum stress}}{\text{maximum stress}} = 0.1$, speed = 30 Hz. uniaxial loading.
**Data represent individual tests from one heat.

ARMCO® 15-5 PH® VAC CE STAINLESS STEEL

Fatigue Strength

FIGURE 2 – UNNOTCHED LONGITUDINAL SPECIMENS



	UTS 1131 MPa (164 ksi)		
	FATIGUE STRENGTH MPa (ksi) at		
R	10^5	10^6	10^7
+ 0.5	1145 (166)	1096 (159)	1089 (158)
+ 0.1	1110 (161)	1048 (152)	1034 (150)
− 1.0	758 (110)	621 (90)	607 (88)

Figure 2

*Constant Life Diagram**
Axial Loaded 15-5 PH, Condition H 1025
Unnotched Longitudinal Specimens
50.8 x 152.4 mm (2 x 6 in.) Section

**Diagram Construction from S-N Curves Developed From One Heat Using Stress Ratio of +0.5, + 0.1 and -1.0.*

ARMCO® 15-5 PH® VAC CE STAINLESS STEEL

Fatigue Strength

FIGURE 3 – UNNOTCHED TRANSVERSE SPECIMENS

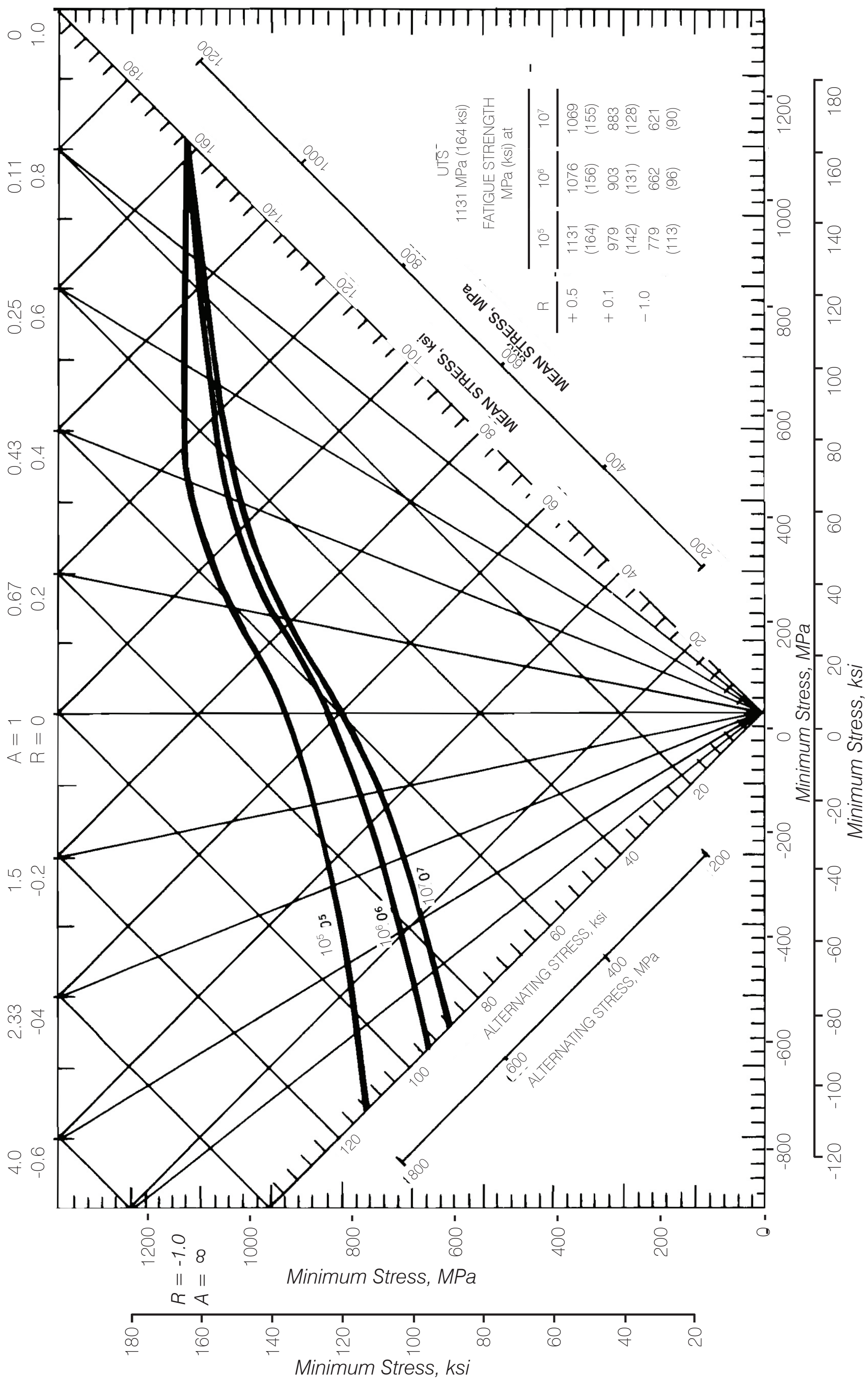


Figure 3

Constant Life Diagram*
Axial Loaded 15-5 PH, Condition H 1025
Unnotched Transverse Specimens
50.8 x 152.4 mm (2 x 6 in.) Section

*Diagram Construction from S-N Curves Developed From One Heat Using Stress Ratio of +0.5, + 0.1 and -1.0.

