Designation: B353 – 12 (Reapproved 2017)

Standard Specification for Wrought Zirconium and Zirconium Alloy Seamless and Welded Tubes for Nuclear Service (Except Nuclear Fuel Cladding)[1]

This standard is issued under the fixed designation B353; 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.

1. Scope

1.1 This specification covers seamless and welded wrought zirconium and zirconium-alloy tubes for nuclear application. Nuclear fuel cladding is covered in Specification B811.

1.2 Five grades of reactor grade zirconium and zirconium alloys suitable for nuclear application are described.

1.2.1 The present UNS numbers designated for the five grades are given in Table 1.

1.3 Unless a single unit is used, for example corrosion mass gain in mg/dm^2, the values stated in either inch-pound or SI units are to be regarded separately as standard. The values stated in each system are not exact equivalents; therefore each system must be used independently of the other. SI values cannot be mixed with inch-pound values.

1.4 *The following precautionary caveat pertains only to the test method portions of this specification. This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.5 *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:*[2]

B350/B350M Specification for Zirconium and Zirconium Alloy Ingots for Nuclear Application
B811 Specification for Wrought Zirconium Alloy Seamless Tubes for Nuclear Reactor Fuel Cladding
E8 Test Methods for Tension Testing of Metallic Materials
E21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials
E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
E112 Test Methods for Determining Average Grain Size
G2/G2M Test Method for Corrosion Testing of Products of Zirconium, Hafnium, and Their Alloys in Water at 680°F (360°C) or in Steam at 750°F (400°C)

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *dimensions, n*—tube dimensions are outside diameter, inside diameter, and wall thickness. Only two of these parameters may be specified in addition to length, except minimum wall may be specified with outside and inside diameter. In each case, ovality and wall thickness variation (WTV) may be specified as additional requirements (see 3.1.5 and 3.1.6).

3.1.2 *hydride orientation fraction, Fn, n*—the ratio of hydride platelets oriented in the radial direction to the total hydride platelets in the field examined.

3.1.3 *Lot Definitions:*

3.1.3.1 *tubes, 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 *mill finish tubes, n*—tubes that have received all finishing operations subsequent to final anneal, which potentially affects tube mechanical, dimensional, or surface condition. These operations include, but are not limited to, pickling, cleaning, outer and inner surface abrasive conditioning, and straightening.

[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 B10.02 on Zirconium and Hafnium.

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[2] 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.

TABLE 1 ASTM and UNS Number Designations for Reactor Grade Zirconium and Zirconium Alloys

Grade	UNS Number
Reactor-grade zirconium	R60001
Zirconium-tin alloy	R60802
Zirconium-tin alloy	R60804
Zirconium-niobium alloy	R60901
Zirconium-niobium alloy	R60904

3.1.5 *ovality, n*—the difference between the maximum and minimum diameter, either outer or inner, as determined at any one transverse cross section of the tube.

3.1.6 *wall thickness variation (WTV), n*—the difference between maximum and minimum wall thickness measured at any one transverse cross section of the tube.

3.1.6.1 *Discussion*—Measurement of ovality and WTV made by a helical scan with a pitch not exceeding 0.25 in. (6.5 mm) shall be considered as equivalent to "at any one cross section of the tube."

3.1.7 *recrystallized, n*—fully annealed condition.

3.1.8 *stress relieved, n*—annealed to remove residual stresses without recrystallization.

4. Ordering Information

4.1 Purchase orders for material covered in this specification should include the following information to describe adequately the desired material:

4.1.1 Quantity,

4.1.2 Grade (see Table 1), and UNS Number,

4.1.3 Condition (recrystallized or stress relieved) (Section 6),

4.1.4 Dimensions, length, and tolerance (see Table 2 with Notes),

4.1.5 Method of manufacture (seamless or welded) (Section 5),

4.1.6 ASTM designation and year of issue,

4.1.7 Surface finish on the inside (ID) and the outside (OD) surfaces (Ra (in micro-inches or micrometres), unless otherwise stated) (6.3),

4.1.8 Surface condition on the inside (ID) and outside (OD) surfaces (as pickled, abraded, etc.), and ends (as-saw cut, machined/chamfered, sheared, etc.) (6.2), and

4.1.9 Mutually agreed-upon inspection standards in accordance with 9.2, 10.2, 10.4, 10.5, 11.1.1.2, 11.1.2.2, and 11.1.2.3.

NOTE 1—A typical order description may read as follows: 1000 pieces of seamless zirconium-tin alloy tube OD abraded and ID pickled, Grade R60804, recrystallized, ¾ in. outside diameter by 0.035 in. wall by 10-ft lengths in accordance with ASTM B353-07. Surface finish to be__ OD, __ ID.

4.2 In addition to the information in 4.1, the following points of agreement between the manufacturer and purchaser should be specified in the purchase order as required:

4.2.1 Filler metal requirements for welded tubes (Paragraph 5.4),

4.2.2 Oxygen concentration limits in R60001, R60802, R60804, and R60904 (Section 7),

4.2.3 Specimen temperature(s) during mechanical testing (Section 8 and Table 3, Footnote *C*),

4.2.4 Method of determining yield strength if other than 0.2 % offset method (Section 8),

4.2.5 Tensile property requirements for conditions or temperatures not listed in Table 3 (Section 8),

4.2.6 Location of the inside diameter plugs in elevated temperature short-time tension test, (see Table 3, Footnote *D*, and Paragraph 8.1.3),

4.2.7 Burst properties (Paragraph 8.2),

4.2.8 Post burst test measurement technique (Annex A1),

4.2.9 Sample condition and visual standards for corrosion test (Section 10),

TABLE 2 Permissible Variations in Diameter, Wall Thickness, and Ovality Measured at Any Location

NOTE 1—The tolerances in this table are applicable to only two of the three following dimensions: outside diameter, inside diameter, and wall thickness.

NOTE 2—The manufacturer should be consulted for applicable tolerances in small tubes (less than 0.187 in. (5 mm) in diameter) or tubes with wall thickness less than 0.010 in. (0.25 mm).

NOTE 3—A wider variation of ±12.5 % of wall thickness is permitted for extra-thick walled tubes having wall thicknesses of 0.75 in. (19 mm) (or greater) or inside diameter 60 % (or less) of the outside diameter.

NOTE 4—Ovality is the difference between maximum and minimum outside diameters measured at any one cross section.

NOTE 5—In tubes with nominal wall thickness less than 3 % of nominal outside diameter, the ovality tolerance is twice the tolerance shown for outside or inside diameter (columns 3 and 4), but the average outside or inside diameter must fall within the tolerance given in columns 3 and 4 of the table.

NOTE 6—The manufacturer should be consulted for ovality tolerances in tubes with wall thickness less than 2 % of nominal outside diameter.

Nominal Outside Diameter		Variation in Diameter Outside or Inside		Ovality See Note 5		Variation in Wall Thickness
in.	mm	in.	mm	in.	mm	%
0.187–0.625, excl	5–16, excl	±0.002	±0.05	0.004	0.10	±10
0.625–1.000, excl	16–25, excl	±0.0025	±0.06	0.005	0.12	±10
1.000–2.000, excl	25–50, excl	±0.004	±0.10	0.008	0.20	±10
2.000–3.000, excl	50–75, excl	±0.005	±0.13	0.010	0.26	±10
3.000–4.000, excl	75–100, excl	±0.007	±0.18	0.014	0.36	±10
4.000–5.000, excl	100–125, excl	±0.010	±0.25	0.020	0.50	±10
5.000–6.000, excl	125–150, excl	±0.015	±0.40	0.030	0.80	±10
6.000–8.000, excl	150–200, excl	±0.020	±0.50	0.040	1.00	±10

TABLE 3 Minimum Tensile Properties of Tubing Tested in the Longitudinal Direction[A,B,C,D,E,F]

Material Condition	Test Temperature[C,F]		Minimum Ultimate Tensile Strength		Minimum 0.2 % Yield Strength		Minimum Elongation, %
	°F	(°C)	psi	(MPa)	psi	(MPa)	
R60001	RT	RT	42 000	(290)	20 000	(140)	25
Recrystallized	572	(300)	[B]	[B]	[B]	[B]	[B]
R60802, R60804	RT	RT	60 000	(415)	35 000	(240)	20
Recrystallized	572	(300)	[B]	[B]	[B]	[B]	[B]
R60802, R60804	RT	(RT)	[B]	[B]	[B]	[B]	[B]
Cold-worked and Stress-relieved	572	(300)	[B]	[B]	[B]	[B]	[B]
R60901, R60904	RT	(RT)	65 000	(450)	45 000	(310)	20
Recrystallized	572	(300)	[B]	[B]	[B]	[B]	[B]
R60901, R60904	RT	(RT)	103 000	(710)	70 000	(485)	12
Cold-worked and Stress-relieved	572	(300)	69 500	(480)	48 000	(330)	12

[A] The strength of zirconium alloys is a function of their metallurgical condition, alloy content, and impurity level, especially oxygen. The strength values listed above are for alloys that contain oxygen concentrations in the range 900 to 1400 ppm. For alloys with other oxygen concentrations, the tensile properties are to be agreed upon between the manufacturer and the purchaser.
[B] To be agreed upon between the manufacturer and the purchaser.
[C] The tensile test is to be carried out at one or more of the temperatures listed in Table 3 (or at another temperature) as agreed upon between the manufacturer and purchaser. If one of the above temperatures is selected, the minimum properties shall be as listed for that temperature. If a different temperature is selected, the minimum properties shall be agreed upon between the manufacturer and purchaser.
[D] Paragraph 6.9.1 in Test Methods E8 allows small diameter tubes to be tested as full size tubular sections with snug-fitting metal plugs inserted into the ends of the tube to permit proper gripping by the test machine jaws, as shown in Fig. 11 in Test Methods E8. Specimens for the testing of large diameter tubes are cut from the wall of the tube and are to satisfy the requirements of Figs. 12 and 13 in Test Methods E8.
[E] The properties in this table apply to tubes 0.125 in. (3.2 mm) outside diameter and larger, and 0.015 in. (0.38 mm) wall and thicker. Mechanical properties of tubes outside these limits are to be agreed upon between the manufacturer and purchaser.
[F] "RT" represents room temperature; Note 4 in Test Methods E8 and E8M indicates that RT shall be considered to be 50 to 100°F (10 to 38°C) unless otherwise specified. Paragraph 9.4.4 in Test Methods E21 states that for the duration of the test, the difference between the indicated temperature and the nominal test temperature is not to exceed ±5°F (3°C) for tests at 1800°F (1000°C) and lower, and ±10°F (6°C) for tests at higher temperatures.

