Standard Specification for
Wrought Zirconium Alloy Seamless Tubes for Nuclear Reactor Fuel Cladding[1]

This standard is issued under the fixed designation B 811; 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 wrought zirconium-alloy tubes for nuclear fuel cladding application, in the outside diameter (OD) size range of 0.200 in. (5.1 mm) to 0.650 in. (16.5 mm) and wall thickness range of 0.010 in. (0.25 mm) to 0.035 in. (0.89 mm).

1.2 Two grades of reactor grade zirconium alloys are described.

1.2.1 The present UNS numbers designated for the two 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.*

2. Referenced Documents

2.1 *ASTM Standards:*
B 350 Specification for Zirconium and Zirconium Alloy Ingots for Nuclear Application[2]
B 353 Specification for Wrought Zirconium and Zirconium Alloy Seamless and Welded Tubes for Nuclear Service Except Nuclear Fuel Cladding[2]
E 8 Test Methods for Tension Testing of Metallic Materials[3]
E 21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials[3]
E 29 Practice for Using Significant Digits in Test Data to

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

Grade	UNS Number
Zirconium-tin alloy	R60802
Zirconium-tin alloy	R60804

Determine Conformance with Specifications[4]
E 112 Test Methods for Determining the Average Grain Size[3]
G 2 Test Method for Corrosion Testing of Products of Zirconium, Hafnium and Their Alloys in Water at 680°F or in Steam at 750°F[5]
G 2M Test Method for Corrosion Testing of Products of Zirconium, Hafnium and Their Alloys in Water at 633°K or in Steam at 673°K (Metric)[5]

2.2 *Other Document:*
ANSI B46.1 Surface Texture (Surface Roughness)[6]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *dimensions*—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.

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

3.1.3 *lot size*—a lot shall consist of all tubes of the same size, shape, condition, and finish produced from the same ingot by the same reduction schedule and heat treatment. The final heat treatment shall be in a single furnace charge.

3.1.4 *mill finish tubes*—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.

3.1.5 *ovality*—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)*—the difference between maximum and minimum wall thickness measured at any one transverse cross-section of the tube.

NOTE 1—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."

3.2 *Lot Definitions:*

3.2.1 *castings*—a lot shall consist of all castings produced from the same pour.

3.2.2 *ingot*—no definition required.

3.2.3 *rounds, flats, tubes, and wrought powder metallurgical products (single definition, common to nuclear and non-nuclear standards)*—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.

3.2.4 *sponge*—a lot shall consist of a single blend produced at one time.

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

4. Ordering Information

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

4.1.1 Quantity,

4.1.2 Grade (see Table 1),

4.1.3 Condition (recrystallization annealed or stress relief annealed),

4.1.4 Tube dimensions and tolerance,

4.1.5 ASTM designation and year of issue,

4.1.6 Surface texture on (roughness) the inside and outside surfaces (R_a (micro-inches or micrometers)),

4.1.7 Surface condition on the inside diameter (ID) and outside diameter (OD) surfaces (as pickled, blasted, abraded, etc.),

4.1.8 Sample test conditions (if other than mill finish condition) and standards for corrosion test (see Section 8.2),

4.1.9 General test requirements and test plan for lots (see Section 10),

4.1.10 Number of tests and resampling plan and requirements (see Section 11), and

4.1.11 Certification of test (see Section 16).

NOTE 2—A typical order description may read as follows: 1500 pieces of seamless zirconium-alloy fuel clad tubes OD abraded and ID pickled, Grade R60804, recrystallization annealed 0.650 in. nominal OD by 0.580 in. nominal ID by 0.032 in. minimum wall by 10 ft long with a maximum OD ovality of 0.004 in. and maximum WTV of 0.005 in. in accordance with B 811 – XX. Maximum surface finish to be 50 μin. Ra OD and 50 μin. Ra 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 Method of determining yield strength if other than 0.2 % offset method (see Section 7),

4.2.2 Initial gage length of mechanical test samples for determining elongation after rupture if other than 2 in. (50 mm),

4.2.3 Mechanical property requirements for tube other than fully recrystallization annealed (see Section 7),

4.2.4 Location of the inside diameter plugs in elevated temperature short-time tension test, when specified (see Section 7.1.3),

4.2.5 Specimen temperature(s) during mechanical testing if other than room temperature and properties and test requirements (see Section 7), and

4.2.6 Grain size requirements and specimen heat treatment method for stress relief annealed tubes (see Section 8.1),

4.2.7 Hydride orientation specimen heat treatment, if required, evaluation method, and magnification of photomicrograph (see Annex A2),

4.2.8 For hydride orientation, angle theta (θ) for determining radial platelets (see Section 8.3 and Annex A2).

4.2.9 Burst property acceptance requirements, when specified (see Section 8.4),

4.2.10 Use of mandrel and post burst test measurement technique (see Annex A1).

4.2.11 Contractile strain ratio acceptance criteria, when specified (see Section 7.3 and Annex A4).

5. Materials and Manufacture

5.1 Tubes covered by this specification shall be made from ingots produced by multiple vacuum arc or electron beam melting in furnaces of a type conventionally used for reactive materials.