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Fatigue Strength

FIGURE 4 – NOTCHED (k_t = 3.0) LONGITUDINAL AND TRANSVERSE SPECIMENS

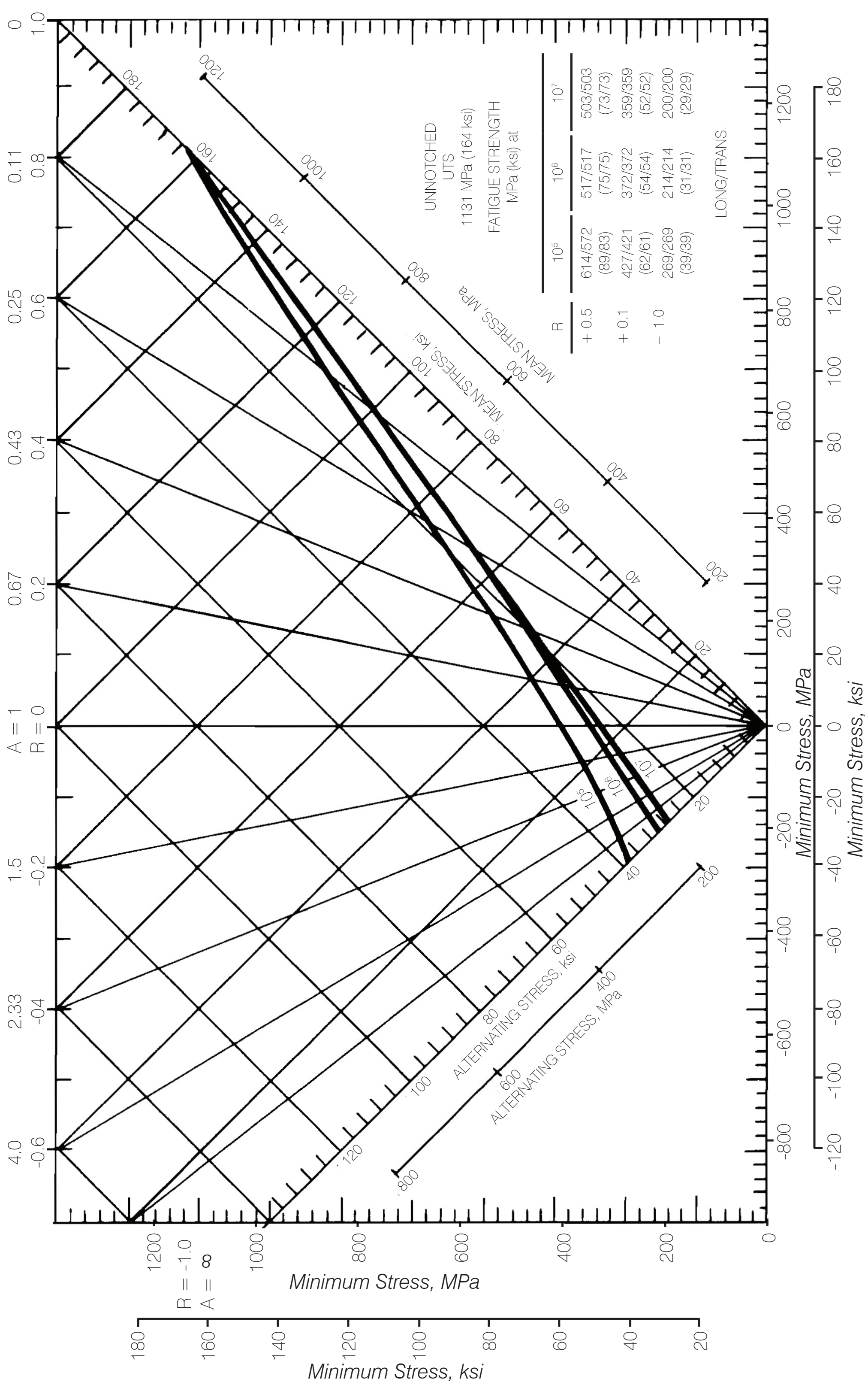

Figure 4

*Constant Life Diagram**
Axial Loaded 15-5 PH, Condition H 1025
Notched (k_t = 3.0) Longitudinal and Transverse Specimens
50.8 x 152.4 mm (2 x 6 in.) Section

*Diagram Construction from S-N Curves Developed From One Heat Using Stress Ratio of +0.5, + 0.1 and -1.0.

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ARMCO® 15-5 PH® VAC CE STAINLESS STEEL

Fatigue Strength

TABLE 9 – MODULUS OF ELASTICITY

	Condition			
	H 900	H 1025	H 1075	H 1150
Modulus in Tension, GPa (Mpsi)	196 (28.5)	–	–	–
Modulus in Torsion, GPa (Mpsi)	77 (11.2)	76 (11.0)	69 (10.0)	69 (10.0)

**Data represent average of two tests from one heat.*

The modulus of elasticity of ARMCO® 15-5 PH® VAC CE Stainless Steel at elevated temperature can be conveniently expressed as % of room temperature modulus. At temperatures ranging from room to 315 °C (600 °F) this material showed the following:

TABLE 10

Temperature, °C (°F)	Modulus of Elasticity* (% of Room Temp. Modulus)
22 (72)	100.0
38 (100)	99.6
93 (200)	97.8
149 (300)	96.3
204 (400)	94.7
260 (500)	93.0
315 (600)	91.4

Poisson's Ratio in all hardened conditions is 0.272.
**Data represent average of two tests from one heat.*