4.2.10 Hydride orientation test procedure, measurement technique, magnification of photomicrograph, and limiting values for *Fn* (Section 12 and Annex A2),

4.2.11 For hydride orientation, angle theta (θ) for determining radial platelets (Section 12 and Annex A2).

4.2.12 General test requirements and test plan for samples (Section 14),

4.2.13 Hydrostatic test requirements (Section 13),

4.2.14 Contractile strain ratio acceptance criteria (Paragraph 8.3 and Annex A4),

4.2.15 Retest sampling plan and requirements (Section 15),

4.2.16 Quantity variance (Section 17),

4.2.17 Certificate of test (Section 19), and

4.2.18 Special packing instructions (Section 20).

5. Materials and Manufacture

5.1 Material covered by this specification shall be made from ingots produced by multiple vacuum arc melting, electron beam melting or other melting processes conventionally used for reactive metals; all melting is to be carried out in furnaces usually used for reactive metals.

5.2 The tubes shall be made by a process approved by the purchaser.

5.3 Seamless tubes may be made by any method that will yield a seamless product that meets the requirements of this specification. One such method is extrusion of billets with subsequent cold working, by drawing, swaging, or rocking, with intermediate anneals until the final dimensions are reached.

5.4 Unless otherwise agreed upon between the manufacturer and purchaser, welded tubing shall be made from flat-rolled products by an automatic or semiautomatic welding process with no addition of filler metal in the welding operation. Other methods of welding, such as the addition of filler metal or hand welding, may be employed if approved by the purchaser and tested by methods agreed upon between the manufacturer and the purchaser. If filler wire is used, it must meet the chemical requirements of the appropriate grade as shown in Table 4. Welded tube is normally cold reduced to the desired dimensions by such methods as drawing, swaging, or rocking. The manufacturer must prevent contamination during welding by use of proper precautions.

6. Condition and Finish

6.1 *Metallurgical Condition:*

6.1.1 Grade R60001 product shall be in the recrystallized condition unless otherwise specified in the purchase order.

6.1.2 Grades R60802, R60804, R60901, and R60904 product can be furnished in the recrystallized condition or cold-worked and stress-relieved condition, as specified in the purchase order.

6.2 Tubes shall be furnished with one of the following finishes as designated in the purchase order:

6.2.1 As cold reduced,

6.2.2 Pickled,

6.2.3 Ground, or

6.2.4 Polished.

6.2.5 Ends (saw cut, machined/chamfered, sheared).

6.3 The surface finish of the inside and outside surfaces of the tubes shall be as specified in the purchase order.

7. Chemical Composition

7.1 The material shall conform to the requirements for chemical composition prescribed in Table 4. The purchaser shall specify the grade desired.

TABLE 4 Chemical Requirements

Element	Composition, Weight %				
	UNS R60001	UNS R60802	UNS R60804	UNS R60901	UNS R60904
Tin	...	1.20–1.70	1.20–1.70	...	...
Iron	...	0.07–0.20	0.18–0.24	...	...
Chromium	...	0.05–0.15	0.07–0.13	...	...
Nickel	...	0.03–0.08	...	...	...
Niobium (columbium)	...	...	...	2.40–2.80	2.50–2.80
Oxygen	[A]	[A]	[A]	0.09–0.15	[A]
Iron + chromium + nickel	...	0.18–0.38	...	...	...
Iron + chromium	...	...	0.28–0.37	...	...
	Maximum Impurities, Weight %				
Aluminum	0.0075	0.0075	0.0075	0.0075	0.0075
Boron	0.00005	0.00005	0.00005	0.00005	0.00005
Cadmium	0.00005	0.00005	0.00005	0.00005	0.00005
Calcium	...	0.0030	0.0030	...	...
Carbon	0.027	0.027	0.027	0.027	0.027
Chromium	0.020	...	...	0.020	0.020
Cobalt	0.0020	0.0020	0.0020	0.0020	0.0020
Copper	0.0050	0.0050	0.0050	0.0050	0.0050
Hafnium	0.010	0.010	0.010	0.010	0.010
Hydrogen	0.0025	0.0025	0.0025	0.0025	0.0010
Iron	0.150	...	...	0.150	0.150
Magnesium	0.0020	0.0020	0.0020	0.0020	0.0020
Manganese	0.0050	0.0050	0.0050	0.0050	0.0050
Molybdenum	0.0050	0.0050	0.0050	0.0050	0.0050
Nickel	0.0070	...	0.0070	0.0070	0.0070
Niobium	...	0.0100	0.0100	...	...
Nitrogen	0.0080	0.0080	0.0080	0.0080	0.0080
Phosphorus	...	...	...	0.0020	0.0020
Silicon	0.0120	0.0120	0.0120	0.0120	0.012
Tin	0.0050	...	...	0.010	0.010
Tungsten	0.010	0.010	0.010	0.010	0.010
Titanium	0.0050	0.0050	0.0050	0.0050	0.0050
Uranium (total)	0.00035	0.00035	0.00035	0.00035	0.00035

[A] When so specified in the purchase order, oxygen shall be determined and reported. Maximum, minimum, or both, permissible values should be specified in the purchase order.

TABLE 5 Permissible Variations in Product Analysis

Alloying Elements	Permissible Variation from the Specification Range (Table 4), wt %
Tin	0.050
Iron	0.020
Chromium	0.010
Nickel	0.010
Iron plus chromium	0.020
Iron plus chromium plus nickel	0.020
Niobium	0.050
Oxygen	0.020
Impurity Elements	
All	20 ppm or 20 %, of the specified limit whichever is smaller

7.2 Analysis shall be made using standard methods. In the event of disagreement as to the chemical composition of the metal, methods of chemical analysis for referee purposes shall be determined by a mutually acceptable laboratory.

7.3 The ingot analysis made in accordance with Specification B350/B350M shall be considered the chemical analysis for material produced to this specification except for oxygen, hydrogen, and nitrogen content which shall be determined on the finished product. Alternatively, the material may be sampled at an intermediate or final size during processing with the same frequency and in the same positions relative to the ingot as specified in Specification B350/B350M to determine the composition, except for hydrogen, oxygen, and nitrogen, which shall be determined on the final product.

7.4 *Product Analysis*—Product analysis is an analysis made for the purpose of verifying the composition of the lot. The product analysis tolerances reflect the variation between laboratories in the measurement of chemical composition. The permissible variation in the product analysis from the specification range is as listed in Table 5.

7.4.1 *Number of Tests*—Two samples for each 4000 lb (1800 kg) or fraction thereof of the product shall be analyzed for hydrogen, nitrogen and oxygen. The location of the samples may be random, or as agreed between the manufacturer and purchaser.

8. Mechanical Properties

8.1 *Tensile Properties:*

8.1.1 The tensile properties of the material shall be determined at one or more of the following temperatures as agreed upon between the manufacturer and purchaser: at room temperature, at 572°F (300°C), at another agreed-upon temperature, or at a combination thereof.

8.1.2 For tensile tests carried out at room temperature, the properties shall conform to the limits listed in Table 3. For tensile tests carried out at other temperatures, the properties shall conform to the values listed in Table 3 for that temperature, or, for conditions not listed in Table 3, the properties shall conform to those agreed upon between the manufacturer and purchaser.

8.1.3 The tension test shall be conducted in accordance with Test Methods E8 or E21. Yield strength shall be determined by the 0.2 % offset method. The tensile properties shall be determined using a strain rate of 0.003 to 0.007 in./in. · min (mm/mm · min) through the yield strength. After the yield strength has been exceeded, the cross head speed may be increased to approximately 0.05 in./in. · min (mm/mm · min) to failure. When an elevated temperature tension test is specified, the positioning of inside diameter plugs shall be mutually agreed upon between the manufacturer and the purchaser.

8.1.4 *Number of Tests*—For each lot, two samples for each 4000 lb (1800 kg) or fraction thereof shall be tested for tensile properties. The location of the samples may be random or as agreed between the manufacturer and purchaser.

8.2 *Burst Properties:*

8.2.1 Burst testing, when specified, shall be performed at room temperature on finished tubing. The burst properties shall conform to the values agreed upon between the manufacturer and purchaser.

NOTE 2—In setting values for burst properties, cognizance should be taken of the variability of this test. Standard deviations of 4.4 % were encountered in the ASTM round robin in tubing with diameter approximately 0.4 in. (10 mm) used to confirm the recommended procedure.

8.2.2 The room temperature burst test shall be conducted in accordance with Annex A1.

8.2.3 *Number of Tests*—For each lot, two samples for each 4000 lb (1800 kg) or fraction thereof shall be tested for tensile properties. The location of the samples may be random or as agreed between the manufacturer and purchaser.

8.3 *Contractile Strain Ratio (CSR):*

8.3.1 When so specified by the purchaser, the contractile strain ratio (CSR) shall be determined at room temperature and shall conform to limits that are to be mutually agreed upon between the manufacturer and purchaser.

NOTE 3—Contractile strain ratio testing was the subject of a 1993 round robin conducted by ASTM Subcommittee B10.02 using specimens with diameter approximately 0.4 in. (10 mm). The variability was relatively large and should be considered in setting specific limits. The following two-sigma limits were determined as an estimate of the test precision: ±0.16 for samples with a CSR of 1.68, and ±0.22 for samples with a CSR of 2.53.

8.3.2 Contractile strain ratio testing shall be conducted in accordance with Annex A4.

8.3.3 *Number of Tests*—For each lot, two samples for each 4000 lb (1800 kg) or fraction thereof shall be tested for CSR properties. The location of the samples may be random or as agreed between the manufacturer and purchaser.