5.2 Tubes shall be made by a process approved by the purchaser.

6. Chemical Composition

6.1 The tubes shall conform to the requirements for chemical composition prescribed in Table 2.

6.2 *Chemical Analysis*:

6.2.1 The ingot analysis made in accordance with Specification B 350 shall be considered the chemical analysis for tubes produced to this specification except for oxygen, hydrogen, and nitrogen content, which shall be determined on the mill finished tube. Alternatively, an intermediate or final size product may be sampled during processing with the same frequency and in the same positions relative to the ingot as specified in Specification B 350 to determine the composition, except for hydrogen, oxygen, and nitrogen, which shall be determined on the mill finished tube.

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

6.2.3 *Product Analysis*—Product analysis is a check analysis made by the purchaser for the purpose of verifying the

TABLE 2 Chemical Requirements

Element	UNS Number R60802	UNS Number R60804
Composition, Weight %:		
Tin	1.20 to 1.70	1.20 to 1.70
Iron	0.07 to 0.20	0.18 to 0.24
Chromium	0.05 to 0.15	0.07 to 0.13
Nickel	0.03 to 0.08	. . .
Oxygen	0.09 to 0.16	0.09 to 0.16
Iron plus chromium plus Nickel	0.18 to 0.38	. . .
Iron plus chromium	. . .	0.28 to 0.37
Maximum Impurities, Weight %:		
Aluminum	0.0075	0.0075
Boron	0.00005	0.00005
Cadmium	0.00005	0.00005
Calcium	0.0030	0.0030
Carbon	0.027	0.027
Cobalt	0.0020	0.0020
Copper	0.0050	0.0050
Hafnium	0.010	0.010
Hydrogen	0.0025	0.0025
Magnesium	0.0020	0.0020
Manganese	0.0050	0.0050
Molybdenum	0.0050	0.0050
Nickel	. . .	0.0070
Niobium	0.0100	0.0100
Nitrogen	0.0080	0.0080
Silicon	0.0120	0.0120
Tungsten	0.0100	0.0100
Titanium	0.0050	0.0050
Uranium (Total)	0.00035	0.00035

composition of the lot. The permissible variation in the product analysis from the specification range is as listed in Table 3.

7. Mechanical Properties

7.1 *Tension Properties*:

7.1.1 Recrystallization annealed tubes shall conform to the requirements for mechanical properties at room temperature prescribed in Table 4. For tubes in the cold worked and stress relief annealed condition, tension property requirements are to be mutually agreed upon between the manufacturer and the purchaser.

7.1.2 When so specified by the purchaser, the tension properties shall also be determined at the elevated temperatures and shall conform to the limits specified by the purchaser.

7.1.3 The tension test shall be conducted in accordance with Test Methods E 8 or E 21. Yield strength shall be determined

TABLE 3 Permissible Variation in Product Analysis

	Permissible Variation from the Specification Range (Table 2), %
Alloying Elements:	
Tin	0.050
Iron	0.020
Chromium	0.010
Nickel	0.010
Iron plus chromium	0.020
Iron plus chromium plus nickel	0.020
Oxygen	0.020
Impurity Element:	
Each	20 ppm or 20 %, whichever is smaller

TABLE 4 Mechanical Properties of Recrystallization Annealed Tubes Tested at Room Temperature[A]

	UNS Numbers R60802 and R60804
Tension Test Properties (Longitudinal Direction):	
Yield Strength (0.2 % Offset), min	35 ksi (240 MPa)
Tensile Strength, min	60 ksi (415 MPa)
Elongation, min %, 2 in. (50 mm) initial gage length	20
Burst Test Properties:	
Ultimate Hoop Strength, min	72.6 ksi (500 MPa)
Percent Total Circumferential Elongation (% TCE), min	20

[A]"RT" represents room temperature; Note 4 in Test Methods E 8 and E 8M 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 E 21 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.

by the 0.2 % offset method. The tension 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.

7.2 *Burst Testing*:

7.2.1 Burst testing, when specified, shall be performed at room temperature on finished tubing. Recrystallization annealed tubes shall conform to the requirements for burst properties at room temperature prescribed in Table 4. If burst test is specified for cold worked and stress relief annealed tubes, the acceptance criteria shall be agreed upon between the manufacturer and the purchaser.

7.2.2 If elevated temperature burst test is specified, the test method and acceptance criteria shall be agreed upon between the manufacturer and purchaser.

NOTE 3—Burst properties obtained at room temperature were the subject of a 1971 round robin conducted by ASTM subcommittee B10.02.[7] Variability in values was relatively large and should be considered in setting specific limits.