TABLE 11 – TORSIONAL AND TENSILE DATA ARMCO 15-5 PH VAC CE STAINLESS BAR STOCK*

Condition	Torsional Shear Modulus, GPa (Mpsi)	Torsional Proportional Limit, MPa (ksi)	0.2% Torsional Yield Strength, MPa (ksi)		Modulus of Rupture, MPa (ksi)	UTS, MPa (ksi)	0.2% YS, Offset, MPa (ksi)	Torsional		Modulus of Rupture, UTS
			√ **	ɛ**				YS (√) Tension YS	YS (□) Tension YS	
Annealed	69 (9.95)	433 (62.8)	576 (84.8)	644 (93.5)	832 (120.7)	1065 (154.4)	845 (122.6)	0.69	0.76	0.78
H 900	75 (10.79)	616 (89.3)	811 (117.6)	871 (126.3)	1129 (163.7)	1311 (190.1)	1174 (170.2)	0.69	0.74	0.86
H 925	76 (11.07)	636 (92.3)	790 (114.7)	849 (123.1)	1074 (155.5)	1255 (182.0)	1160 (168.3)	0.68	0.73	0.85
H 1025	75 (10.93)	627 (90.8)	743 (107.7)	787 (114.2)	946 (137.1)	1110 (161.0)	1084 (157.3)	0.68	0.73	0.85
H 1100	74 (10.66)	553 (80.1)	683 (99.0)	726 (105.3)	876 (127.0)	1034 (150.0)	1002 (145.2)	0.68	0.73	0.85
H 1150	74 (10.76)	398 (57.7)	594 (86.2)	643 (93.3)	863 (125.1)	977 (141.8)	887 (128.1)	0.67	0.73	0.88
H 1150-M	65 (9.56)	262 (38.0)	409 (59.4)	465 (67.5)	782 (113.4)	910 (132.0)	627 (90.9)	0.65	0.74	0.86

**Average of two tests from one heat — specimens machined from 25.4 mm (1 in.) bar stock*
*** √ — Offset determined by shearing strain (√) = 0.002*
ɛ — Offset determined by normal strain (ɛ) = 0.002
Reference: Test Method described in paper, "Mechanical Properties of Shafting and Valve Stem Materials.'' by John N. Macadam, published in Proceedings of the American Society for Testing and Materials, Vol. 64. page 765.

Elevated Temperature Properties

TABLE 12 – SHORT-TIME TENSILE PROPERTIES*

Property and Condition	Temperature, °C (°F)					
	24 (75)	204 (400)	315 (600)	426 (800)	538 (1000)	648 (1200)
UTS, MPa (ksi)						
H 925	1317 (191)	1158 (168)	1096 (159)	1027 (149)	758 (110)	400 (58)
H 1025	1145 (166)	1014 (147)	958 (139)	917 (133)	724 (105)	372 (54)
H 1100	1069 (155)	951 (138)	910 (132)	848 (123)	662 (96)	–
H 1150-M	896 (130)	765 (111)	717 (104)	676 (98)	552 (80)	–
0.2% YS, MPa (ksi)						
H 925	1213 (176)	1048 (152)	965 (140)	869 (126)	634 (92)	317 (46)
H 1025	1110 (161)	958 (139)	903 (131)	820 (119)	627 (91)	283 (41)
H 1100	1034 (150)	924 (134)	869 (126)	786 (114)	607 (88)	–
H 1150-M	717 (104)	689 (100)	662 (96)	607 (88)	462 (67)	–
Elongation % in $4D_0$						
H 925	16	15	14	15	17	26
H 1025	17	15	14	15	18	28
H 1100	19	16	14	14	18	–
H 1150-M	23	20	19	17	20	–
Reduction of Area, %						
H 925	59	54	59	60	70	83
H 1025	64	58	57	60	70	83
H 1100	67	62	57	60	71	–
H 1150-M	75	64	70	69	74	–

**Data represent average of four tests consisting of duplicate tests on each of two heats one on 25.4 mm (1 in.) diameter bar and the other on 31.8 mm (1.25 in.) diameter bar.*

ARMCO® 15-5 PH® VAC CE STAINLESS STEEL

Corrosion Resistance

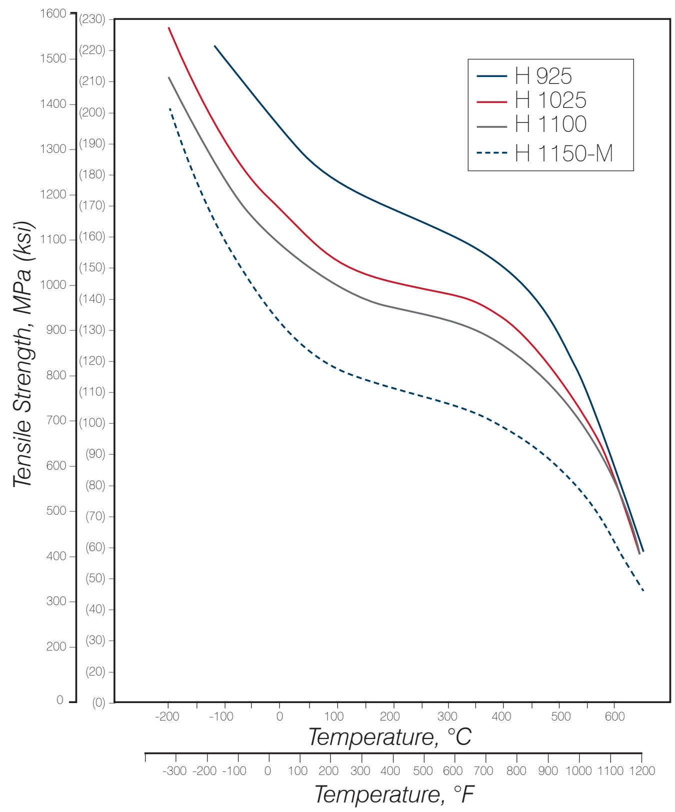
SUB-ZERO MECHANICAL PROPERTIES

ARMCO® 15-5 PH® VAC CE Stainless Steel maintains good ductility at sub-zero temperatures. This property makes it an ideal material for applications such as valves and aircraft parts that must operate at low temperatures. No general statement can be made regarding preferred heat treatment for cryogenic applications because much depends on design requirements. However, many engineers have approved ARMCO 15-5 PH VAC CE Stainless Steel to the following temperature limits:

TABLE 13 – LOWER TEMPERATURE LIMIT FOR SUB-ZERO 15-5 VAC CE

Condition	Temperature, °C (°F)	
H 925	Down to -18 °C (0 °F) for general use.	For non-impact applications it is useful at temperatures as low as -196 °C (-320 °F). For example, valve seats.
H 1025	Down to -46 °C (-50 °F)	Design with caution when using large diameter bars.
H 1100	Down to -79 °C (-110 °F)	Design with caution when using large diameter bars.
H 1150-M	Down to -196 °C (-320 °F)	–

FIGURE 5 – ULTIMATE TENSILE STRENGTH VS. TEST TEMPERATURE* ALL AGED CONDITIONS



*These curves constructed using data from duplicate tests on 2 heats.

Sub-Zero Mechanical Properties

TABLE 14 – SHORT-TIME TENSILE PROPERTIES*

Property and Condition	Temperature, °C (°F)		
	-196 (-320)	-73 (-100)	24 (75)
UTS, MPa (ksi)			
H 925	–	1462 (212)	1317 (191)
H 1025	1558 (226)	1269 (184)	1145 (166)
H 1100	1448 (210)	1186 (172)	1069 (155)
H 1150-M	1386 (201)	1041 (151)	896 (130)
0.2% YS. MPa (ksi)			
H 925	–	1372 (199)	1213 (176)
H 1025	1524 (221)	1234 (179)	1110 (161)
H 1100	1413 (205)	1145 (166)	1034 (150)
H 1150-M	1007 (146)	738 (107)	717 (104)
Elongation % in $4D_0$			
H 925	–	17	16
H 1025	15	18	17
H 1100	18	19	19
H 1150-M	27	25	23
Reduction of Area, %			
H 925	–	61	59
H 1025	55	67	64
H 1100	60	66	67
H 1150-M	65	74	75

**Data represent average of four tests consisting of duplicate tests on each of two heats one on 25.4 mm (1 in.) diameter bar and the other on 31.8 mm (1.25 in.) diameter bar.*

TABLE 15 – IMPACT AT SUB-ZERO TEMPERATURES* V-NOTCH CHARPY IMPACT, J (ft·lbs)

Condition	Temperature, °C (°F)				
	24 (75)	-12 (10)	-40 (-40)	-79 (-110)	-196 (-320)
H 925	79 (58)	38 (28)	22 (16)	9 (7)	–
H 1025	114 (84)	62 (46)	31 (23)	12 (9)	2.7 (2)
H 1100	130 (96)	108 (80)	73 (54)	37 (27)	4.7 (3.5)
H 1150-M	236(174)	233 (172)	226(167)	206 (152)	45 (33)

**Data represent average of four tests consisting of duplicate tests of two heats: one on 25.4 mm (1 in.) diameter bar and theother on 31.8 mm (1.25 in.) diameter bar.*

TABLE 16 – IMPACT AT SUB-ZERO TEMPERATURES* PRECRACKED CHARPY IMPACT, mm·N/mm² (in.·lbs/in²)

Condition	Temperature, °C (°F)				
	24 (75)	-12 (10)	-40 (-40)	-79 (-110)	-196 (-320)
H 925	464 (2650)	131 (750)	53 (300)	35 (200)	–
H 1025	893 (5100	333 (1900)	158 (900)	61 (350)	–
H 1100	1208 (6900)	727 (4150)	377 (2150)	149 (850)	–
H 1150-M	2145 (12 250)	2084 (11 900)	1997 (11 400)	1734(9900	193 (1100)

**Data represent average of four tests consisting of duplicate tests of two heats: one on 25.4 mm (1 in.) diameter bar and the other on 31.8 mm (1.25 in.) diameter bar.*

Physical Properties

TABLE 17 – TYPICAL SUB-ZERO V-NOTCH CHARPY IMPACT* 150 x 150 mm (6 x 6 in.) SECTION LONGITUDINAL — INTERMEDIATE CONDITION H 1150-M

Test Temperature, °C (°F)	Charpy V-Notch, J (ft·lbs)
Room	136 (100)
-79 (-110)	102 (75)
-115 (-175)	54 (40)
-196 (-320)	27 (20)