9. Grain Size

9.1 The average grain size of recrystallized tubes shall be equal to ASTM micrograin Size No. 7 or finer when determined in accordance with Test Methods E112. The test shall be performed on a longitudinal section.

9.2 When specified, the grain size in the welded and heat affected zones of welded tubes shall be examined in sections that are transverse to the weld. The grain sizes in the weld and heat affected zones shall be smaller than those found in the corresponding regions of a standard that is acceptable to the manufacturer and purchaser.

9.3 *Number of Samples*—For each lot, the grain size shall be determined for two samples for each 4000 lb (1800 kg) or fraction thereof. The location of the samples may be random or as agreed upon between the manufacturer and purchaser.

10. Corrosion Properties

10.1 When specified, a corrosion test in steam at 750°F (400°C) and 1500 psi (10.3 MPa) may be performed on Grades R60802, R60804, R60901, and R60904. If specified, the test may be performed in water at 680°F (360°C). The tests shall be conducted in accordance with Test Methods G2/G2M.

10.2 When specified in the purchase order, the samples may be tested in a mill finished condition. In this case, visual acceptance standards shall be agreed upon between the manufacturer and the purchaser and the mass gain limits of 10.5.1, 10.5.2, or 10.6 shall apply.

10.3 *Number of Samples*—For each lot, the specified corrosion test shall be carried out on two samples for each 4000 lb (1800 kg) or fraction thereof. The location of the samples may be random, or as agreed between the manufacturer and purchaser.

10.4 *Post-test Examination*—After the test, all specimens shall be examined for color, lustre, surface irregularities, and corrosion products, and compared against visual standards previously agreed upon between the purchaser and the manufacturer. The mass gain shall be determined using the method prescribed in Test Methods G2/G2M.

10.5 *Acceptance Criteria for Steam Test:*

10.5.1 *Grades UNS R60802 and UNS R60804*—The specimens shall have a continuous black oxide film and be free of white and brown corrosion product in excess of the standards. The specimens shall exhibit a mass gain of not more than 22 mg/dm^2 in a 72-h test or 38 mg/dm^2 in a 336-h test.

10.5.2 *Grades UNS R60901 and UNS R60904*—The specimens shall have a continuous uniform dark gray oxide film, and shall exhibit a mass gain of not more than 35 mg/dm^2 in a 72-h test, or 60 mg/dm^2 in a 336-h test.

10.5.3 If the mass gain of a specimen from any lot exceeds the 72-h test limits, the manufacturer has two options: (*1*) Continue the corrosion test on the lot that failed the test to a total of 336 h with the same specimens at the same prescribed temperature and pressure, or (*2*) Resample the lot that failed for twice the original number of specimens and conduct a 336-h corrosion test. In either case, if the specimens from the lot being retested pass the 336-h test requirements (mass gain and visual), the lot shall be acceptable.

10.6 *Acceptance Criteria for Water Test*—The acceptance criteria for the water corrosion test shall be agreed upon between the manufacturer and purchaser.

11. Inspection

11.1 The manufacturer shall inspect the entire length of the mill finished tubes covered by this specification, prior to shipment, for dimensions, outer and inner surfaces, straightness, and surface and internal flaws as follows:

11.1.1 *Surface and Internal Flaw Inspection:*

11.1.1.1 *Ultrasonic Inspection Test Methods*—Each tube shall be inspected by the ultrasonic test method in accordance with Annex A3.

11.1.1.2 *Ultrasonic Reference Standard*—The test equipment shall be calibrated with an artificially defected standard tube of the same nominal material, diameter, wall thickness, surface finish, fabrication process, and final thermal treatment as the lot being tested. The standard shall contain not less than four defects oriented as follows: (*1*) outer tube surface, parallel to tube axis; (*2*) outer tube surface, transverse to tube axis; (*3*) inner tube surface, parallel to tube axis; and (*4*) inner tube surface, transverse to tube axis. The defects shall be notches with a depth to be agreed upon between the manufacturer and purchaser. The minimum dimensions of the artificial defect shall be 0.0015 in. (0.038 mm) deep and 0.065 in. (1.65 mm) long.

11.1.1.3 *Rejection*—Any tube showing an ultrasonic indication equal to or greater than the standard in 11.1.1.2 shall be rejected.

11.1.2 *Outer and Inner Surfaces, Visual Inspection:*

11.1.2.1 *Test Method*—Each tube shall be inspected over its entire length. The outside surface shall be inspected under a minimum light intensity of 100 fc (1100 lux). The inner surface shall be inspected from each end against a suitable light background.

11.1.2.2 *Acceptance Criteria*—The tubes shall not contain oxides, cracks, seams, slivers, blisters, pits, laps, foreign particles, or scratches exceeding the mutually agreed-upon inspection standard.

11.1.2.3 The finished tubes shall be visibly free of all grease, oil, residual lubricants, and other extraneous materials, as determined by mutually agreed-upon standards.

11.1.3 *Straightness:*

11.1.3.1 *Test Method*—Each tube shall be inspected for straightness by rolling on a surface plate and observing for the maximum deflection (bow) in the vertical plane between two points of contact, or by another method acceptable to the purchaser.

11.1.3.2 *Acceptance Criteria*—The tubes shall be free of bends or kinks, and the maximum bow of lengths up to 10 ft (3.0 m) shall not exceed 1 part in 1200. For lengths greater than 10 ft, the maximum bow shall not exceed 1 part in 800.

11.1.4 *Dimensional Inspection:*

11.1.4.1 *Test Method*—Each tube shall be inspected over its entire length by using a method agreed upon between the manufacturer and purchaser.

11.1.4.2 *Acceptance Criteria*—The tubes shall meet the dimensional requirements of Table 2.

11.1.5 *Length*—When tubing is ordered cut to length, the usable length shall be not less than that specified; but a variation of 0.125 in. (3.0 mm) will be permitted for lengths up to 6 ft (2.0 m). In lengths over 6 ft (2.0 m), a variation of 0.25 in. (6 mm) will be permissible.

11.1.6 *Purchaser Inspection:*

11.1.6.1 The manufacturer shall inspect tubes covered by this specification prior to shipment and, on request, shall furnish the purchaser with certificates of test. When specified on the purchase order, the purchaser or his representative may witness the testing and inspection of the tubes at the place of manufacture. In such cases, the purchaser shall state in his purchase order which tests he desires to witness. The manufacturer shall give ample notice to the purchaser as to the time and place of the designated tests. If the purchaser's representative is not present at the time agreed upon for the testing and if no new date is agreed upon, the manufacturer shall consider the requirement for purchaser's inspection at place of manufacture to be waived.

11.1.6.2 When the inspector representing the purchaser appears at the appointed time and place, the manufacturer shall afford him all reasonable facilities to see that the material is being furnished in accordance with this specification. This inspection shall be so conducted as not to interfere unnecessarily with production operations.

12. Hydride Orientation

12.1 Hydride orientation, *Fn*, when specified, shall be determined on finished tubing and shall conform to the values agreed upon between the manufacturer and the purchaser.

12.2 *Number of Samples*—For each lot, the hydride orientation shall be determined for two samples for each 4000 lb (1800 kg) or fraction thereof. The location of the samples may be random or as agreed between the manufacturer and purchaser.

12.3 The hydride orientation shall be determined in accordance with Annex A2.

13. Hydrostatic Test

13.1 When so specified in the purchase order, each tube shall withstand, without showing bulges, leaks, or other defects, an internal hydrostatic pressure that will produce in the tube wall a stress of 50 % of the minimum specified yield strength at room temperature. The pressure shall be determined by the equation:

$$P = 2St/D \tag{1}$$

where:

P = minimum hydrostatic test pressure (psi or MPa),
S = allowable fiber stress of one half of the minimum yield strength (psi or MPa),
t = wall thickness (in. or mm), and
D = outside diameter (in. or mm).

13.2 The maximum hydrostatic test pressure shall not exceed 2500 psi (17.0 MPa) for size 3 in. (75 mm) and under, or 4000 psi (28 MPa) for sizes over 3 in. (75 mm). Hydrostatic pressure shall be maintained for not less than 15 s.

14. Number of Tests

14.1 *Sampling*—Samples shall be taken for each of the tests specified in 14.2. The minimum sampling frequency shall be in accordance with the number of samples given in the appropriate paragraphs.

14.2 Each sample chosen in accordance with 14.1 shall be tested as follows: (*1*) product chemistry (Section 7), (*2*) tension test, at a temperature and using specimens as mutually agreed upon (8.1), (*3*) burst test when specified (8.2), (*4*), contractile strain ratio when specified (8.3), (*5*) grain size (Section 9), (*6*) corrosion test when specified (Section 10), and (*7*) hydride orientation when specified and as mutually agreed upon (Section 12).

15. Retest

15.1 If any sample or specimen exhibits obvious surface contamination or improper preparation disqualifying it as a truly representative sample, it shall be discarded and replaced by a new sample or specimen.

15.2 If the results of the tube inspection of a lot are not in conformance with the requirements of this specification, the lot may be reworked at the option of the manufacturer, providing the rework steps are within the previously approved specifications and procedures used for the original fabrication. Deviations must be approved by the purchaser.

15.3 If the result of any test in Section 14.2 does not meet the specification requirements, retests shall be performed on twice as many samples as originally tested for the characteristic, or using retest procedures mutually agreed upon between the manufacturer and the purchaser.

15.3.1 All test results including the original test results shall be reported to the purchaser. Retest results shall be indicated with the suffix "*R*."

15.3.2 Only one set of retests is permitted and all retest results shall conform to the specification requirements for the retested characteristic. Following a failed test, 100 % testing is not considered to be a retest.

16. Significance of Numerical Limits

16.1 For the purpose of determining compliance with the specified limits of property requirements, an observed value or a calculated value shall be rounded in accordance with the rounding method of Practice E29.

Test	Rounded Units for Observed or Calculated Value
Chemical composition, tolerance (when expressed in decimals)	nearest unit in the last right hand place of figures of the specified limit
Tensile strength and yield strength	nearest 1000 psi (10 MPa)
Elongation	nearest 1 %

17. Quantity Variance

17.1 The manufacturer may overship an order by up to 10 % when the order calls for 1000 lb (450 kg) or less. For larger quantities, the permissible overshipment shall be agreed upon between the manufacturer and the purchaser.

