Designation: B338 – 17

Standard Specification for Seamless and Welded Titanium and Titanium Alloy Tubes for Condensers and Heat Exchangers[1]

This standard is issued under the fixed designation B338; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope*

1.1 This specification[2] covers the requirements for 28 grades of titanium and titanium alloy tubing intended for surface condensers, evaporators, and heat exchangers, as follows:

1.1.1 *Grade 1*—UNS R50250. Unalloyed titanium,

1.1.2 *Grade 2*—UNS R50400. Unalloyed titanium,

1.1.2.1 *Grade 2H*—UNS R50400. Unalloyed titanium (Grade 2 with 58 ksi (400 MPa) minimum UTS),

1.1.3 *Grade 3*—UNS R50550. Unalloyed titanium,

1.1.4 *Grade 7*—UNS R52400. Unalloyed titanium plus 0.12 to 0.25 % palladium,

1.1.4.1 *Grade 7H*—UNS R52400. Unalloyed titanium plus 0.12 to 0.25 % palladium (Grade 7 with 58 ksi (400 MPa) minimum UTS),

1.1.5 *Grade 9*—UNS R56320. Titanium alloy (3 % aluminum, 2.5 % vanadium),

1.1.6 *Grade 11*—UNS R52250. Unalloyed titanium plus 0.12 to 0.25 % palladium,

1.1.7 *Grade 12*—UNS R53400. Titanium alloy (0.3 % molybdenum, 0.8 % nickel),

1.1.8 *Grade 13*—UNS R53413. Titanium alloy (0.5 % nickel, 0.05 % ruthenium),

1.1.9 *Grade 14*—UNS R53414. Titanium alloy (0.5 % nickel, 0.05 % ruthenium),

1.1.10 *Grade 15*—UNS R53415. Titanium alloy (0.5 % nickel, 0.05 % ruthenium),

1.1.11 *Grade 16*—UNS R52402. Unalloyed titanium plus 0.04 to 0.08 % palladium,

1.1.11.1 *Grade 16H*—UNS R52402. Unalloyed titanium plus 0.04 to 0.08 % palladium (Grade 16 with 58 ksi (400 MPa) minimum UTS),

1.1.12 *Grade 17*—UNS R52252. Unalloyed titanium plus 0.04 to 0.08 % palladium,

1.1.13 *Grade 18*—UNS R56322. Titanium alloy (3 % aluminum, 2.5 % vanadium) plus 0.04 to 0.08 % palladium,

1.1.14 *Grade 26*—UNS R52404. Unalloyed titanium plus 0.08 to 0.14 % ruthenium,

1.1.14.1 *Grade 26H*—UNS R52404. Unalloyed titanium plus 0.08 to 0.14 % ruthenium (Grade 26 with 58 ksi (400 MPa) minimum UTS),

1.1.15 *Grade 27*—UNS R52254. Unalloyed titanium plus 0.08 to 0.14 % ruthenium,

1.1.16 *Grade 28*—UNS R56323. Titanium alloy (3 % aluminum, 2.5 % vanadium) plus 0.08 to 0.14 % ruthenium,

1.1.17 *Grade 30*—UNS R53530. Titanium alloy (0.3 % cobalt, 0.05 % palladium),

1.1.18 *Grade 31*—UNS R53532. Titanium alloy (0.3 % cobalt, 0.05 % palladium),

1.1.19 *Grade 33*—UNS R53442. Titanium alloy (0.4 % nickel, 0.015 % palladium, 0.025 % ruthenium, 0.15 % chromium),

1.1.20 *Grade 34*—UNS R53445. Titanium alloy (0.4 % nickel, 0.015 % palladium, 0.025 % ruthenium, 0.15 % chromium),

1.1.21 *Grade 35*—UNS R56340. Titanium alloy (4.5 % aluminum, 2 % molybdenum, 1.6 % vanadium, 0.5 % iron, 0.3 % silicon),

1.1.22 *Grade 36*—UNS R58450. Titanium alloy (45 % niobium),

1.1.23 *Grade 37*—UNS R52815. Titanium alloy (1.5 % aluminum),

1.1.24 *Grade 38*—UNS R54250. Titanium alloy (4 % aluminum, 2.5 % vanadium, 1.5 % iron), and

1.1.25 *Grade 39*—UNS R53390. Titanium alloy (0.25 % iron, 0.4 % silicon).