**Data represent average of duplicate tests on one heat.*

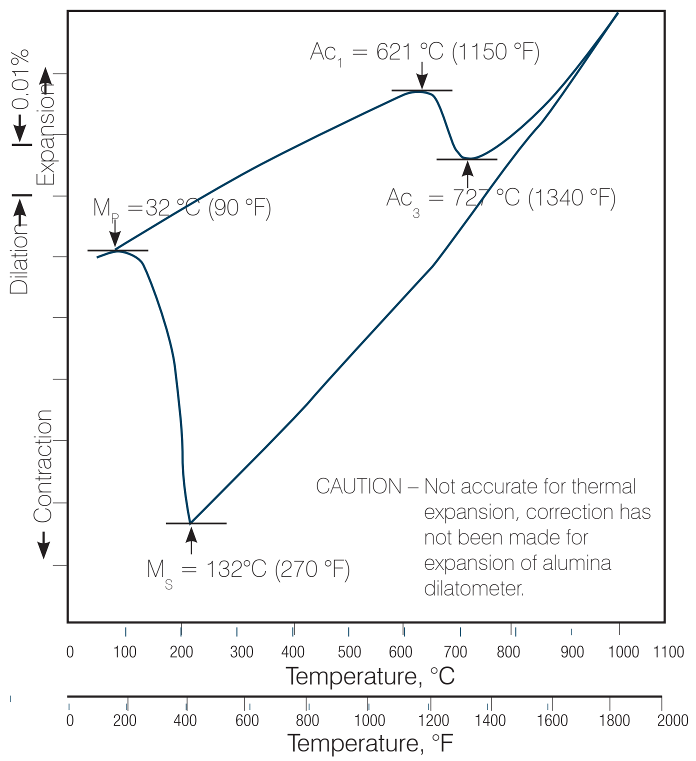
TABLE 18 – PHYSICAL PROPERTIES

	Condition*			
	A	H 900	H 1075	H 1150
Density, g/cm³ (lbs/in³)	7.78 (0.281)	7.80 (0.282)	7.81 (0.282)	7.82 (0.283)
Electrical Resistivity, μΩ•cm	98	77	–	–
Mean Coefficient of Thermal Expansion, μm/m•K (in./in./°F)				
-73/21 °C (-100/70 °F)	–	10.4 (5.8 x 10^{-6})	–	11.0 (6.1 x 10^{-6})
21/93 °C (70/200 °F)	10.8 (6.0 x 10^{-6})	10.8 (6.0 x 10^{-6})	11.3 (6.3 x 10^{-6})	11.9 (6.6 x 10^{-6})
21/204 °C (70/400 °F)	10.8 (6.0 x 10^{-6})	10.8 (6.0 x 10^{-6})	11.7 (6.5 x 10^{-6})	12.4 (6.9 x 10^{-6})
21/315 °C (70/600 °F)	11.2 (6.2 x 10^{-6})	11.3 (6.3 x 10^{-6})	11.9 (6.6 x 10^{-6})	12.8 (7.1 x 10^{-6})
21/426 °C (70/800 °F)	11.3 (6.3 x 10^{-6})	11.7 (6.5 x 10^{-6})	12.2 (6.8 x 10^{-6})	13.0 (7.2 x 10^{-6})
21/482 °C (70/900 °F)	–	–	–	13.1 (7.3 x 10^{-6})
Thermal Conductivity, W/m•K (BTU/hr/ft²/in./°F)				
149 °C (300 °F)	–	17.9 (124)	–	–
260 °C (500 °F)	–	19.5 (135)	–	–
460 °C (860 °F)	–	22.5 (156)	–	–
482 °C (900 °F)	–	22.6 (157)	–	–
Specific Heat, J/kg•K (BTU/lbs/°F)				
0/100 °C (32/212 °F)	–	418 (0.10)	–	–

**Data represent one test from one heat.*

Physical Properties

FIGURE 6 – DILATOMETER CURVE OF ARMCO® 15-5 PH®



Magnetic Properties

Normal induction and hysteresis curves are shown in Figures 7 and 8. There is little difference in the magnetic properties of material heat treated to Conditions H 900 and H 1075. However, magnetic properties of material heated to Condition H 1150 are significantly lower.

FIGURE 7 – NORMAL INDUCTION CURVES

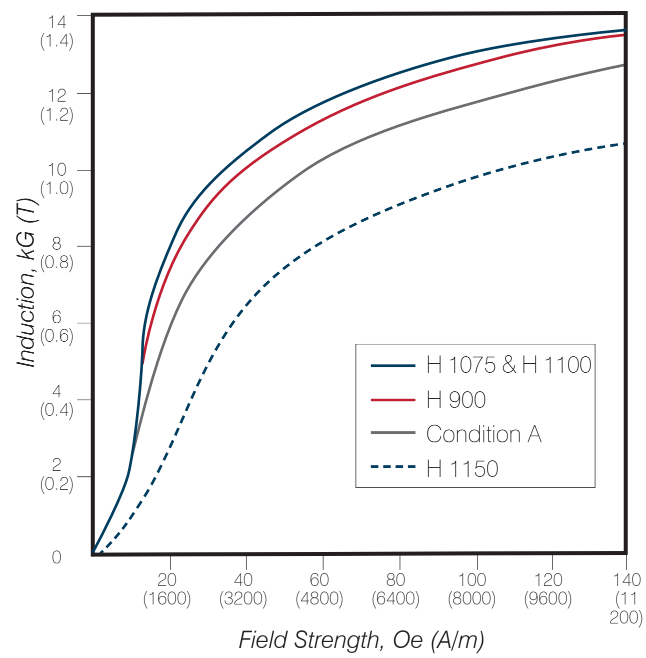
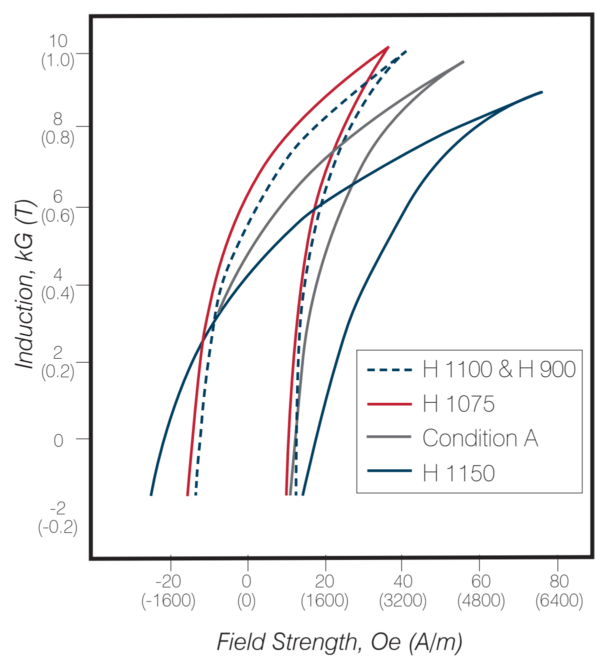