18. Rejection

18.1 Rejection for failure of the material to meet this specification shall be reported to the manufacturer within 60 calendar days from the receipt of the material by the purchaser unless otherwise agreed upon. Rejected material may be returned to the manufacturer at the manufacturer's expense, unless the purchaser receives, within three weeks of the notice of rejection, other instructions for disposition.

19. Certification

19.1 The manufacturer shall furnish the purchaser with a certificate that the material was manufactured, sampled, tested, and inspected in accordance with this specification and order, and has been found to meet the requirements. The certificate shall be supplied at the time of shipment unless otherwise agreed upon, and shall include a report of the test results.

20. Packaging and Package Marking

20.1 Each bundle, box, or carton shall be legibly and conspicuously marked or tagged with the following information:

20.1.1 Purchase order or contract number,
20.1.2 Name of manufacturer,
20.1.3 Grade,
20.1.4 Size,
20.1.5 Lot or ingot number,
20.1.6 Gross, net and tare weights, and
20.1.7 ASTM Standard Number.

20.2 All material shall be packed in such a manner as to ensure safe delivery to its destination when properly transported by any common carrier. Any special requirements or instructions must be specified by the customer.

21. Referee

21.1 In the event of disagreement between the manufacturer and the purchaser on the conformance of the material to the requirements of this specification or any special test specified by the purchaser, a mutually acceptable referee shall perform the tests in question. The results of the referee's testing shall be used in determining conformance of the material to this specification.

22. Keywords

22.1 nuclear application; seamless tubing; welded tubing; zirconium; zirconium alloy

ANNEXES

(Mandatory Information)

A1. RECOMMENDED CLOSED-END BURST TESTING PROCEDURE FOR ZIRCONIUM ALLOY TUBING

A1.1 Scope

A1.1.1 This annex covers the determination of burst test mechanical properties of zirconium-base alloy tubing.

A1.1.2 Burst test results are affected by very small changes in procedure. The following items are identified and defined to minimize variation in testing procedures and to obtain reproducibility of test results.

A1.2 Apparatus

A1.2.1 The test system shall be designed with adequate capacity to test at the stress levels and temperatures needed. If elevated temperature tests are to be performed on the same equipment used for room temperature tests, it is essential that special fluids be used which are stable at the elevated test temperatures. Special consideration should be given to the following system items:

A1.2.1.1 *Pump*—The pump should be capable of increasing system pressure at a steady rate. The pressurization rate during elastic loading shall be 2000 ± 200 psi/min (14.0 ± 1.4 MPa/min), and the same initial fluid volume pumping rate shall be maintained for the duration of the test. The pump should not produce a pressure surge with each stroke. The system should be "stiff," that is, its stored energy should be as low as practical.

A1.2.1.2 *Valves*—Suitable valving shall be included for the following functions: control, regulation, and safety.

A1.2.1.3 *Gages*—Suitable gages of adequate capacity shall be used to monitor system pressure and to record the maximum fluid pressure attained.

A1.3 Preparation of Specimen

A1.3.1 The sample shall be selected and tested in the mill finished condition.

A1.3.2 Minimum unsupported length shall be 10 times the average outside diameter.

A1.3.3 End fittings must be such as to produce a 2:1 circumferential to axial stress ratio.

A1.3.4 Use of a mandrel inside the test specimen shall be on agreement between the manufacturer and the purchaser and shall be noted on test reports.

A1.3.5 Mandrels shall meet the following requirements:

A1.3.5.1 Mandrel outside diameter = mean inside diameter of tubing minus 0.010 ± 0.002 in. (0.25 ± 0.05 mm), except an axial relief groove may be cut in the mandrel to facilitate movement of the fluid within the specimen.

A1.3.5.2 The ends of the mandrel shall be tapered or otherwise shaped so as not to restrict axial deformation of tubing during test.

A1.3.6 All free gases shall be vented from the specimen prior to test.

A1.4 Procedure

A1.4.1 Measurements shall be made of the outside diameter and wall thickness of the specimen such that the mean average diameter and minimum wall thickness can be determined to an accuracy of 0.0005 in. (0.013 mm). Recommended measurements are as follows:

A1.4.1.1 Pretest the measurements of the outside diameter at three equally spaced locations around the circumference at each end of the specimen and at the center. Pretest the measurement of the wall thickness at six equally spaced locations at each end of the specimen.

A1.4.1.2 Individual pretest measurements shall be to an accuracy of ±0.0002 in. (0.005 mm).

A1.4.1.3 Post-test circumferential elongation shall be determined at the point of maximum bulge, excluding the opening of the rupture, and to an accuracy of ±0.005 in. (0.13 mm). The measurement technique is to be mutually agreed upon between the manufacturer and the purchaser.

A1.5 Report

A1.5.1 The following data should be reported:

A1.5.1.1 Measurements taken from test specimens.

A1.5.1.2 Maximum fluid pressure.

A1.5.1.3 Ultimate hoop strength, calculated as follows:

$$s = \frac{PD}{2t} \qquad \text{(A1.1)}$$

where:

s = ultimate hoop strength, psi or MPa,
p = maximum fluid pressure, psi or MPa,
D = average outside diameter minus average wall thickness, in. or mm, and
t = minimum pretest wall thickness, in. or mm.

NOTE A1.1—For thick-wall tubes, consideration should be given to using the more general thick-wall formula.

A1.5.1.4 Total circumferential elongation.

A2. RECOMMENDED PROCEDURE FOR DETERMINATION OF HYDRIDE ORIENTATION IN ZIRCONIUM-ALLOY TUBING

A2.1 Test Criteria

A2.1.1 The following test criteria shall be mutually agreed upon between the manufacturer and the purchaser:

A2.1.1.1 Number of specimens per lot,

A2.1.1.2 Number of determinations per specimen,

A2.1.1.3 Magnification of photomicrographs,

A2.1.1.4 Number and description of layers across the wall thickness,

A2.1.1.5 Definition of typical hydride microstructure,

A2.1.1.6 Value of theta (θ), the angle from radial direction, and

A2.1.1.7 Hydride fraction value, *Fn*.

A2.2 Procedure

A2.2.1 Inoculate specimens from each lot of finished tubing with about 100 ppm hydrogen to produce uniformly distributed hydride platelets as follows:

A2.2.1.1 Introduce hydrogen into the specimens by methods such as autoclaving in steam or lithium hydroxide, electrolytic deposition, or absorption of hydrogen gas. The treatment temperature shall not exceed 775°F (414°C). The method of hydriding shall not result in excessive hydride concentration on the surface. Such concentration would obscure the determination of hydride orientation. No surface removal is allowed after hydriding.

A2.2.1.2 When agreed upon, heat treat the specimen at 750 ± 25°F (399 ± 14°C) for 5 ± 1 h in an inert atmosphere either during or after hydriding. If vacuum heat treatment is used, the pressure shall not be less than 10^{-5} torr (1.33 mPa) to prevent dehydriding. The cooling rate from temperature shall be less than 25°F (14°C)/min.

A2.3 Measurement

A2.3.1 Cut transverse metallographic sections from each hydrided specimen and prepare for microscopical examination. Do not use either heat or pressure in preparation. The final etch or chemical polish shall be capable of delineating the hydride platelets. An anodizing procedure is recommended following the etch or polish.

A2.3.2 Make determinations, as agreed upon between the manufacturer and the purchaser, on the entire wall thickness. A suitable magnification in the range 100× to 500× shall be used for the measurement, and the measured area shall be typical of the hydride microstructure.

A2.3.3 From the micrograph of each layer, count all hydride platelets equal to or longer than 0.000625 in. (0.015 mm) at 1× magnification (1⁄16 in. or 1.5 mm at 100× magnification). Also count each platelet segment that extends in a secondary direction longer than 0.000625 in. (0.015 mm) at 1× magnification as a separate platelet.

A2.3.4 For each layer count all radial platelets. A radial platelet is defined as one oriented within theta (θ) degrees of the radial direction of the tube and meeting the requirements of A2.3.3.

A2.3.5 Calculate the value of the hydride fraction, *Fn*, as the ratio of radial platelets to total platelets in a given layer. It shall conform to the value mutually agreed upon between the manufacturer and the purchaser.

A3. RECOMMENDED PROCEDURE FOR ULTRASONIC TESTING OF ZIRCONIUM AND ZIRCONIUM ALLOY TUBING FOR NUCLEAR SERVICE

A3.1 Scope

A3.1.1 This annex covers procedures for detecting discontinuities in zirconium alloy nuclear tubing. Guides for the selection and positioning of transducers for shear-wave and Lamb-wave procedures are included in Appendix X1 and Appendix X2.

A3.1.2 The immersed ultrasonic pulse-echo technique is employed.

A3.1.3 Artificial longitudinal and transverse reference notches are employed as the means of calibrating the ultrasonic system.

A3.2 Terminology

A3.2.1 *Definitions:*

A3.2.1.1 *relevant indication of a discontinuity*—a repeatable rejectable indication.

A3.2.1.2 Definitions of additional terms and formulae are given in A3.8.2.3.

A3.3 Surface Condition

A3.3.1 All surfaces shall be clean and free of scale, dirt, grease, paint, or other foreign material that will interfere with the interpretation of the test results. The methods used for cleaning and preparing the surfaces for ultrasonic inspection shall not be detrimental to the base metal or the surface finish. The surface finish may be specified by contractual agreement between the purchaser and manufacturer.

NOTE A3.1—Excessive surface roughness or scratches provide signals (noise) that interfere with the test.

A3.3.2 The tubes shall be within the requirements of Specification B353 for dimensions at time of test. Straightening operations shall be performed prior to ultrasonic testing.

A3.4 Apparatus

A3.4.1 The instruments and accessory equipment shall be of the pulse-echo type and shall be capable of distinguishing the reference notches to the extent required in the calibration procedure. Fig. A3.1(a) illustrates the characteristic oblique entry of sound into the tube wall and the circumferential direction of ultrasonic energy propagation used to detect longitudinal notches. Fig. A3.1(b) illustrates the characteristic oblique angle and the longitudinal direction of ultrasonic energy propagation used to detect circumferential notches.