7.3 *Contractile Strain Ratio (CSR)*:

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

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

NOTE 4—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. Other Requirements

8.1 *Grain Size*—The average grain size of recrystallization annealed tubes in the longitudinal section shall be equal to

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[7] *STP 551*, "Zirconium in Nuclear Applications," ASTM, 1974, pp. 14–28.

ASTM micrograin Size No. 7 or finer when determined in accordance with Test Methods E 112. When specified per 4.2.6, the average grain size of stress relief annealed tubes shall meet the requirements as agreed upon between manufacturer and purchaser.

8.2 *Corrosion Properties*:

8.2.1 A corrosion test in steam shall be performed in accordance with Test Method G 2 or its metric companion Test Method G 2M. The specimens tested shall be representative of the mill finish condition unless otherwise stated by the purchaser.

8.2.2 *Acceptance Criteria*:

8.2.2.1 *Mass Gain*—Specimens shall exhibit a mass gain of not more than 2.2 g/m^2 in a 72-h test or 3.8 g/m^2 in a 336-h test.

8.2.2.2 *Post-Test Visual Appearance*—Mill finish specimens shall be free of white or brown corrosion products in excess of the acceptance standards mutually agreed between the manufacturer and the purchaser. Specimens etched per Test Method G 2 or Test Method G 2M (if stated by the purchaser) shall exhibit a continuous black lustrous oxide film and shall be free of white or brown corrosion products in excess of standards.

8.3 *Hydride Orientation Fraction*:

8.3.1 Hydride orientation fraction, Fn, shall be determined on samples taken from mill finished tubes.

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

8.3.3 *Acceptance Criteria*—Stress relief annealed specimens shall have an Fn value not more than 0.30. Recrystallization annealed specimens shall have an Fn value not greater than 0.50.

8.4 *Outer and Inner Surface Texture (Roughness)*—Outer and inner surface texture (roughness) shall be determined in accordance with ANSI B46.1 or its national or international equivalent for conformance to purchase order surface texture (roughness) requirements.

9. Permissible Variations in Dimensions

9.1 *Diameter*—The permissible variations in outside or inside diameter shall be ±0.002 in. (±0.05 mm).

9.2 *Wall Thickness*—The permissible variations in wall thickness shall be ±0.003 in. (±0.08 mm).

9.3 *Length*—The permissible variation in length shall be ±0.030 in. (±0.76 mm).

10. Sampling

10.1 For certification purposes, a minimum of two random sample tubes shall be taken from each lot for laboratory tests. All tubes in a lot shall have been inspected for each inspection characteristic given in Section 12.

11. Number of Tests and Resampling

11.1 Specimens cut from each sample tube, chosen in accordance with Section 10 for laboratory testing, shall be tested as follows: (*1*) tube chemical analysis (see Section 6), (*2*) tension test (see 7.1), (*3*) burst test (see 7.2), (*4*) contractile strain ratio test (see 7.3), (*5*) grain size (see 8.1), (*6*) corrosion test (see 8.2), (*7*) hydride orientation (see 8.3), and (*8*) surface texture (see 8.4).

11.2 *Resampling*:

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

11.2.2 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, provided the rework steps are within the previously approved process.

11.2.2.1 The reworked tubes shall be inspected for conformance to this specification.

11.2.2.2 Reworked lot shall be resampled for tests affected by the rework in accordance with Section 10.

11.2.3 If any sample fails to conform to the specification requirement, the test for the nonconforming attribute shall be performed on specimens taken from twice as many random sample tubes as originally used.

11.2.3.1 All test results, including the original test results, shall be reported to the purchaser.

11.2.3.2 Only one set of resampling is permitted, and all results of resampling shall conform to the specification requirements for the characteristic tested.

12. Inspection

12.1 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:

12.1.1 *Surface and Internal Flaw Inspection*:

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

12.1.1.2 *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 equal to 10 % of the nominal wall thickness. In no case, however, shall the artificial defect be deeper than 0.002 in. (0.05 mm) or longer than 0.065 in. (1.65 mm).

12.1.1.3 *Rejection*—Any tube showing an ultrasonic indication equal to or greater than the standard set forth in 12.1.1.2 shall be rejected.

12.1.2 *Outer and Inner Surfaces*:

12.1.2.1 *Test Method*—Each tube shall be inspected over its entire length. The outside surface shall be inspected on a table under a minimum light intensity of 100 fc (1076 1x). The inner surface shall be inspected from each end against a suitable fluorescent light background.

12.1.2.2 *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.

12.1.3 *Straightness*:

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

12.1.3.2 *Acceptance Criteria*—The tubes shall be free of bends or kinks. The maximum deflection (bow) in the vertical plane shall not exceed 0.01 in. (0.25 mm) between any two adjacent points of contact. In no case shall the bow exceed 0.01 in. (0.25 mm) per foot (305 mm) of the span length, irrespective of the tube diameter.