NOTE 1—H grade material is identical to the corresponding numeric grade (that is, Grade 2H = Grade 2) except for the higher guaranteed minimum UTS, and may always be certified as meeting the requirements of its corresponding numeric grade. Grades 2H, 7H, 16H, and 26H are intended primarily for pressure vessel use.

1.2 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical

[1] This specification is under the jurisdiction of ASTM Committee B10 on Reactive and Refractory Metals and Alloys and is the direct responsibility of Subcommittee B10.01 on Titanium.

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[2] For ASME Boiler and Pressure Vessel Code applications, see related Specification SB-338 in Section II of that Code.

*A Summary of Changes section appears at the end of this standard conversions to SI units that are provided for information only and are not considered standard.

1.3 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

A370 Test Methods and Definitions for Mechanical Testing of Steel Products
E8 Test Methods for Tension Testing of Metallic Materials
E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
E213 Practice for Ultrasonic Testing of Metal Pipe and Tubing
E426 Practice for Electromagnetic (Eddy Current) Examination of Seamless and Welded Tubular Products, Titanium, Austenitic Stainless Steel and Similar Alloys
E499 Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the Detector Probe Mode
E1409 Test Method for Determination of Oxygen and Nitrogen in Titanium and Titanium Alloys by Inert Gas Fusion
E1447 Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by Inert Gas Fusion Thermal Conductivity/Infrared Detection Method
E1941 Test Method for Determination of Carbon in Refractory and Reactive Metals and Their Alloys by Combustion Analysis
E2371 Test Method for Analysis of Titanium and Titanium Alloys by Direct Current Plasma and Inductively Coupled Plasma Atomic Emission Spectrometry (Performance-Based Test Methodology)
E2626 Guide for Spectrometric Analysis of Reactive and Refractory Metals (Withdrawn 2017)[4]

3. Terminology

3.1 *Lot Definitions:*

3.1.1 *castings, n*—a lot shall consist of all castings produced from the same pour.

3.1.2 *ingot, n*—no definition required.

3.1.3 *rounds, flats, tubes, and wrought powder metallurgical products (single definition, common to nuclear and non-nuclear standards), n*—a lot shall consist of a material of the same size, shape, condition, and finish produced from the same ingot or powder blend by the same reduction schedule and the same heat treatment parameters. Unless otherwise agreed between manufacturer and purchaser, a lot shall be limited to the product of an 8 h period for final continuous anneal, or to a single furnace load for final batch anneal.

3.1.4 *sponge, n*—a lot shall consist of a single blend produced at one time.

3.1.5 *weld fittings, n*—definition is to be mutually agreed upon between manufacturer and the purchaser.

4. Ordering Information

4.1 Orders for material to this specification shall include the following information, as required:

4.1.1 Quantity,
4.1.2 Grade number (Section 1),
4.1.3 Diameter and wall thickness (Note 2) (Section 12),
4.1.4 Length (Section 12),
4.1.5 Method of manufacture and finish (Sections 5 and 13),
4.1.6 Restrictive chemistry, if desired (Section 6 and Table 1),
4.1.7 Product analysis, if desired (Section 7 and Table 2),
4.1.8 Special mechanical properties, if desired (Section 8 and Table 3),
4.1.9 Nondestructive tests (Section 11),
4.1.10 Packaging (Section 23),
4.1.11 Inspection (Section 17), and
4.1.12 Certification (Section 21).

NOTE 2—Tube is available to specified outside diameter and wall thickness. Average OD and wall are the standard. Maximum or minimum OD or wall should be stated.

4.2 Optional supplementary requirements are provided and, when one or more of these are desired, each shall be so stated in the order.

5. Materials and Manufacture

5.1 Seamless tube shall be made from hollow billet by any cold reducing or cold drawing process that will yield a product meeting the requirements of this specification. Seamless tube is produced with a continuous periphery in all stages of manufacturing operations.