A3.4.1.1 The practice for a refracted shear wave in a tube wall is with the effective beam width of the transducer within the tube wall in the range of ½ to 1½ of the tube wall thickness.

A3.4.2 The test system shall consist of two- or four-channel pulse-echo flaw detection equipment, one or two two-channel strip chart recorders or equivalent, tubing transport system (handling equipment), immersion tank, two to four search units, and assorted coaxial cables and connectors. The test system may have a water heater and water filter as optional equipment. Commercially available electronic equipment, when used with applicable search units, shall be capable of producing ultrasonic test frequencies of at least 5 MHz.

A3.4.2.1 The method of plugging ends of product is to be mutually agreed upon between the manufacturer and the purchaser.

A3.4.3 The ultrasonic test shall be monitored automatically by one or more of the following: (*1*) a chart recorder, (*2*) magnetic tape, (*3*) electronically shutting down and stopping the handling equipment, or (*4*) a paint or ink marking system.

A3.4.3.1 The test-monitoring system shall have the capability to pick up the standard notch and defect indications.

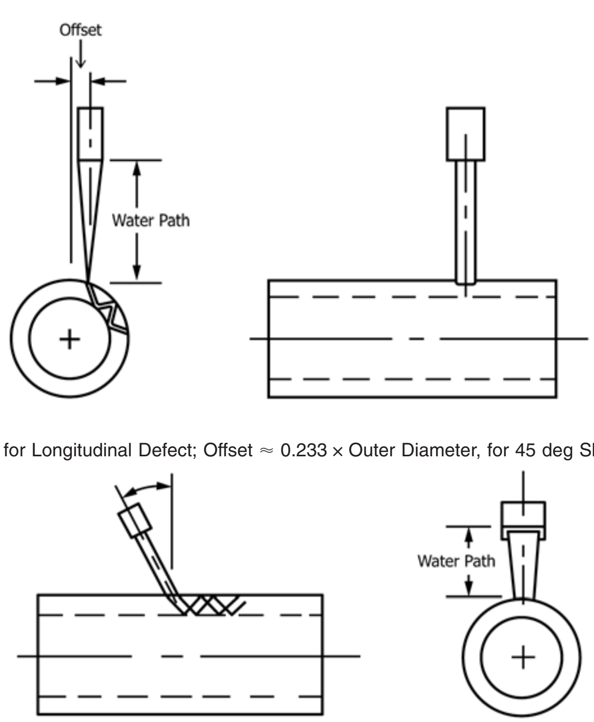
A3.4.3.2 The automatic gating system must be equipped with an electronic circuit that will make it impossible for more than one pulse to remain unrecorded. The system used shall contain one of the following: (*1*) a pulse stretcher, (*2*) a one-shot multivibrator, (*3*) a pulse counter-recorder combination, or (*4*) equivalent devices.

A3.4.4 An advisory guide to transducer selection is given in Appendix X1. Transducers other than those described in Appendix X1 that produce the response required in A3.7 may be used, provided their use is mutually agreed upon between the manufacturer and the purchaser.

A3.4.5 *Types of Transducers:*

A3.4.5.1 *Line Focus Transducer (or Cylindrically Focus Transducer)*—This type of transducer transmits a wedge of energy that is distributed along a line. To calculate the maximum revolutions per minute (rpm), two dimensions will be required: (*1*) the effective beam length (EBL) and (*2*) the effective beam width (EBW), at the focal point (sometimes referred to as the Y_0^+ point). See Fig. A3.2.

A3.4.5.2 *Spot Focus Transducer*—This type of transducer transmits a cone of energy. To calculate the maximum revolutions per minute, only one dimension (EBW) will be required: the diameter of the beam (or the beam width or the focal diameter) at the focal point (Y_0^+). See Fig. A3.3.



(a) Transducer set up for Longitudinal Defect; Offset ≈ 0.233 × Outer Diameter, for 45 deg Shear Wave in Zr Alloys.

(b) Transducer set up for Transverse Defect; Incident Angle φ ≈ 28 deg, for 45 deg Shear Wave in Zr Alloys.

FIG. A3.1 Shear Wave Test for Longitudinal and Transverse Defects

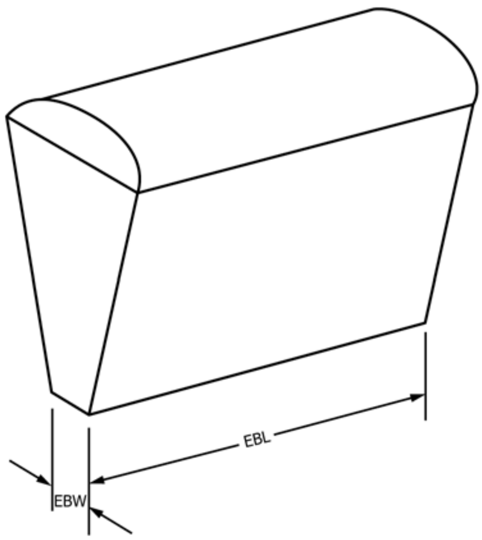


FIG. A3.2 Description of EBL and EBW for a Line Focus Transducer

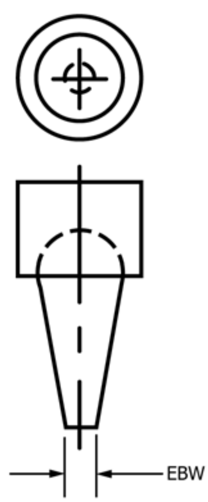


FIG. A3.3 Description of EBW for a Spot Focus Transducer

A3.5 Couplant

A3.5.1 Water shall be used as the couplant conducting ultrasonic energy between the transducer and the tube. Rust and algae inhibitors, softeners, and wetting agents approved by the purchaser may be added to the water. The couplant with all additives shall wet the tube's outside surface to provide adequate coupling efficiency.

A3.5.2 The inside surface of the tube must be kept dry and free of couplant to avoid misleading signals.

A3.5.3 The water must be kept free of debris and visible air bubbles that interfere with the ultrasonic inspection.

A3.6 Calibration Standards

A3.6.1 This section describes the size, shape, preparation, and positioning of artificial defects to be employed as calibration standards for use in testing with this procedure.

A3.6.2 A calibration (reference) standard of a convenient length shall be prepared from a length of tube of the same nominal material, diameter, wall thickness, surface finish, fabrication process, and final thermal treatment as the tubes to be inspected. The calibration tube shall be inspected prior to manufacture of notches to ensure freedom from discontinuities or other conditions producing indications that can interfere with or be confused with detection of the reference notches.

A3.6.3 Unless otherwise specified by the purchaser, four notches shall be required: one each on the inner and outer surfaces aligned in the longitudinal direction, and one each on the inner and outer surfaces aligned in the transverse (circumferential) direction.

A3.6.4 Reference notches shall be sufficiently distant from one another and from the end of the tube to avoid interference or interpretation difficulty during the test.

A3.6.5 The notch dimensions, which are length, depth, width (and for V-notches, the included angle) and the relationship to sound beam dimensions shall be mutually agreed upon between the purchaser and the manufacturer. Fig. A3.4 illustrates the common notch configurations and the dimension to be measured (Note A3.2). Reflections from V-, buttress-, and U-shaped notches of equal dimensions may vary widely depending on the angle and vibrational mode of the interrogating beam.

NOTE A3.2—In Fig. A3.4(a) and Fig. A3.4(d), the sharp corners are for ease of illustration. It is recognized that in normal machining practice, a radius will be generated. Notches produced by electro-machining typically will have a radius at the bottom of the notch that increases with the depth of the notch. For example, a 0.001-in. (0.025-mm) deep notch will have a 0.0002-in. (0.005-mm) radius, while a 0.004 in. (0.10-mm) deep notch might have a 0.0005-in. (0.013-mm) radius.

NOTE A3.3—The length of the calibration notch should be chosen with some care, especially when line focus transducers are employed. If a notch is short with respect to the transducer beam length along its (the notch's) long axis, the test will be unnecessarily sensitive to long shallow defects. Conversely, if the calibration standard is long compared with the beam length, then the test will be insensitive to defects that are short compared with the beam length. The best compromise is a notch/beam length ratio between 0.3 and 1.

A3.6.6 All upset metal and burrs associated with the reference notches shall be removed.

A3.6.7 The notch depth shall be an average measured from the tube surface to the maximum and minimum penetration of the notch. Measurements may be made by optical, replicating, or other mutually agreed upon techniques. Destructive means may be used on duplicate notches that produce identical (within 5 %) ultrasonic response. Notch depth shall be within ±0.0005 in. (0.013 mm) of the specified value for notches

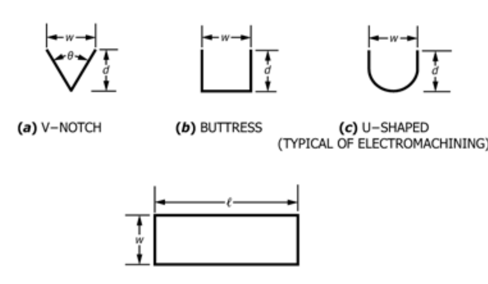


FIG. A3.4 Common Notch Shapes

0.004 in. (0.10 mm) or less in depth, and within ±15 % of the specified value or ±0.004 in. (±0.1 mm) (whichever is smaller) for deeper notches.

A3.6.8 The width of the notches should be as small as possible, but shall not exceed twice the depth or 0.005 in. (0.13 mm), whichever is larger.

A3.6.9 Other types and orientations of reference discontinuities may be specified upon contractual agreement between the purchaser and the manufacturer.

A3.6.10 All calibration notch standards shall be given a permanent identification marking and shall be traceable as to material composition, heat treatment, location and positioning of notches, and methods and results of each notch measurement.