12.1.4 *Dimensional Inspection*:

12.1.4.1 *Test Method*—Each tube shall be inspected over its entire length by using a helix of measurement with the pitch not exceeding 2 in. (50.8 mm).

12.1.4.2 *Acceptance Criteria*—The tubes shall meet the permissible variations specified in Section 9.

12.1.5 *Purchaser Inspection*:

12.1.5.1 The manufacturer shall inspect tubes covered by this specification prior to shipment and, on request, shall furnish the purchaser with certificates of test. If so 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 desired 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.

12.1.5.2 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.

13. Significance of Numerical Limits

13.1 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 E 29.

13.1.1 All observed and calculated values, except those listed below, are to be rounded to the nearest unit in the right hand place of figures of the specified limit.

Test	Rounded Unit for Observed or Calculated Value
Tensile strength, yield strength, and burst strength	nearest 1000 psi (10 MPa)

14. Rejection

14.1 Tubes that fail to conform to the requirements of this specification may be rejected. Rejection should be reported to the manufacturer promptly and in writing. In case of dissatisfaction with the results of the test, the manufacturer may claim for referee in accordance with Section 15.

15. Referee

15.1 In the event of disagreement between the manufacturer and the purchaser on the conformance of the tubes 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.

16. Certification

16.1 The purchaser shall be furnished with a test certificate stating that samples representing each lot have been tested and inspected as directed in this specification, and the requirements have been met.

17. Packaging and Package Marking

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

17.1.1 Purchase order or contract number,

17.1.2 Name of manufacturer,

17.1.3 Grade,

17.1.4 Size,

17.1.5 Lot or ingot number,

17.1.6 Gross, net and tare weights, and

17.1.7 ASTM designation.

17.2 All tubes 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 purchaser.

18. Keywords

18.1 fuel cladding; nuclear fuel; nuclear reactor; seamless; tubing; zirconium alloy

ANNEXES

(Mandatory Information)

A1. ROOM TEMPERATURE CLOSED-END BURST TESTING PROCEDURE FOR ZIRCONIUM ALLOY NUCLEAR FUEL CLADDING TUBES

A1.1 Scope

A1.1.1 This annex covers the determination of burst test mechanical properties at room temperature of zirconium alloy nuclear fuel cladding tubes.

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.

A1.1.3 This procedure is not appropriate for testing at elevated temperatures.

A1.2 Apparatus

A1.2.1 The test system shall be designed with adequate capacity to test at the stress levels and temperatures needed. Special consideration should be given to the following items:

NOTE A1.1—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.

A1.2.1.1 *Pump*, capable of increasing system pressure at a steady rate. The pressurization rate during elastic loading shall be 2000 ± 200 psi/min (13.8 ± 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*, shall be included for the following functions: control, regulation, and safety.

A1.2.1.3 *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 ten 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 (if agreed upon) shall meet the following requirements:

A1.3.5.1 The mandrel outside diameter shall be 0.010 in. ± 0.002 in. (0.25 mm ± 0.05 mm) less than the average inside diameter of the tube, 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 the specimen 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 measurements of the outside diameter at three equally spaced locations around the circumference at each end of the specimen and at the center. Pretest measurements 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 Report the following data:

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:

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

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; and

A1.5.1.4 Percent total circumferential elongation (% TCE):

$$\% \text{ TCE} = \frac{C_2 - C_1}{C_1} \times 100 \qquad (A1.2)$$

where:
C_1 = pretest circumference, and
C_2 = post test circumference excluding burst opening.

A2. PROCEDURE FOR DETERMINATION OF RADIAL HYDRIDE ORIENTATION FRACTION IN ZIRCONIUM ALLOY NUCLEAR FUEL CLADDING TUBES

A2.1 Scope

A2.1.1 This annex covers the determination of radial hydride orientation fraction, Fn, of zirconium alloy nuclear fuel cladding tubes.

A2.1.2 The radial hydride orientation fraction, Fn, shall be evaluated by either the measurement method or the micrograph comparison method given in Section A2.4, as specified by the purchaser.

A2.2 Procedure

A2.2.1 Inoculate specimen with sufficient hydrogen to produce uniformly distributed hydride platelets as follows:

A2.2.1.1 Introduce hydrogen into the specimen 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/min (14°C/min).

A2.3 Preparation of Micrograph

A2.3.1 Cut transverse metallographic sections from each hydrided specimen and prepare for microscopical examination. Do not use 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 Divide each transverse tube wall section into three equal layers covering the entire wall thickness (outer, middle, and inner wall sections) and make determinations per Section A2.4 on each layer. A suitable magnification in the range 100× to 500× (as specified by the purchaser) shall be used for the measurement, and the measured area shall be typical of the hydride microstructure in the entire specimen cross section.

A2.4 Evaluation Method

A2.4.1 *Measurement Method*:

A2.4.1.1 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.