5.2 Welded tube shall be made from annealed, flat-rolled product by an automatic arc-welding process or other method of welding that will yield a product meeting the tensile requirements found in Table 3 of this specification. Welded tubing shall be heat treated by at least a stress relief after forming and welding. Use of filler material is not permitted.

5.3 Welded/cold worked tube (WCS) shall be made from welded tube manufactured as specified in 5.2. The welded tube shall be sufficiently cold worked to final size in order to transform the cast weld microstructure into a typical equiaxed microstructure in the weld upon subsequent heat treatment. The product shall meet the requirements for seamless tube of this specification.

5.4 Grades 9, 18 and 28, which, at the option of the purchaser, can be furnished in either the annealed or the cold worked and stress relieved condition, defined as at a minimum temperature of 600°F (316°C) for not less than 30 min.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] The last approved version of this historical standard is referenced on www.astm.org.

TABLE 1 Chemical Requirements

Grade	UNS Number	Carbon, max.	Oxygen range or max.	Nitrogen, max.	Hydrogen, max.	Iron range or max.	Aluminum	Vanadium	Palladium	Ruthenium	Nickel	Molybdenum	Chromium	Cobalt	Zirconium	Niobium	Tin	Silicon	Other Elements, max. each	Other Elements, max. total
		Composition, Weight Percent[A,B,C,D,E]																		
1	R50250	0.08	0.18	0.03	0.015	0.20	...	...	...	...	...	...	...	...	...	...	...	...	0.1	0.4
2/2H	R50400	0.08	0.25	0.03	0.015	0.30	...	...	...	...	...	...	...	...	...	...	...	...	0.1	0.4
3	R50550	0.08	0.35	0.05	0.015	0.30	...	...	...	...	...	...	...	...	...	...	...	...	0.1	0.4
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—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
7/7H	R52400	0.08	0.25	0.03	0.015	0.30	...	...	0.12-0.25	...	...	...	...	...	...	...	...	...	0.1	0.4
9	R56320	0.08	0.15	0.03	0.015	0.25	2.5-3.5	2.0-3.0	...	...	...	...	...	...	...	...	...	...	0.1	0.4
11	R52250	0.08	0.18	0.03	0.015	0.20	...	...	0.12-0.25	...	...	...	...	...	...	...	...	...	0.1	0.4
12	R53400	0.08	0.25	0.03	0.015	0.30	...	...	...	...	0.6-0.9	0.2-0.4	...	...	...	...	...	...	0.1	0.4
13	R53413	0.08	0.10	0.03	0.015	0.20	...	...	...	0.04-0.06	0.4-0.6	...	...	...	...	...	...	...	0.1	0.4
14	R53414	0.08	0.15	0.03	0.015	0.30	...	...	...	0.04-0.06	0.4-0.6	...	...	...	...	...	...	...	0.1	0.4
15	R53415	0.08	0.25	0.05	0.015	0.30	...	...	...	0.04-0.06	0.4-0.6	...	...	...	...	...	...	...	0.1	0.4
16/16H	R52402	0.08	0.25	0.03	0.015	0.30	...	...	0.04-0.08	...	...	...	...	...	...	...	...	...	0.1	0.4
17	R52252	0.08	0.18	0.03	0.015	0.20	...	...	0.04-0.08	...	...	...	...	...	...	...	...	...	0.1	0.4
18	R56322	0.08	0.15	0.03	0.015	0.25	2.5-3.5	2.0-3.0	0.04-0.08	...	...	...	...	...	...	...	...	...	0.1	0.4
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26/26H	R52404	0.08	0.25	0.03	0.015	0.30	...	...	...	0.08-0.14	...	...	...	...	...	...	...	...	0.1	0.4
27	R52254	0.08	0.18	0.03	0.015	0.20	...	...	...	0.08-0.14	...	...	...	...	...	...	...	...	0.1	0.4
28	R56323	0.08	0.15	0.03	0.015	0.25	2.5-3.5	2.0-3.0	...	0.08-0.14	...	...	...	...	...	...	...	...	0.1	0.4
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31	R53532	0.08	0.35	0.05	0.015	0.30	...	...	0.04-0.08	...	...	...	...	0.20-0.80	...	...	...	...	0.1	0.4
—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
33	R53442	0.08	0.25	0.03	0.015	0.30	...	...	0.01-0.02	0.02-0.04	0.35-0.55	...	0.1-0.2	...	...	...	...	...	0.1	0.4
34	R53445	0.08	0.35	0.05	0.015	0.30	...	...	0.01-0.02	0.02-0.04	0.35-0.55	...	0.1-0.2	...	...	...	...	...	0.1	0.4
35	R56340	0.08	0.25	0.05	0.015	0.20-0.80	4.0-5.0	1.1-2.1	...	...	...	1.5-2.5	...	...	...	...	...	0.20-0.40	0.1	0.4
36	R58450	0.04	0.16	0.03	0.015	0.03	...	...	...	...	...	...	...	...	...	42.0-47.0	...	...	0.1	0.4
37	R52815	0.08	0.25	0.03	0.015	0.30	1.0-2.0	...	...	...	...	...	...	...	...	...	...	...	0.1	0.4