FIGURE 8 – HYSTERESIS CURVES*



**Data represents single tests from three heats*

Corrosion Resistance

The general level of corrosion resistance of ARMCO® 15-5 PH® VAC CE Stainless Steel exceeds that of Types 410 and 431, and is approximately equal to that of ARMCO® 17-4 PH® Stainless Steel. This is indicated by laboratory tests in both strongly oxidizing and reducing media, as well as by atmospheric exposures. In all heat-treated conditions, ARMCO 15-5 PH VAC CE Stainless Steel exhibits very little rusting after 500 hours exposure to 5% salt fog at 35 °C (95 °F). When exposed to marine atmosphere for long periods of time, ARMCO 15-5 PH VAC CE Stainless Steel gradually develops a superficial overall layer of rust like other precipitation hardening stainless steels. The general level of corrosion resistance of ARMCO 15-5 PH VAC CE Stainless Steel is best in the fully hardened condition, and decreases slightly as the aging temperature is increased.

STRESS CORROSION RESISTANCE

The following data were obtained on 1.3 mm (0.052 in.) strip samples of ARMCO 15-5 PH VAC CE Stainless Steel from two heats exposed to a marine atmosphere 24 m (80 ft.) from the ocean.

TABLE 19

Condition	Applied Stress* MPa (ksi)		Results**
A (Heat 1)	918.1 686.6	(133.2) (99.9)	3 NF 3 NF
H 900 (Heat 1)	1189.0 892.0	(172.5) (129.40	3 – 21 days 2 – 21 days; 1 – 28 days
H 900 (Heat 2)	1240.7 930.6	(180.0) (135.0)	3 – 22 days 3 – 22 days
H 925 (Heat 1)	1142.9 857.5	(165.8) (124.4)	3 – 23 days 3 – 23 days
H 925 (Heat 2)	1184.2 888.5	(171.8) (128.9)	2 – 22 days; 1 – 266 days 2 – 22 days; 1 – 109 days
H 975 (Heat 1)	1096.0 822.3	(159.0) (119.3)	3 NF 3 NF
H 975 (Heat 2)	1118.7 838.9	(162.3) (121.7)	3 NF 3 NF
H 1025 (Heat 2)	1096.7 822.3	(159.1) (119.3)	3 NF 3 NF

**Applied stresses were 100% and 75% of the 0.2% yield strength, using smooth bent beam specimens in the longitudinal direction.*
***NF indicates no failure in samples tested for periods up to 18 years.*

These data indicate ARMCO 15-5 PH VAC CE Stainless Steel is highly resistant to stress corrosion cracking in marine atmosphere in Condition A and when aged at temperatures of 523 °C (975 °F) and higher. Heat treating to the hardened conditions, especially at the higher end of the temperature range, stress-relieves the structure and may provide more reliable resistance to stress corrosion cracking than Condition A.

Fabrication

HEAT TREATMENT

For maximum hardness and strength, material in the solution annealed condition is heated for one hour at 482 °C ± 8 °C (900 °F ± 15 °F)* and air cooled to room temperature. If material purchased in the solution annealed condition (Condition A) is hot worked, it must be solution annealed after such working and before hardening. Likewise, material age hardened at one temperature cannot be rehardened at a lower temperature without re-solution heat treating.

All surfaces should be free of cutting lubricants, paint, adhesives, labels, and other foreign matter before any heat-treating operation is performed.

Where ductility in the hardened condition is especially important, better toughness can be obtained by raising the temperature of the hardening heat treatment. Unlike regular hardenable materials which require a hardening plus a tempering or stress-relieving treatment, solution heat treated ARMCO® 15-5 PH® VAC CE Stainless Steel can be hardened to the final desired properties in one operation. By heat treating at temperatures from 482 – 621 °C (900 – 1150 °F), a wide range of properties can be attained. A heat treatment of four hours is generally used for all hardening heat treatments except 482 °C (900 °F), for which a one-hour treatment is used.

If ARMCO 15-5 PH VAC CE Stainless Steel is not ductile enough in any given hardened condition, it can be reheat-treated at a higher temperature to increase impact strength and elongation. This retreatment can be made without a solution treatment prior to the final heat treatment. However, if the material is not hard enough or strong enough, it must be solution annealed and then hardened at a lower temperature.

For material hot worked or forged, a solution treatment of 1022 – 1050 °C (1875 – 1925 °F) for one-half hour, followed by cooling to at least 32 °C (90 °F) must be done prior to hardening. Oil quenching or water polymer quenching rather than air cooling may be used on small, simple sections. This treatment will refine the grain size and make hardened material more uniform. Multiple solution heat treatments will continue grain refinement to the benefit of toughness.