A2.4.1.2 Count all radial platelets for each layer. A radial platelet is defined as one oriented within theta (θ) degrees of the radial direction of the tube and meeting the requirements of A2.4.1.1.

A2.4.1.3 Calculate the value of the radial hydride fraction, Fn.

A2.4.2 *Micrograph Comparison Method*:

A2.4.2.1 Compare the specimen micrograph against the purchaser-approved micrograph standard with an assigned value of Fn. The specimen Fn is acceptable if the fraction of radial hydrides in the specimen micrograph is equal to or less than the purchaser-approved standard.

A3. PROCEDURE FOR ULTRASONIC FLAW TESTING OF ZIRCONIUM ALLOY NUCLEAR FUEL CLADDING TUBES

A3.1 Scope

A3.1.1 This annex covers procedures for detecting discontinuities in zirconium alloy nuclear fuel cladding tubes. 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 electronic signal in excess of rejection criteria.

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 mill finished tubes shall have surfaces that are 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.

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 this specification for dimensions at time of test.

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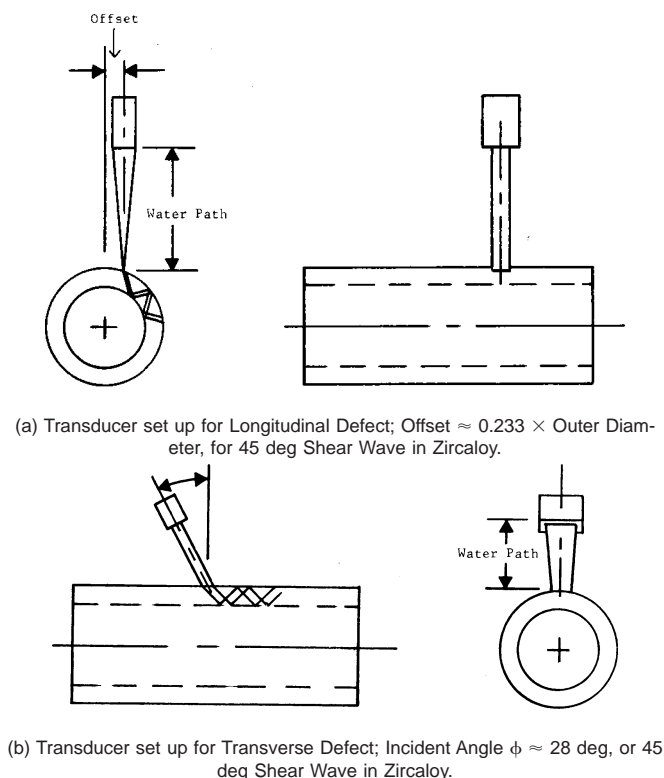
(a) Transducer set up for Longitudinal Defect; Offset ≈ 0.233 × Outer Diameter, for 45 deg Shear Wave in Zircaloy.

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

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

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 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 2-channel strip chart recorders or equivalent, tube 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.

A3.4.3 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*) 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 Section 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 (r/min), 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_o+ 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 r/min, only one dimension (EBW) will be required; the diameter of the beam (or the beam width or the focal diameter) or the focal point (Y_o+). See Fig. A3.3.

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 carefully examined
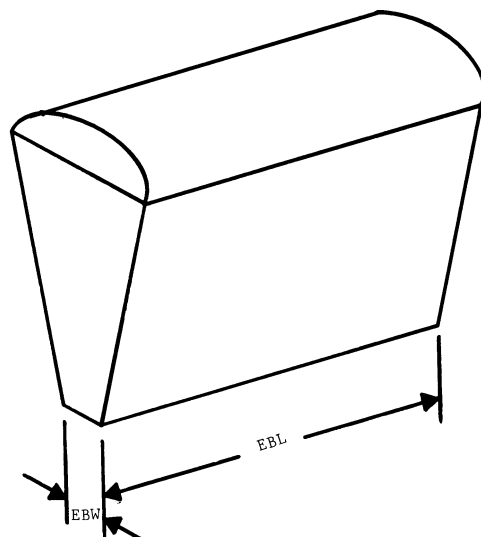

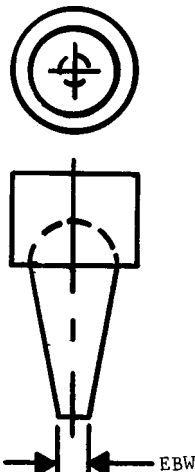**FIG. A3.2 Description of EBL and EBW for a Line Focus Transducer**

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

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 Four notches, minimum, shall be required; one each on the inner and outer surfaces aligned in the longitudinal (axial) 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). References 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 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 0.002 in. (0.05 mm) deep notch might have a 0.0003 in. (0.0075 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 the notch's long
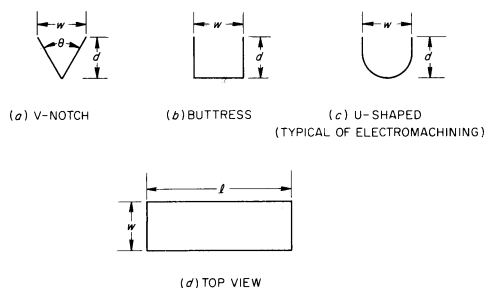

FIG. A3.4 Common Notch Shapes

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 length/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.