TABLE 1 *Continued*

Grade	UNS Number	Carbon, max.	Oxygen range or max.	Nitrogen, max.	Hydrogen, max.	Iron range or max.	Aluminum	Vanadium	Palladium	Ruthenium	Nickel	Molybdenum	Chromium	Cobalt	Zirconium	Niobium	Tin	Silicon	Other Elements, max. each	Other Elements, max. total
		Composition, Weight Percent[A,B,C,D,E]																		
38	R54250	0.08	0.20-0.30	0.03	0.015	1.2-1.8	3.5-4.5	2.0-3.0	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	0.1	0.4
39	R53390	0.08	0.15	0.03	0.015	0.15-0.40	—	—	—	—	—	—	—	—	—	—	—	0.30-0.50	0.1	0.4

[A] At minimum, the analysis of samples from the top and bottom of the ingot shall be completed and reported for all elements listed for the respective grade in this table.
[B] Final product hydrogen shall be reported. Ingot hydrogen need not be reported. Lower hydrogen may be obtained by negotiation with the manufacturer.
[C] Single values are maximum. The percentage of titanium is determined by difference.
[D] Other elements need not be reported unless the concentration level is greater than 0.1 % each, or 0.4 % total. Other elements may not be added intentionally. Other elements may be present in titanium or titanium alloys in small quantities and are inherent to the manufacturing process. In titanium these elements typically include aluminum, vanadium, tin, chromium, molybdenum, niobium, zirconium, hafnium, bismuth, ruthenium, palladium, yttrium, copper, silicon, cobalt, tantalum, nickel, boron, manganese, and tungsten.
[E] The purchaser may, in the written purchase order, request analysis for specific elements not listed in this specification.

TABLE 2 Permissible Variations in Product Analysis

Element	Maximum or Specified Range (%)	Permissible Variation in Product Analysis (%)
Aluminum	0.5 to 2.5	±0.20
Aluminum	2.5 to 3.5	±0.40
Carbon	0.10	+0.02
Chromium	0.1 to 0.2	±0.02
Cobalt	0.2 to 0.8	±0.05
Hydrogen	0.015	+0.002
Iron	0.80	+0.15
Iron	1.2 to 1.8	±0.20
Molybdenum	0.2 to 0.4	±0.03
Molybdenum	1.5 to 4.5	±0.20
Nickel	0.3 to 0.9	±0.05
Niobium	>30	±0.50
Nitrogen	0.05	+0.02
Oxygen	0.30	+0.03
Oxygen	0.31 to 0.40	±0.04
Palladium	0.01 to 0.02	±0.002
Palladium	0.04 to 0.25	±0.02
Ruthenium	0.02 to 0.04	±0.005
Ruthenium	0.04 to 0.06	±0.005
Ruthenium	0.08 to 0.14	±0.01
Silicon	0.06 to 0.50	±0.02
Vanadium	2.0 to 3.0	±0.15
Residuals[A] (each)	0.1	+0.02

[A] A residual is an element present in a metal or an alloy in small quantities inherent to the manufacturing process but not added intentionally. In titanium these elements include aluminum, vanadium, tin, iron, chromium, molybdenum, niobium, zirconium, hafnium, bismuth, ruthenium, palladium, yttrium, copper, silicon, cobalt, tantalum, nickel, boron, manganese, and tungsten.