A3.7 Calibration of the Apparatus

A3.7.1 *Static Calibration*—Using the calibration standard specified in A3.6 adjust the equipment statically to produce clearly identifiable indications from both the inner and outer surface notches. An advisory guide to transducer positioning is given in Appendix X2. The relative response from the inner and outer surface notches shall be as nearly equal as possible. If the responses are not equal, the smaller response shall be the reject level. It is recommended that the smaller response be not less than 80 % of the larger response. The actual rejection level as a percent of standard notch amplitude response can be mutually agreed upon between the manufacturer and the purchaser.

A3.7.1.1 The amplitude of the indication from the inside diameter and outside diameter notches must be 50 to 90 % of the full screen amplitude.

A3.7.1.2 On large diameter or heavy wall tubing, when the responses from the inner and outer surface notches cannot be made equal because of tube wall thickness and inside diameter curvature, the rejection level for inside diameter and outside diameter defects shall be equal to the notch responses from the inside diameter and outside diameter notches, respectively.

A3.7.2 Dynamically calibrate the system with the reference standard moving in the same manner, in the same direction, and at the same speed as will be used during the inspection of tubing.

A3.7.3 Make a minimum of three dynamic calibration runs before beginning production testing and after any adjustment or setup change, and detect each reference notch above the reject level at least one time on each run.

A3.8 Inspection Procedure

A3.8.1 The tubing to be inspected or the search unit assembly shall have a rotating motion and translation relative to each other such that a helical scan of the tubing surface will be described. Maintain the speed of rotation and translation constant within ±10 %.

A3.8.2 Determine the pitch of the helix and the number of tests per rotation by one of the following considerations:

A3.8.2.1 Criteria agreed upon between manufacturer and the purchaser.

A3.8.2.2 Purchase transducers certified as to EBW and EBL and use the certified values in the formulae.

A3.8.2.3 Establish the effective beam width (EBW) (and the effective beam length (EBL), if it is a line focus transducer) by passing the ultrasonic beam over a standard or reference notch with the notch 90° to the beam while maintaining a signal strength of 70 % of the maximum signal and a minimum overlap of 25 %. This measurement should be performed from a longitudinal notch if the transducer is used to detect longitudinal (*L*) defects, and it should be performed on a transverse notch if the transducer is used for transverse (*T*) defects, as shown in Fig. A3.5.

A3.8.2.4 The surface speed, revolution per minute, feed rate, and test time are given by the following equations:

$$\text{Surface Speed (mm/s)} = (1 - y) \times \text{P.R.R.} \times (\text{EBW}) \quad (A3.1)$$

where:

EBW	=	effective beam width, mm,
P.R.R.	=	pulse repetition rate of ultrasonic equipment, pulses/s, and
y	=	fraction of overlap required, for $y = o$ the surface speed is maximum.

$$\text{Revolution Per Minute (r/min)} = \frac{19 \times (\text{EBW})}{\text{OD}} \times P.R.R.\,(1 - y) \quad (A3.2)$$

$$\text{Feed Rate (mm/min)} = (\text{EBL})(1 - y) \times \text{r/min, for line focus transducer} \quad (A3.3)$$

$$= (\text{EBW})(1 - y) \times \text{r/min, for spot focus transducer}$$

$$\text{Total Inspection Time} = \frac{\text{tube length}}{\text{feed}} \quad (A3.4)$$

A3.8.2.5 In the Lamb-wave technique test, the revolution speed shall allow for a minimum of 120 pulses per revolution.

A3.8.3 Unless otherwise specified, inspect the tubing in both circumferential and both longitudinal directions under the identical conditions to those used in calibration under A3.7. The method used by the manufacturer may be either two transducers with reversing the tube end-for-end and testing a second time or four transducers for a single bidirectional test.

NOTE A3.4—Identical conditions shall include all instrument settings, mechanical motions, transducer attitude, and positions that are relative to the tube, liquid couplant, and any other factor that may affect the validity of the technique.

A3.8.4 During a continuous inspection run, verify the equipment calibration by passing the calibration standard through the inspection system once, at a frequency mutually agreed upon between the manufacturer and the purchaser. Any time the equipment does not present a clearly defined, rejectable signal from both the inner and outer surface notches of the calibration standard, recalibrate the equipment in accordance with A3.7.

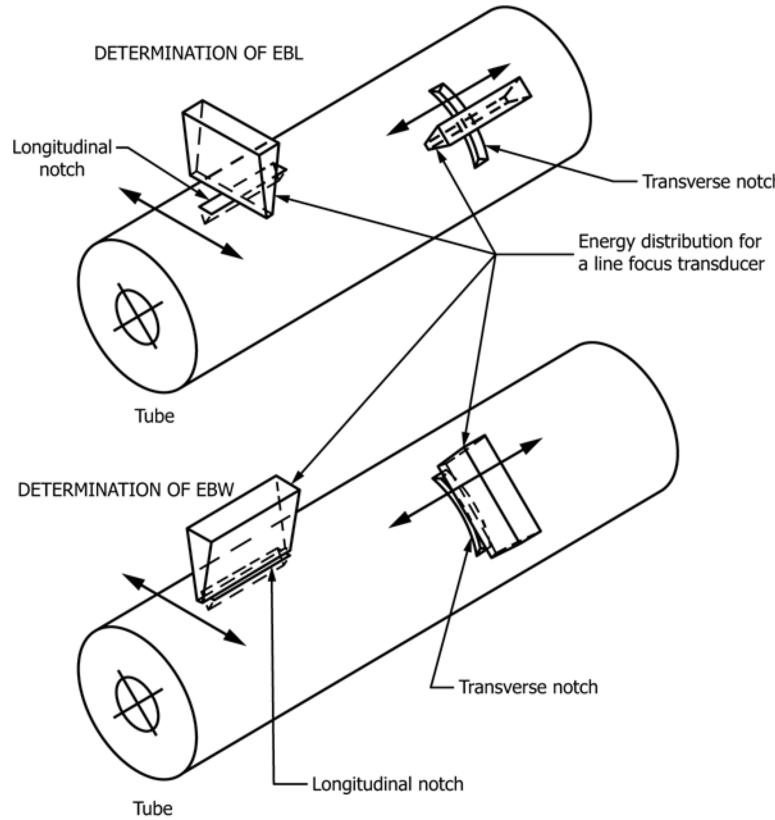


FIG. A3.5 Determination of the Ultrasonic Beam. The Arrows Indicate the Movement of the Transducer Relative to the Notch

A3.8.5 In the event the equipment does not present signals as outlined in A3.8.4, retest all tubing inspected subsequent to the last preceding acceptable calibration after recalibration has been accomplished.

A3.8.6 Equipment adjustments are permissible only at the time of calibration as noted in A3.7 and A3.8.4.

A3.9 Interpretation of Results

A3.9.1 Any relevant indication of a discontinuity (A3.2.1.1) that is equal to or greater than the reject level described in A3.7.1 shall be cause for rejection of the tube being tested.

A3.9.2 Any tube not showing a relevant indication shall be considered as having passed this ultrasonic inspection except as noted in A3.8.5.

A3.10 Report

A3.10.1 The seller shall certify the results of tube inspections to the above procedure and shall maintain records of the inspection that will include the following:

A3.10.1.1 Identification of the material by process lot,

A3.10.1.2 Identification of the inspection equipment and accessories,

A3.10.1.3 Description of the inspection technique including transducer details, inspection speed, sound frequency, helical pitch, and calibration details,

A3.10.1.4 Description of the calibration standard and its contained notches together with notch measurements and method of measurement, and

A3.10.1.5 Results of the inspection.

A4. RECOMMENDED PROCEDURE FOR CONTRACTILE STRAIN RATIO TESTING OF ZIRCONIUM ALLOY TUBING

A4.1 Scope

A4.1.1 This annex covers the determination of the contractile strain ratio at room temperature of zirconium alloy tubing.

A4.1.2 Contractile strain ratio test results are affected by small changes in procedure. The following items are identified and defined to minimize variation in testing procedures and to obtain reproducibility of test results.

A4.2 Apparatus

A4.2.1 Apparatus for the straining of the contractile strain ratio specimen shall be in accordance with Test Methods E8.

A4.3 Preparation of Specimen

A4.3.1 Select and test the sample in the mill finished condition.

A4.3.2 Lightly scribe, prick punch, or otherwise mark the intersections of a grid to a maximum depth of 0.0005 in. (0.013 mm) over a 2 in. (50 mm) gage length in the center of the tube specimen. The grid is described by longitudinal lines located at 0, 90, 180, and 270° positions around the tube, and by circumferential lines located at 1 in. (25 mm) intervals along the 2 in. (50 mm) gage length. Fig. A4.1 illustrates this type of grid. The longitudinal grid lines shall be located with a tolerance of ±2°.

A4.3.2.1 Grid marks must be reproducibly locatable both before and after specimen straining. A stylus or needle may be used for this purpose.

A4.3.2.2 Circumferential scribe marks must be at right angles to the tube axis with no evidence of spiraling.

A4.3.2.3 Axial lines must be parallel to the tube axis.

A4.3.2.4 To enhance the readability of the scribe marks and to minimize the scribe mark depth, the area covered by the scribe marks may be first coated with ink or layout dye prior to scribing the gage lines.

A4.3.2.5 Since the measuring locations before and after straining must be at the same locations, it is recommended that the grid be labeled in some fashion similar to Fig. A4.1.

A4.4 Procedure

A4.4.1 Make pretest measurements of the outside diameter at 1 in. (25 mm) intervals along one of the axial gage lengths at locations next to the circumferential scribe lines. Then rotate the specimen 90° and repeat the pretest measurements of the outside diameter. Record a total of six pretest outside diameter measurements, along with the precise location at which each diameter was measured.

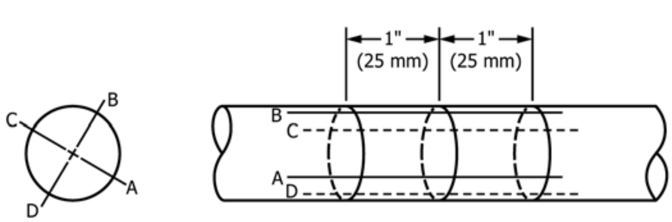


FIG. A4.1 Circumferential and Axial Scribe Lines for the Determination of Contractile Strain Ratio

A4.4.1.1 Make pretest measurements of the length of each axial scribe line between the two outermost circumferential scribe lines for a total of four values.