On hardening ARMCO 15-5 PH VAC CE Stainless Steel, a dimensional change will take place. Typical dimensional changes are shown in Table 20. They can vary from heat to heat.

*AMS 5622 specifies a tighter range of 402 ± 6 °C and 1 hour± 0.1 minutes.
900 ± 10 °F

TABLE 20 – CONTRACTION FROM HEAT TREATMENT COMING FROM CONDITION A*

Condition		Results
H 900		0.00045 mm/mm (in./in.)
H 925		0.00051 mm/mm (in./in.)
H 1025		0.00053 mm/mm (in./in.)
H 1100		0.0009 mm/mm (in./in.)
H 1150		0.0022 mm/mm (in./in.)
H 1150-M	1400 °F 1150 °F	0.00037 mm/mm (in./in.) 0.00206 mm/mm (in./in.)
	∴ 1400 + 1150 °F	0.00243 mm/mm (in./in.)

*Data represent single tests from one heat.

IMPORTANCE OF COOLING TO 32 °C (90 °F) IN FABRICATING AND HEAT TREATING ARMCO 15-5 PH VAC CE STAINLESS STEEL

In fabricating ARMCO 15-5 PH VAC CE Stainless Steel, it is important to keep in mind the low temperatures at which the start of transformation to martensite (M_s) and the finish of the martensite transformation (M_f) occur. These temperatures are approximately 132 °C (270 °F) and 32 °C (90 °F), respectively.

Because of this characteristic, it is necessary to cool parts in process at least to 32 °C (90 °F) prior to applying subsequent heat treatments if normal final properties are to be obtained. This practice is essential to assure grain refinement, and to assure the product will have the good ductility of which this alloy is capable. Examples of situations where cooling to 32 °C (90 °F) is an important step follow:

1) Cool a forged part to 32 °C (90 °F) after final forging before solution annealing.
2) Cool to 32 °C (90 °F) after heat treating at 760 °C (1400 °F) prior to aging at 621 °C (1150 °F) in the H 1150-M treatment.
3) Cool to 32 °C (90 °F) after solution annealing prior to applying any of the precipitation hardening treatments.

Fabrication

SURFACE HARDENING

ARMCO® 15-5 PH® VAC CE Stainless Steel can be nitrided when increased resistance to galling and wear is required. An advantage obtained in using ARMCO 15-5 PH VAC CE Stainless Steel rather than a standard chromium or chromium-nickel stainless steel is that the core is simultaneously strengthened and toughened during the nitriding treatment.

Using the gas-phase method, case hardnesses of approximately Rockwell C67 have been obtained to a depth of 0.1 – 0.15 mm (0.004 – 0.006 in.). This method of nitriding utilizes a temperature of about 565 °C (1050 °F) and results in a tough core with a hardness of about Rockwell C36. However, nitriding considerably decreases the corrosion resistance of ARMCO 15-5 PH VAC CE Stainless Steel (as it does with any stainless steel). Nitrided ARMCO 15-5 PH VAC CE Stainless Steel should be used only in mildly corrosive applications.

FORGING

Forging is an excellent method for forming intricate shapes of ARMCO 15-5 PH VAC CE Stainless Steel. Forging blanks should be heated uniformly to 1176 – 1204 °C (2150 – 2200 °F) and held at temperature at least 15 minutes before forging. On large sections over 19 mm (0.75 in.) diameter or thickness, the material should be heated for one-half hour per inch (25.4 mm) of thickness at 1176 – 1204 °C (2150 – 2200 °F) and held for one-half to one hour at temperature prior to forging. Heating above 1204 °C (2200 °F) may cause undesirable grain coarsening and ferrite formation. The steel should be cooled down below 32 °C (90 °F) and reheated to proper forging temperatures if overheating occurs. After forging, the material should be cooled below 32 °C (90 °F) to assure complete transformation. To secure optimum toughness in the final hardened condition, forged parts must first be put into Condition A by reheating to 1022 – 1050 °C (1875 – 1925 °F) and air cooled (or oil quenching small simple parts) to below 32 °C (90 °F).

ARMCO 15-5 PH stainless is austenitic on cooling from forging or solution treating temperatures until approximately 121 °C (250 °F) is reached. Transformation to martensite then begins. The transformation is not complete until the temperature has reached approximately 32 °C (90 °F) throughout the piece. Cooling through this range should be as uniform as possible to reduce residual stresses.

Upon completion of the forging operation, forgings less than 75 mm (3 in.) in maximum thickness and simple in shape should be air cooled to 32 °C (90 °F) or below before further processing. Forgings smaller than 75 mm (3 in.) in maximum thickness, but intricate in shape, should be returned to a furnace and equalized at 1038 – 1176 °C (1900 – 2150 °F) before cooling to 32 °C (90 °F) or below.

Forgings 75 mm (3 in.) and larger, after equalizing, should be cooled fairly rapidly until black. They should then be covered immediately and completely with a light-gauge metal cover (nothing galvanized) or thin insulative blankets and allowed to cool undisturbed to room temperature (room temperature means atmospheric temperature in the area of cooling). Cooling should be done in areas which are reasonably free of drafts and which are away from furnaces, where temperatures in the surrounding area may be high.

In critical types of upset-forgings and flattening operations, ARMCO 17-4 PH Stainless Steel may split and rupture. ARMCO 15-5 PH VAC CE Stainless Steel will perform better because it has no delta ferrite, superior steel cleanliness and minimal directionality.