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

A3.6.9 Other types of orientations of reference discontinuities may be specified under 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 Section 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 surface and outside surface notches must be between 50 to 90 % of the full screen amplitude.

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 adjustments 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 tubes 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. EBL measurement should be performed from a longitudinal notch if the transducer is used to detect transverse defects (T), and it should be performed on a transverse notch if the transducer is used to detect longitudinal (L) defects.

A3.8.2.4 The surface speed, r/min, feed rate, and test time are given by the following equations:

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

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

$$\text{Revolution Per Minute (r/min)} = \frac{19 \times (\text{EBW})}{\text{OD}} \times \text{PRR} \ (1 - y)$$

$$(\text{A3.2})$$

Feed Rate (mm/min)
  = (EBL)$(1 - y) \times$ r/min, for line focus transducer
  = (EBW)$(1 - y) \times$ r/min, for spot focus transducer

$$\text{Total Inspection Time} = \frac{\text{tube length}}{\text{feed}} \qquad (\text{A3.3})$$

NOTE A3.4—If a line focus transducer is used for the detection of transverse flaws, EBL should be used in the equation for determining revolutions per minute (r/min).

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 tubes in both circumferential and both longitudinal directions under the identical conditions to those used in calibration under Section 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 A3.5—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
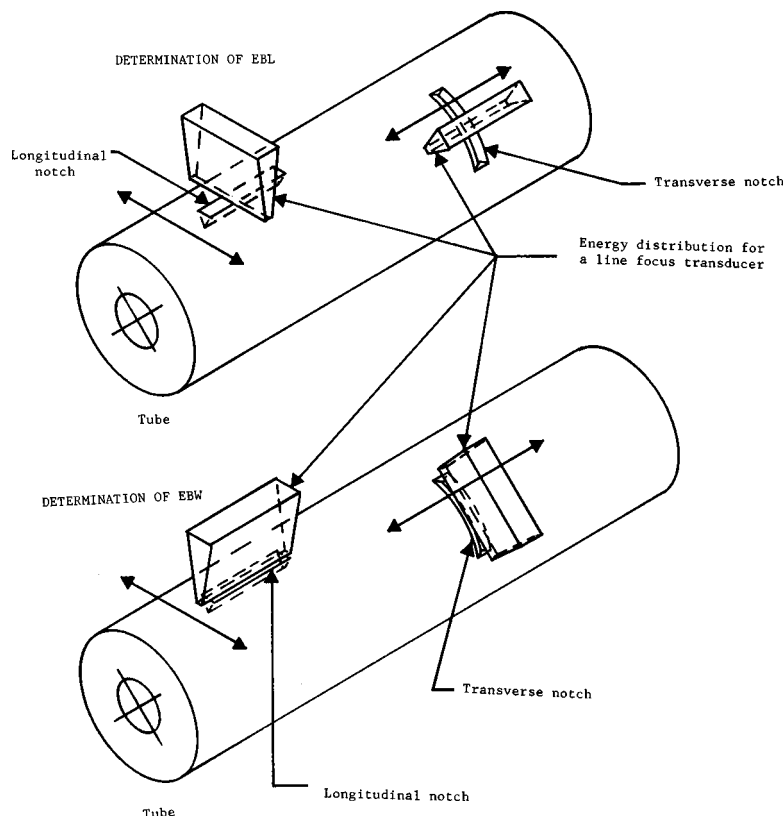

FIG. A3.5 Determination of the Ultrasonic Beam. The Arrows Indicate the Movement of the Transducer Relative to the Notch

time the equipment does not present a clearly defined, reject-able signal from both the inner and outer surface notches of the calibration standard, recalibrate the equipment in accordance with Section A3.7.

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 A3.8.4 and Section A3.7.

A3.9 Interpretation of Results

A3.9.1 Any relevant indication of a discontinuity (A3.2.1) 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 that is equal to or greater than the reject level described in A3.7.1

shall be considered as having passed this ultrasonic inspection except as noted in A3.8.5.

A3.10 Report

A3.10.1 The manufacturer 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 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 methods 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 contrac-tile 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 E 8.

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 locations at which each diameter was measured.

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 E 8, 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 %.