A4.4.1.2 Pretest measurements of the outside diameter shall be to an accuracy of ±0.0002 in. (0.005 mm). Individual pretest measurements of the axial scribe line lengths shall be to an accuracy of ±0.0005 in. (0.013 mm).

A4.4.2 Strain the specimen in a room temperature axial test in accordance with Test Methods E8, except as follows:

A4.4.2.1 Tight-fitting end plugs shall be installed into the specimen ends to minimize distortion or ovalization during testing,

A4.4.2.2 The strain rate shall be 0.003 to 0.007 in./in. - min (mm/mm - min),

A4.4.2.3 The specimen shall be strained to a total plastic axial strain of 3 to 6 %.

NOTE A4.1—Contractile strain ratio testing was the subject of a 1993 round robin conducted by ASTM Committee B10.02. It was determined that variability in contractile strain ratio values was minimized when test conditions were performed at the low end of the allowable range for strain rate, and at the high end of the allowable range for strain level. It was also concluded that although hold time after straining was not a significant factor, the majority of the participants observed some increase in the contractile strain ratio value after a specified hold time.

A4.4.3 Post-test measurements of the outside diameter and axial scribe line lengths shall be made at the same locations that were used for the pretest measurements as described in A4.4.1 and A4.4.1.1, and to the same accuracy specified for the pretest measurements as specified in A4.4.1.2.

A4.5 Calculation

A4.5.1 Calculate the average prestrain outside diameter using the six diameter measurements from A4.4.1.

A4.5.2 Calculate the average prestrain axial length using the four length measurements from A4.4.1.1.

A4.5.3 Calculate the average post strain outside diameter using the six diameter measurements from A4.4.3.

A4.5.4 Calculate the average post strain axial length using the four length measurements from A4.4.3.

A4.5.5 Calculate the true circumferential strain, *Ec*, as follows:

$$Ec = 1\text{n}\left[\frac{\text{average post strain diameter}}{\text{average prestrain diameter}}\right] \tag{A4.1}$$

A4.5.6 Calculate the true axial strain, *Ea*, as follows:

$$Ea = 1\text{n}\left[\frac{\text{average post strain gage length}}{\text{average prestrain gage length}}\right] \tag{A4.2}$$

A4.5.7 Calculate the true radial strain, *Er*, as follows:

$$Er = -Ea - Ec \tag{A4.3}$$

A4.5.8 Calculate the contractile strain ratio (CSR) as follows:

$$CSR = \left[\frac{Ec}{Er}\right] \tag{A4.4}$$

APPENDIXES

(Nonmandatory Information)

X1. AN ADVISORY GUIDE TO TRANSDUCER SELECTION

X1.1 This supplement is only an advisory guide and not a mandatory requirement for selection of transducers.

X1.2 Focused immersion transducers can be classified in spot focus and line focus.

X1.3 The four most important characteristics of a focused transducer are as follows:

X1.3.1 The apex angle of the cone,

X1.3.2 The dimension of the focal spot,

X1.3.3 The frequency, and

X1.3.4 The damping coefficient, δ.

X1.4 Transducers for Shear-Wave Inspection

X1.4.1 The apex angle of the cone can be expressed as the ratio of transducer focal length to the diameter of the transducer. The transducer is assigned an "*F*-number" based on the aforementioned ratio; for example, a focal length of 13 mm from a 6.5-mm element has the designation $F = 2$, a 25-mm focal length from a 12.5-mm element is also $F = 2$, but a 25-mm focal length from a 6.25-mm element is designated $F = 4$ (see Fig. X1.1). Most precision testing is carried out with transducer assemblies between $F = 2$ and $F = 5$. Inside the material the cone shortens at approximately the velocity ratio between the longitudinal wave in water and the shearwave in the metal. Thick walls cannot be tested with $F = 2$ transducers but require a longer, narrow cone, for example, $F = 4$.

X1.4.2 The focal spot size is chosen on the basis of the type of defect to be detected. To resolve very small defects (for example, pinholes in tubing), and to make the system more sensitive to defect depth as a percentage of wall thickness, the spot size should be as small as possible. The diameter of the focal spot of a point focus transducer, *d*, is the effective diameter of the transducer. The diameter of the focal spot in water of a point focus transducer may be calculated from

$$D = \frac{1.03\lambda f}{d} \text{ (or) } 1.03\lambda\,(F - \text{number}) \tag{X1.1}$$

where:

D	=	the focal spot diameter to the − 3 dB point,
λ	=	the wavelength (in water),
f	=	the focal length (in water),
d	=	the effective diameter of the transducer, and
F-number	=	f/d

The diameter for the focal spot shall not exceed 0.5 mm (0.020 in.). For a rectangular line focus transducer, the width of the focal line is given by

$$W = \frac{0.88\lambda f}{w} \text{ (or) } 0.88\lambda\,(F - \text{number}) \tag{X1.2}$$

where:

W	=	the width of the focal line to the − 3 dB point,
λ	=	the wavelength,
f	=	the focal length,
w	=	the effective width of the transducer in the plane in which focusing occurs, and
F-number	=	f/w

X1.4.3 High frequency transducers can be manufactured with good quality focal length and diameter, even with small elements and lenses. Low frequency transducers cannot be focused as sharp as the high frequency ones.

X1.4.4 For damping, it is recommended that crystals be used that oscillate less than two cycles before the amplitude is reduced to half.

X1.4.5 Dimensions of the stuffing box, requirements of resolution, pulse strength of electronic equipment, tube wall thickness, etc., eventually determine the required transducer characteristics. An example of a compromise of transducer characteristics for inspection of nuclear fuel clad tubing might be as follows:

Apex cone	$F = 4$
Frequency	10 MHz
Damping coefficient	2.0
Focal dimension	0.4-mm diameter (for Spot Focus) or width (for Line Focus)

X1.4.6 Transducers with a line focus can also be classed with an *F*-number, but the length of the line is important in that it covers a larger area that results in a substantially reduced reflection of a smaller defect or a reference notch.

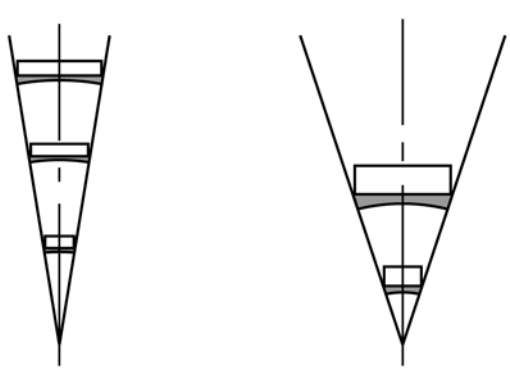


FIG. X1.1 Examples of Transducer Designations

X1.4.7 Line focus transducers may be used for the detection of longitudinal or transverse defects, or both. The line of the focus should be parallel with the length of the reference notch. Other parameters such as off-set, frequency, sensitivity, damping, etc., are similar as for W-spot focus transducers, but it should be possible to increase the helical pitch testing with a line focus transducer.

X1.5 Transducers for Lamb-Wave Inspection

X1.5.1 Line focus or spot focus transducers may be used.

X1.5.2 A focal length of 20 mm (0.8 in.) is recommended, although a focal length of 15 to 40 mm (0.6 to 1.6 in.) may be used. The actual focal length should be known within ±10 %.

X1.5.3 The sound beam of the transducers used must be symmetrical. Maximum permissible variation within the theoretical width of the sound beam shall be ±3 dB. The sound beam is allowed to deflect by a maximum of 2° from the axis of the transducer in any of the main directions of testing. For line focused transducers the length of the sound beam at the focal plane shall not be greater than 7 mm (0.280 in.) and the width a maximum of 1.9 mm (0.075 in.). For spot focused transducers the maximum size of the focal point shall be 1.9 mm (0.075 in.).

X1.5.4 A damping factor of 3 is recommended. The damping factor must not be greater than 5.

X1.5.5 Transducer frequency chosen according to Fig. X1.2.

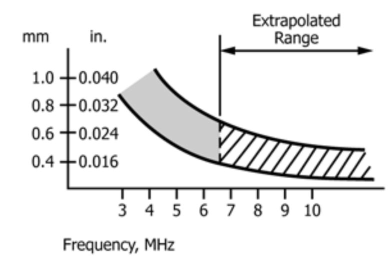


FIG. X1.2 Recommended Frequency Interval for Different Tube Wall Thicknesses

X2. AN ADVISORY GUIDE TO TRANSDUCER POSITIONING

X2.1 This supplement is only an advisory guide and not a mandatory requirement to transducer positioning.

X2.2 Transducer Positioning for Shear Wave Testing

X2.2.1 *For Longitudinal Defects*—Positioning an inspection transducer for the detection of longitudinal defects using a refracted shear wave test with a spot or line focused beam is accomplished as follows (see Fig. A3.1(a)):

X2.2.1.1 If a line focused transducer is used, adjust the transducer so that the major dimension of the beam is parallel to the axis of the tube.

X2.2.1.2 Normalize the transducer to the top surface of the reference standard tube from a position directly above the tube. Normalization should be performed at a water distance equal to or greater than focal length in order to produce the maximum surface signal.

X2.2.1.3 Set the transducer water path at its specified focal distance directly above the reference tube's top surface by adjusting for a maximum surface signal.

X2.2.1.4 The refracted shear wave is achieved by moving the transducer a specified offset distance perpendicular to the tube axis from the transducer's top dead center position. The specified offset distance is calculated by the following equation:

$$\text{Offset} = \left\{ \frac{\text{velocity of sound in water}}{\text{velocity of shear wave in tube material}} \right\} \times \text{tube radius} \times \text{Sin}\ \theta \qquad (X2.1)$$

For Zircaloy tubes, offset

$$\approx 0.325 \times \text{O.D. for } \theta = 80°$$
$$\approx 0.285 \times \text{O.D. for } \theta = 60°$$
$$\approx 0.233 \times \text{O.D. for } \theta = 45°$$

where θ is the refracted angle in the tube.