6. Chemical Requirements

6.1 The titanium shall conform to the chemical requirements prescribed in Table 1.

6.1.1 The elements listed in Table 1 are intentional alloy additions or elements that are inherent to the manufacture of titanium sponge, ingot, or mill product.

6.1.2 Elements intentionally added to the melt must be identified, analyzed, and reported in the chemical analysis.

6.2 When agreed upon by the producer and the purchaser and requested by the purchaser in the written purchase order, chemical analysis shall be completed for specific residual elements not listed in this specification.

7. Product Analysis

7.1 When requested by the purchaser and stated in the purchase order, product analysis for any elements listed in Table 1 shall be made on the completed product.

7.1.1 Elements other than those listed in Table 1 are deemed to be capable of occurring in the grades listed in Table 1 by, and only by way of, unregulated or unanalyzed scrap additions to the ingot melt. Therefore, product analysis for elements not listed in Table 1 shall not be required unless specified and shall be considered to be in excess of the intent of this specification.

7.2 Product analysis tolerances, listed in Table 2, do not broaden the specified heat analysis requirements, but cover variations between different laboratories in the measurement of chemical content. The manufacturer shall not ship the finished product that is outside the limits specified in Table 1 for the applicable grade.

8. Tensile Requirements

8.1 The room temperature tensile properties of the tube in the condition normally supplied shall conform to the requirements prescribed in Table 3. Mechanical properties for conditions other than those given in this table may be established by agreement between the manufacturer and the purchaser. (See Test Methods E8.)

9. Flattening Test

9.1 Tubing shall withstand, without cracking, flattening under a load applied gradually at room temperature until the distance between the load platens is not more than H in. H is calculated as follows:

$$H\text{, in. (mm)} = \frac{(1+e)t}{e+t/D} \quad (1)$$

where:

H = the minimum flattened height, in. (mm),
t = the nominal wall thickness, in. (mm), and
D = the nominal tube diameter, in. (mm).

For Grades 1, 2, 2H, 7, 7H, 11, 13, 14, 16, 16H, 17, 26, 26H, 27, 30, 33, and 39:

$$e = 0.07 \text{ in. for all diameters} \quad (2)$$

For Grade 3, 31, and 34:

$$e = 0.04 \text{ through 1 in. diameter} \quad (3)$$

$$e = 0.06 \text{ over 1 in. diameter} \quad (4)$$

For Grades 9, 12, 15, 18, 28, 35, 36, 37, and 38:

e shall be negotiated between the producer and the purchaser.

9.1.1 For welded tubing, the weld shall be positioned on the 90 or 270° centerline during loading so as to be subjected to a maximum stress.

9.1.2 When low D-to-t ratio tubular products are tested, because the strain imposed due to geometry is unreasonably high on the inside surface at the six and twelve o'clock locations, cracks at these locations shall not be cause for rejection if the D-to-t ratio is less than ten (10).

9.2 The results from all calculations are to be rounded to two decimal places. Examination for cracking shall be by the unaided eye.

9.3 Welded tube shall be subjected to a reverse flattening test in accordance with Annex 2 of Test Methods and Definitions A370. A section of the tube, approximately 4 in. (102 mm) long, that is slit longitudinally 90° either side of the weld, shall be opened and flattened with the weld at the point of maximum bend. No cracking is permitted.