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

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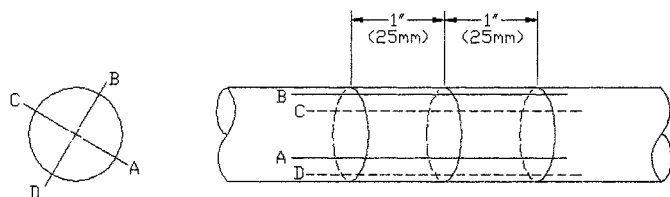
that variability in contractile strain ratio values was minimized when test conditions were performed at the low end of the allowable range for strain rate, and at the high end of the allowable range for strain level. It was also concluded that hold time after straining was not a significant factor.

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:

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

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

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

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

$$Er = -Ea - Ec \quad \text{(A4.3)}$$

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

$$CSF = \left[\frac{Ec}{Er} \right] \quad \text{(A4.4)}$$

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 the transducer focal length to the diameter of the transducer. The transducer is assigned a "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
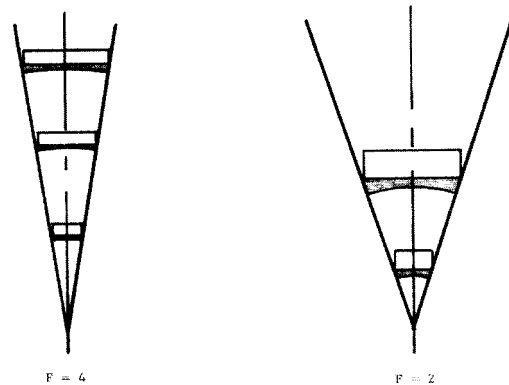

F = 4   F = 2

FIG. X1.1 Examples of Transducer Designations

diameter of the transducer. The diameter of the focal spot in water of a point focus transducer may be calculated from

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

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 0.020 in. (0.5 mm). For a rectangular line focus transducer, the width of the focal line is given by

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

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.

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, damp-ing, 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 0.8 in. (20 mm) is recommended, although a focal length of 0.6 to 1.6 in. (15 to 40 mm) 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 0.280 in. (7 mm) and the width a maximum of 0.075 in. (1.9 mm). For spot focused transducers the maximum size of the focal point shall be 0.075 in. (1.9 mm).

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

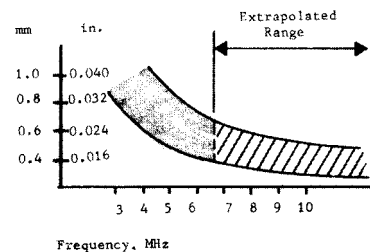X1.5.5 Transducer frequency chosen according to Fig. X1.2.

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:

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

For Zircaloy tubes, offset
$$\approx 0.325 \times \text{OD for } \phi = 80°$$
$$\approx 0.285 \times \text{OD for } \phi = 60°$$
$$\approx 0.233 \times \text{OD for } \phi = 45°$$

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.

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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:

$$\text{Incident angle, } \theta \qquad (X2.2)$$

$$= \text{Sin}^{-1} \left\{ \frac{\text{velocity of sound in water}}{\text{velocity of shear wave in tube material}} \right\} \times \text{Sin}$$

For Zircaloy tubes, incident angle $\approx 28°$.

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.
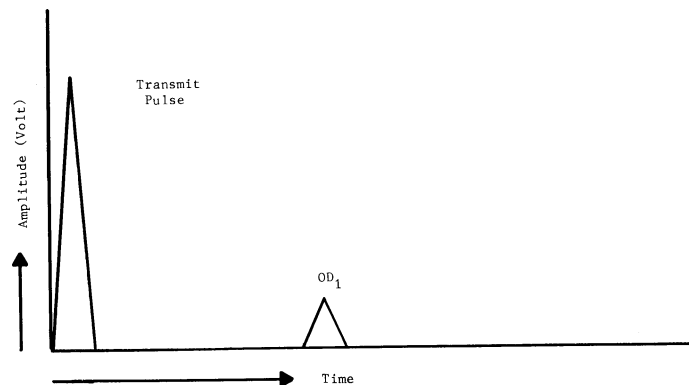
(a) Tube with no defect, only a surface signal is observed at the OD_1 location.
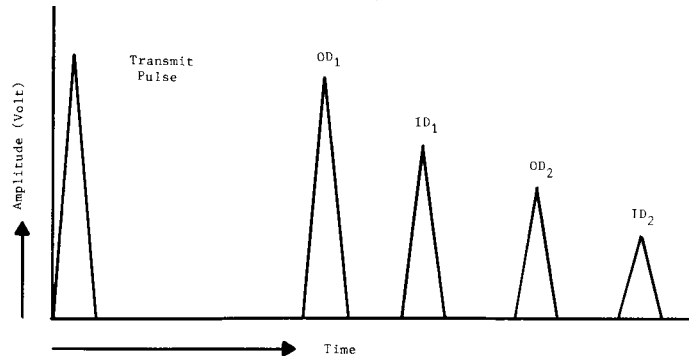
(b) Tube with outside diameter and inside diameter notches, the OD_1 location includes the surface signal and the first outside diameter multiple.