Welding

Sound weld joints can easily be produced in ARMCO® 15-5 PH® VAC CE Stainless Steel with proper welding practice. Properties comparable to those of the parent metal can be secured in the weld by postweld heat treatment. Procedures employed for welding are similar to those ordinarily used for the austenitic types, even though the composition of ARMCO 15-5 PH VAC CE Stainless Steel and its structure more closely resemble that of a martensitic stainless steel. Any of the arc and resistance welding processes used on the regular grades of stainless steel are suitable for ARMCO 15-5 PH VAC CE Stainless Steel. The most outstanding welding property of this steel is its ability to withstand welding operations without requiring preheating.

Favorable composition accounts for the good performance of ARMCO 15-5 PH VAC CE stainless in welding. The very low carbon content is an important feature because it restricts the hardness of rapidly cooled material and avoids the formation of cracks in the weld metal and the heat-affected zone of the base metal. This eliminates the need for pre-heating. While the ARMCO 15-5 PH VAC CE Stainless Steel base metal shows no susceptibility to spontaneous underbead cracking from weld hardening, it does not possess the high ductility and toughness of austenitic Cr-Ni steels. Therefore, it should not be subjected to high levels of biaxial or triaxial stress from severely restrained weldments or exposed to notched conditions. Weldment design should be given the same attention required for any high-strength alloy steel to avoid the concentration of residual welding stress or reaction stress at square corners, unfused notches and sharp threads.

In fusion welding, it is important that consideration be given to proper control of the weld deposit composition. Autogenous welds, such as are possible with the gas tungsten arc, plasma arc and electron beam processes represent a borderline condition with respect to producing best metallurgical structures for hot crack resistance. Even with such a borderline condition, few instances of hot cracking have been reported in either the laboratory or field welding of ARMCO 15-5 PH Stainless Steel. While confidence that crack-free welds can be made is high, it is still conceivable that changes in product and/or weld procedures could cause cracking to occur. Cracking of this type, if it were to occur, can be detected easily at the time of welding.

The precipitation hardening class of stainless steels is generally considered to be weldable by the common fusion and resistance techniques. Special consideration is required to achieve optimum mechanical properties by considering the best heat-treated conditions in which to weld and which heat treatments should follow welding. This particular alloy is generally considered to have equivalent weldability to the most common alloy of this stainless class, ARMCO 17-4 PH Stainless Steel. When a weld filler is needed, AWS E/ER 630 is most often specified. ARMCO 15-5 PH VAC CE Stainless Steel is well known in reference literature and more information can be obtained in
the following ways:

1. ANSI/AWS A5.9, A5.22, and A5.4 (stainless steel filler metals, welding electrode specifications).
2. “Welding of Stainless Steels and Other Joining Methods,” SSINA, (www.ssina.com).

ARMCO® 15-5 PH® VAC CE STAINLESS STEEL

MACHINING

ARMCO® 15-5 PH® VAC CE Stainless Steel steel can be machined in either the solution-treated or any of the heat-treated conditions. One of the important advantages of the alloy is it can be finish machined in Condition A, then heat treated. Because the final hardening temperatures are low, there is no harmful scaling or distortion. Design allowance can be made for the predictable contraction on hardening.

Machining rates for ARMCO 15-5 PH VAC CE Stainless Steel in Condition A are similar to those for Types 302 and 304 stainless steels. In the hardened condition (H 900) this material should be machined at 60% of the rate used for Condition A. Surface finishes in either condition are excellent. Best tool life is achieved from Condition H 1150-M; however, higher cutting forces may be encountered.

CUTTING

In general, the cutting procedures commonly used for the standard chromium-nickel types also apply to ARMCO 15-5 PH VAC CE Stainless Steel.

Cold sawing is recommended for cutting bars and forging billets. Hot cutting or abrasive wheel cutting with a large volume of coolant has been used successfully. However, it should be noted that abrasive wheel cutting can cause small surface cracks on the cut face unless in the overaged condition.

Torch cutting ARMCO 15-5 PH VAC CE Stainless Steel requires a process suited for cutting stainless steel, such as plasma-arc, powder cutting, oxy-arc or arc-air methods.

Since the heat-affected zones of ARMCO 15-5 PH VAC CE Stainless Steel are not significantly hardened or embrittled by the localized heat of welding or torch cutting, this alloy offers good possibilities for oxygen or air torch cutting. ARMCO 15-5 PH VAC CE Stainless Steel bars can be torch cut by flux-injection or iron powder processes.

DESCALING

The hardening treatments for ARMCO 15-5 PH Stainless Steel produce only a light heat tint on the surfaces. The presence of this film may degrade the corrosion resistance of the alloy. The heat tint can be removed easily either by mechanical means, such as wet grit blasting, or by light pickling for several minutes in 10% nitric acid – 2%; hydrofluoric acid (by volume) solution at 43 – 60 °C (110 – 140 °F). Prolonged exposure to this solution should be avoided to minimize surface etching and the possibility of hydrogen embrittlement. Where pickling is undesirable, the heat tint may be removed by light electropolishing. The latter two treatments also passivate or clean the surfaces for maximum corrosion resistance.

The most satisfactory method of removing scale resulting from the solution treatment or forging is grit blasting. This should be followed by immersion in 10% nitric acid-2% hydrofluoric acid (by volume) solution at 43 – 60 °C (110 – 140 °F) for several minutes to remove any debris that may have been embedded in the surface by the blasting operation. Again, prolonged exposure to this solution should be avoided to minimize the possibility of hydrogen embrittlement.

ARMCO® 15-5 PH® VAC CE STAINLESS STEEL

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July 2022