10. Flaring Test

10.1 For tube 3½ in. (88 mm) in outside diameter and smaller, and 0.134 in. (3.4 mm) in wall thickness and thinner, a section of tube approximately 4 in. (102 mm) in length shall withstand being flared with a tool having a 60° included angle until the tube at the mouth of the flare has been expanded in accordance with Table 4. The flared end shall show no cracking or rupture visible to the unaided eye. Flaring tests on larger

TABLE 3 Tensile Requirements

Grade	Tensile Strength, min		Yield Strength, 0.2 % Offset				Elongation in 2 in. or 50 mm, min, %
			min		max		
	ksi	MPa	ksi	MPa	ksi	MPa	
1[A]	35	240	20	138	45	310	24
2[A]	50	345	40	275	65	450	20
2H[A,B,C]	58	400	40	275	65	450	20
3[A]	65	450	55	380	80	550	18
7[A]	50	345	40	275	65	450	20
7H[A,B,C]	58	400	40	275	65	450	20
9[D]	125	860	105	725	...	...	10
9[A]	90	620	70	483	...	...	15[E]
11[A]	35	240	20	138	45	310	24
12[A]	70	483	50	345	...	...	18[E]
13[A]	40	275	25	170	...	...	24
14[A]	60	410	40	275	...	...	20
15[A]	70	483	55	380	...	...	18
16[A]	50	345	40	275	65	450	20
16H[A,B,C]	58	400	40	275	65	450	20
17[A]	35	240	20	138	45	310	24
18[D]	125	860	105	725	...	...	10
18[A]	90	620	70	483	...	...	15[E]
26	50	345	40	275	65	450	20
26H[A,B,C]	58	400	40	275	65	450	20
27	35	240	20	138	45	310	24
28	90	620	70	483	...	...	15
30	50	345	40	275	65	450	20
31	65	450	55	380	80	550	18
33	50	345	40	275	65	450	20
34	65	450	55	380	80	550	18
35	130	895	120	828	...	...	5
36	65	450	60	410	95	655	10
37	50	345	31	215	65	450	20
38	130	895	115	794	...	...	10
39	75	515	60	410	90	620	20

[A] Properties for material in the annealed condition.
[B] Material is identical to the corresponding numeric grade (that is, Grade 2H = Grade 2) except for the higher guaranteed minimum UTS, and may always be certified as meeting the requirements of its corresponding numeric grade. Grade 2H, 7H, 16H, and 26H are intended primarily for pressure vessel use.
[C] The H grades were added in response to a user association request based on its study of over 5200 commercial Grade 2, 7, 16, and 26 test reports, where over 99 % met the 58 ksi minimum UTS.
[D] Properties for cold-worked and stress-relieved material.
[E] Elongation for welded tubing manufactured from continuously cold rolled and annealed strip from coils for Grades 9, 12, and 18 will be 12 %.

TABLE 4 Flaring Requirements

Grade	Expansion of Inside Diameter, min, %
1	22
2, 2H	20
3	17
7, 7H	20
9[A]	20
11	22
12	17
13	22
14	20
15	17
16, 16H	20
17	22
18[A]	20
26, 26H	20
27	22
28[A]	20
30	20
31	17
33	20
34	17
35	10
37	20
38	15
39	20

[A] Annealed.

diameter tube or tubing outside the range of Table 4 shall be as agreed upon between the manufacturer and the purchaser.

11. Nondestructive Tests

11.1 *Welded Tubes* shall be nondestructively tested using the following procedures:

11.1.1 Eddy Current Test, see 11.3.

11.1.2 Ultrasonic Test, see 11.4.1.1.

11.1.3 Hydrostatic Test, see 11.6, or pneumatic test, see 11.7.

11.2 *Seamless and Welded/Cold Worked Tubes* shall be nondestructively tested using the following procedures:

11.2.1 Ultrasonic Test, see 11.4.1.2.

11.2.2 Eddy Current Test, see 11.3, or hydrostatic test, see 11.6, or pneumatic test, see 11.7.

11.3 *Eddy Current Test:*

11.3.1 Perform the nondestructive test in accordance with Practice E426. The entire volume of the tube shall be tested.

11.3.1.1 *Drilled Hole*—The calibration tube shall contain three or more holes, equally spaced circumferentially around the tube and longitudinally separated by a sufficient distance to allow distinct identification of the signal from each hole. The