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

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, ΔWP.

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

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.

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.
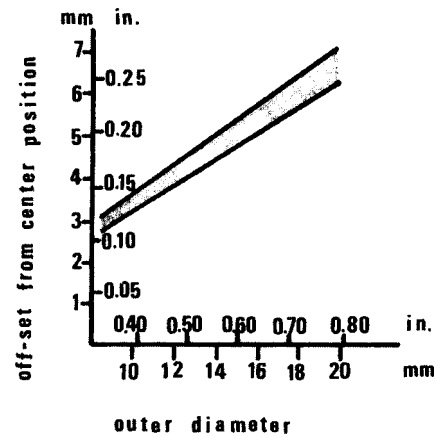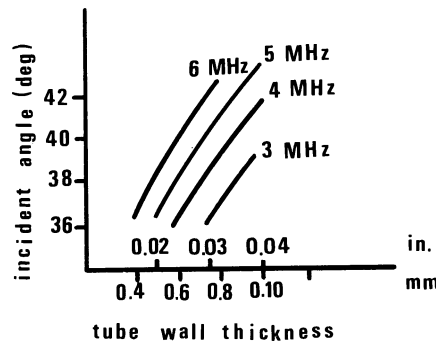

FIG. X2.2 Lamb-Wave Longitudinal Flaw Testing. Transducer Offset Positioning as Function of Tube Outer Diameter

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

X3. RATIONALE (COMMENTARY)

X3.1   At the December 1988 Subcommittee B10.02 meeting, a motion was approved to develop a new standard for nuclear fuel cladding. The basis for this decision was to separate fuel cladding requirements from the existing general purpose Specification B 353. This new standard was therefore developed to exclusively cover wrought zirconium-alloy seamless tubes for nuclear cladding and has retained the appropriate requirements previously specified in Specification B 353.

X3.2   This specification does not preclude the addition or modification of requirements through the purchase contract; however, any product must meet all of the criteria of this specification in order to be certified as meeting the requirements of this specification.

X3.3   For those interested in tubes for nuclear service other than fuel cladding tubes (for example, structural tubes, instrumentation tubes, larger diameter tubes, etc.), the existing Specification B 353 will continue to apply.

X3.4   Ordering Information, Section 4, includes items which are required by this specification (see 4.1) and items which require mutual agreement between purchaser and manufacturer (see 4.2).

X3.5   In Section 5 on Materials and Manufacture, a statement on the manufacturer using the purchaser-approved process for tubing is included to account for the effect of manufacturing process on the corrosion resistance of the tubes.

X3.6   In Table 2, requirements for calcium (0.0030 % max) have been added. This element is automatically determined by ICP, and no additional cost is involved. The range of oxygen is now fixed at 0.09 to 0.16 %, and is considered an alloying element. The limiting values reflect the current industry-wide requirement specified by most of the users.

X3.7   Section 6 Chemical Composition (see 6.2.1) currently provides alternate methods for sampling, either at the ingot stage or at some intermediate or final stage. Results of sampling for composition at an intermediate or final product is more likely to be representative of the composition than samples taken from the surface of large ingots. To this effect, Subcommittee B10.02 may convert to sampling an intermediate product in the next revision. The manufacturers of ingots and intermediate products are encouraged to establish sufficient history on analytical chemistry data on ingots and corresponding intermediate products in preparation for the next revision.

X3.8   Table 4 shows tensile properties in the longitudinal direction at room temperature for recrystallization annealed tubes. Properties for cold worked and stress relief annealed tubes are to be mutually agreed upon between purchaser and manufacturer.

X3.9   Paragraph 7.2 on burst testing identifies the room temperature burst test requirements for recrystallization annealed tube and references the ASTM round robin. In addition, it stipulates that the following be mutually agreed upon between purchaser and manufacturer:

X3.9.1 Acceptance criteria for room temperature burst test for cold worked and stress relief annealed tubes, when specified, and

X3.9.2 Method and acceptance criteria for elevated temperature burst test.

X3.10   In paragraph 8.1 on grain size determination, the requirements for stress relief annealed tubes, when specified, are stipulated to be as mutually agreed upon between manufacturer and purchaser.

X3.11   Since the majority of nuclear fuel cladding tubes are corrosion tested in the mill finish, the corrosion testing of mill finished specimens is standardized in 8.2. Definition of mill finish is included under terminology.

X3.12   In paragraph 8.3.3, the hydride orientation (Fn) values for stress relief annealed tubes and recrystallization annealed tubes have been separated at 0.30 and 0.50. The definition of hydride orientation fraction has been included under terminology.

X3.13   It is recognized that the industry-wide method for dimensional inspection is by ultrasonic test. It is the intention of the subcommittee to include an ultrasonic test for dimensional inspection. To this effect a separate task group has been established to develop a suitable ultrasonic dimensional test. The test method, when developed, will be balloted separately for inclusion in this specification.