The following steps provide nearly equal response from the inner and outer surface notches (inside diameter and outside diameter notches, respectively). This is achieved by adjusting the transducer to place the focal point within the tube wall.

X2.2.1.5 Translate the standard tube (or the transducer) so that the longitudinal outside diameter (OD) notch is directly across the transducer; a large OD_1 multiple is obtained. Rotate the standard slightly to observe successive appearance and disappearance of OD_2, OD_3, etc., multiples produced by the shear wave response from the outside diameter notch (see Fig. X2.1).

X2.2.1.6 At the location of the OD_2 multiple, adjust the focal distance so that a maximum OD_2 multiple is obtained.

X2.2.1.7 Repeat steps X2.2.1.5 and X2.2.1.6 for the longitudinal inside diameter notch to observe ID_1, ID_2, etc., multiples. If necessary, readjust the transducer focal distance to obtain nearly equal amplitudes of OD_2 and ID_1 multiples. The same procedure may also be used to obtain nearly equal amplitudes of OD_2 and ID_2 multiples. The flaw gate is positioned to include either OD_2, ID_1 multiples or OD_2, ID_2 multiples, whichever gives the best indication. Do not gate OD_1.

X2.2.1.8 For bidirectional testing, the two transducers should be positioned equal distance away from the tube center line and on opposite sides of the tube center line.

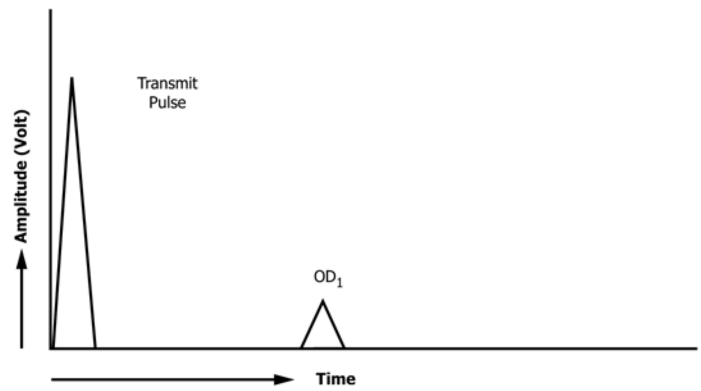
X2.2.2 *For Transverse Defects*—Positioning an inspection transducer for the detection of transverse defects using a refracted shear wave test with a spot or line focused beam is accomplished as follows (see Fig. A3.1(b)):

X2.2.2.1 Same as X2.2.1.1.

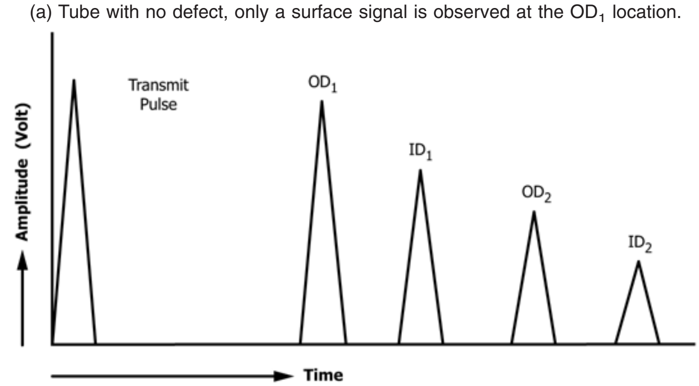
X2.2.2.2 Same as X2.2.1.2.

X2.2.2.3 Same as X2.2.1.3.

X2.2.2.4 The refracted shear wave is obtained by setting the incident angle calculated by the following equation:



(a) Tube with no defect, only a surface signal is observed at the OD_1 location.



(b) Tube with outside diameter and inside diameter notches, the OD_1 location includes the surface signal and the first outside diameter multiple.

NOTE 1—OD_1 is a surface reflected signal and not a refracted shear wave. Do not gate OD_1.

FIG. X2.1 Shear Wave Response from a Tube

$$\text{Incident angle, } \varphi = \text{Sin}^{-1}\left\{\frac{\text{velocity of sound in water}}{\text{velocity of shear wave in tube material}}\right\} \times \text{Sin} \quad (X2.2)$$

For Zircaloy tubes, incident angle ≈28°.

X2.2.2.5 Translate the standard tube (or the transducer) so that the transverse outside diameter notch is directly across the transducer; a large OD_1 multiple is obtained. Translate the standard (or the transducer) slightly to observe OD_2, OD_3, etc., multiples (similar to Fig. X2.1).

X2.2.2.6 At the location of the OD_2 multiple, adjust the focal distance so that a maximum OD_2 multiple is obtained. Tube or transducer translation may be necessary to maintain the notch signal at its maximum.

X2.2.2.7 Repeat steps X2.2.2.5 and X2.2.2.6 for the transverse inside diameter notch to observe ID_1, ID_2, etc., multiples. If necessary, readjust the transducer focal distance to obtain near equal amplitudes of OD_2 and ID_1 multiples. The same procedure may also be used to obtain equal amplitudes of OD_2 and ID_2 multiples. The flaw gate is positioned to include either OD_2, ID_1 multiples or OD_2, ID_2 multiples, whichever gives the best indication.

X2.3 Transducer Positioning for Lamb Wave Inspection

X2.3.1 *Guide to Transducer Positioning for a Lamb-Wave, Line Focus Test for Longitudinal Defects:*

X2.3.1.1 Normalize the transducer to the top surface of the reference standard tube from a position directly above the tube.

X2.3.1.2 Set the transducer water path at its specified distance directly above the reference tube top surface. The specified water path is the transducer focal length minus the water path correction, Δ *WP*.

$$\Delta WP = \text{tube OD} \times 0.117 \quad (X2.3)$$

X2.3.1.3 A Lamb-wave is achieved by moving the transducer a specified offset distance perpendicular to the tube axis from the transducer's top dead center position. The specified offset distance is adjusted within the values recommended in Fig. X2.2 for highest possible sensitivity.

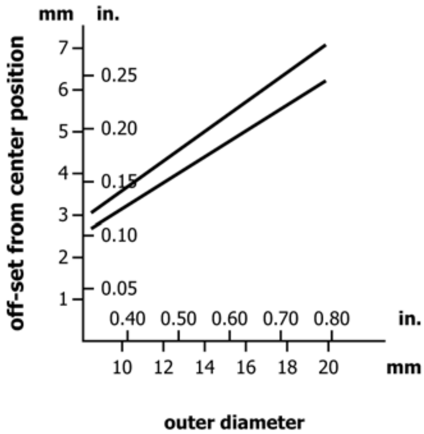
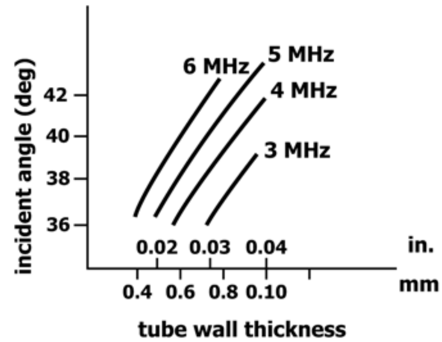


FIG. X2.2 Lamb-Wave Longitudinal Flaw Testing. Transducer Offset Positioning as Function of Tube Outer Diameter



NOTE 1—It is recognized that additional information is required for higher frequencies, thinner walls or smaller incident angles.

FIG. X2.3 Lamb-Wave Transverse Flaw Testing. Transducer Incident Angle as Function of Frequency and Tube Wall Thickness

X2.3.2 *Guide to Transducer Positioning for a Longitudinal Lamb-Wave Search for Circumferential (Transverse) Defects:*

X2.3.2.1 Normalize the transducer to the top surface of the reference standard tube from a position directly above the tube.

X2.3.2.2 Set the specified incident angle according to Fig. X2.3.

X2.3.2.3 Direct the transducer against the outside diameter standard notch by axially moving the standard tube, and adjust for the focal distance.

X2.3.2.4 The incident angle and the water path are adjusted for highest possible sensitivity from the inside diameter and outside diameter standard defects, detected through the metal.

X3. RATIONALE (COMMENTARY)

X3.1 The 1988 edition of this specification attempted to cover all types of tubing for nuclear service.

X3.2 Specification B811–90 originally was written to cover wrought zirconium alloy seamless tubes used for nuclear fuel cladding.

X3.3 This specification continues to cover tubing for nuclear service other than fuel cladding. It is to be used for structural tubes, instrumentation tubes, and larger diameter tubes.

X3.4 Paragraph 5.4 was included because the corrosion resistance of zirconium alloy tubes can be affected by the manufacturing processes used.

X3.5 The tensile properties in previous versions of this specification were measured at room temperature. The present version allows the tensile properties to be measured at room temperature, or at 572°F (300°C), or at another temperature, or at a combination thereof. The properties measured in the room temperature tests must satisfy the minimum values listed for room temperature in Table 3. The values from tests at other temperatures must satisfy the specified minimum values listed in Table 3 for that temperature, or, for conditions not listed in Table 3, satisfy the values agreed upon between the manufacturer and purchaser.

X3.6 It is not the intention to specify that the tensile properties must be measured at two or more temperatures. The aim is to allow the purchaser to select one or more test temperatures other than room temperature that may be more appropriate to the reactor operating conditions. Acceptable properties measured in tests at one temperature will satisfy the requirements of this specification.

X3.7 The hydrostatic pressure test, when specified, subjects the tube to a hoop stress of 50 % of the specified minimum room temperature yield strength. It is one of the tests used to ensure that the tube will be acceptable for end use; the tube must withstand the hydrostatic test with no evidence of bulges, leaks, or other flaws.

X3.8 Previous versions of this specification used inch-pound units as the standard, with metric units given in parentheses for information only. The current version of this specification uses both inch-pound and metric units as standard. Conversions made between them were rounded, so that they are not exact equivalents. Because of this rounding, the metric and the inch-pound values must be used independently of each other. Inch-pound values cannot be selected with other metric values to obtain an "easier" version of this specification.