Designation: ~~B811 – 13~~ B811 – 13$^{\varepsilon 1}$

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

This standard is issued under the fixed designation B811; 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.

ε[1] NOTE—Equations in Section A4.5 were corrected editorially in August 2014.

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:*[2]

B350/B350M Specification for Zirconium and Zirconium Alloy Ingots for Nuclear Application

B353 Specification for Wrought Zirconium and Zirconium Alloy Seamless and Welded Tubes for Nuclear Service (Except Nuclear Fuel Cladding)

E8 Test Methods for Tension Testing of Metallic Materials

E8M Test Methods for Tension Testing of Metallic Materials [Metric] (Withdrawn 2008)[3]

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)

2.2 *Other Document:*

ANSI B46.1 Surface Texture (Surface Roughness) [4]

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.

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[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.

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

[4] Available from American Iron and Steel Institute (AISI), 1140 Connecticut Ave., NW, Suite 705, Washington, DC 20036, http://www.steel.org.

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

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

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 size, n*—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, 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.

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.

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

3.2.2 *ingot, n*—no definition required.

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

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

3.2.5 *weld fittings, n*—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 B811 – 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 Materials covered by this specification shall be produced in accordance with Specification B350/B350M; all processes to be done in furnaces usually used for reactive metals.

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 analysis of the material produced to this specification shall be the one made by the manufacturer on the ingot in accordance with Specification B350/B350M. This analysis can be performed by the manufacturer on the ingot itself, or on intermediate or final products with the same frequency and in the same positions relative to the ingot as required in Specification B350/B350M. The chemical analysis of hydrogen, oxygen and nitrogen shall be determined on the finished product.

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 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.

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

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 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.

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 E8 or E21. Yield strength shall be determined 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.[5] 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.

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

8. Other Requirements

8.1 *Grain Size—*The average grain size of recrystallization annealed tubes in the longitudinal section shall be equal to ASTM micrograin Size No. 7 or finer when determined in accordance with Test Methods E112. 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 G2/G2M. 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 G2/G2M (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 E29.

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. The reporting must be done according to the agreement between the manufacturer and the purchaser; if not, the reporting will be done not later than 60 calendar days from the receipt of the material by the purchaser. 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 manufacturer shall supply at least one copy of the report certifying that the material supplied has been manufactured, inspected, sampled, and tested in accordance with the requirements of this specification and that the results of chemical analysis, tensile, and other tests meet the requirements of this specification for the grade specified. The report shall include results of all chemical analysis, tensile tests, and all other tests required by the specification.

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 ± 0.002 in. (0.25 ± 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:

$$s = \frac{PD}{2t} \tag{A1.1}$$

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):

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

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~~ discontinuity, n*—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 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.