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Standard Guide for Conducting Supplemental Surveillance Tests for Nuclear Power Reactor Vessels, E 706 (IH)[1]

This standard is issued under the fixed designation E 636; 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 guide covers test methods and procedures that can be used in conjunction with, but not as alternatives to, those required by Practice E 185 for the surveillance of nuclear reactor vessels. The supplemental test methods outlined permit the acquisition of additional information on radiation-induced changes in fracture toughness, notch ductility, and tensile strength properties of the reactor vessel steels.

1.2 This guide provides recommendations for the preparation of test specimens for irradiation, and identifies special precautions and requirements for reactor surveillance operations and postirradiation test planning. Guidance on data reduction and computational procedures also is given for individual test methods. Reference is made to other ASTM test methods for the physical conduct of specimen tests and for raw data acquisition.

2. Referenced Documents

2.1 *ASTM Standards:*

E 8 Test Methods for Tension Testing of Metallic Materials[2]

E 23 Test Methods for Notched Bar Impact Testing of Metallic Materials[2]

E 184 Practice for Effects of High-Energy Neutron Radiation on the Mechanical Properties of Metallic Materials, E 706 (IB)[3]

E 185 Practice for Conducting Surveillance Tests for Light Water Cooled Nuclear Power Reactor Vessels, E 706 (IF)[3]

E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[2]

E 482 Guide for Application of Neutron Transport Methods for Reactor Vessel Surveillance, E 706 (IID)[3]

E 560 Practice for Extrapolating Reactor Vessel Surveillance Dosimetry Results, E 706 (IC)[3]

E 616 Terminology Relating to Fracture Testing[2]

E 812 Test Method for Crack Strength of Slow-Bend Precracked Charpy Specimens of High-Strength Metallic Materials[2]

E 813 Test Method for J_{Ic}, a Measure of Fracture Toughness[2]

E 992 Practice for Determination of Fracture Toughness of Steels Using Equivalent Energy Methodology[2]

E 1152 Test Method for Determining J-R Curves[2]

E 1221 Test Method for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{1a}, of Ferritic Steels[2]

2.2 *Other Standard:*

ASME Boiler and Pressure Vessel Code, Section III, Subsection NB (Class 1 Components)[4]

3. Significance and Use

3.1 Practice E 185 describes a minimum program for the surveillance of reactor vessel materials, specifically mechanical property changes that occur in service. Guide E 636 may be applied where radiation space limitations are not overly stringent and where the inclusion of additional specimen types is desirable to generate additional specific fracture toughness property information on radiation-induced property changes to better assist the determination of the optimum reactor vessel operation schemes.

4. Supplemental Test Methods

4.1 *Compact Specimen Test*—This test involves the dynamic or static testing of a fatigue-precracked compact specimen during which a record of load versus displacement is used to determine material fracture toughness properties such as the plane strain fracture toughness (K_{Ic}), the *J*-integral fracture toughness (J_{Ic}), and the *J-R* curve (see Test Methods E 399, E 813, and E 1152, respectively). These test methods generally apply to elastic, elastic-plastic, or fully plastic (upper shelf) behavior. The rate of specimen loading or stress intensity increase required for test classification as static or dynamic is indicated by the referenced test methods.

4.2 *Precracked Charpy Impact Test*—This test involves impact testing of Charpy V-notch specimens that have been fatigue precracked. A load versus deflection or time record, or both, are obtained during the test to determine an estimate of

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[2] *Annual Book of ASTM Standards*, Vol 03.01.

[3] *Annual Book of ASTM Standards*, Vol 12.02.

[4] Available from American Society of Mechanical Engineers, 345 E. 47th St., New York, NY 10017.

material fracture toughness properties. The test method applies to the brittle/ductile transition region.

4.3 *Instrumented Charpy V-Notch Test*—This test involves the impact testing of standard Charpy V-notch specimens using a conventional tester (Test Methods E 23) equipped with supplemental instrumentation that provides a load versus deflection or time record, or both, to augment standard test data. The test record is used primarily to estimate dynamic yield stress, fracture initiation and propagation energies, and to identify fully ductile (upper shelf) fracture behavior.

4.4 Other test methods not covered by ASTM standards, for example, miniature, nondestructive, nonintrusive, or in-situ testing techniques, can be utilized to accommodate limitations of material availability or irradiation facility configuration, or both. However, the user should establish the method's technical validity and correlation with existing test methods.

5. General Test Requirements

5.1 *Specimen Orientation and Preparation*:

5.1.1 *Orientation*—It is recommended that specimens for supplemental surveillance testing be taken from the quarter thickness location of plate and forging materials, as defined in NB 2300 of ASME Code Section III, and at a distance at least one material thickness from a quenched edge. Specimens from near surface material also may be considered for special studies, if required. For weld deposits, it is recommended that the specimens be taken from a thickness location at least 12.7 mm (½ in.) removed from the root and the surfaces of the weld. Consistent with Practice E 185, it is further recommended that the specimens be oriented to represent the transverse orientation (T-L, per Test Method E 399) in plate and forging materials. Specimens having the longitudinal orientation (L-T, per Test Method E 399) also may be used given sufficient material and space in the surveillance capsule. For weld deposits, the specimen shall be oriented to make the plane of fracture parallel to the welding direction and perpendicular to the weldment surface, with the direction of crack growth along the welding direction. Examples of specimen orientations are given in Fig. 1.

5.1.1.1 *Specimen Notch Orientation*—The specimen notch root in all cases shall be oriented normal to the plate, forging, or weldment surface. For weld deposits, the notch also should be located at the approximate weld deposit centerline. The centerline and the width of the weld deposit about the notch shall be determined from the weld fusion lines revealed by etching. It is recommended that the location of the weld fusion lines be permanently marked for reference for post-irradiation testing. The general appearance of the etched weld deposit in terms of individual weld bead size (large vs. small) and the number of weld beads across the weld deposit should be determined and recorded.

5.1.1.2 *Specimen Marking*—A suitable specimen identification, marking, and documentation system shall be used whereby the location and orientation of each specimen within the source plate, forging, or weldment can be traced. The traceability of weld specimens is particularly important because of the possibility for variations through the weldment thickness.

5.1.2 *Preparation*—All specimens shall be prepared from material that has been fully heat-treated, including stress-relief annealing, as recommended in Practice E 185.

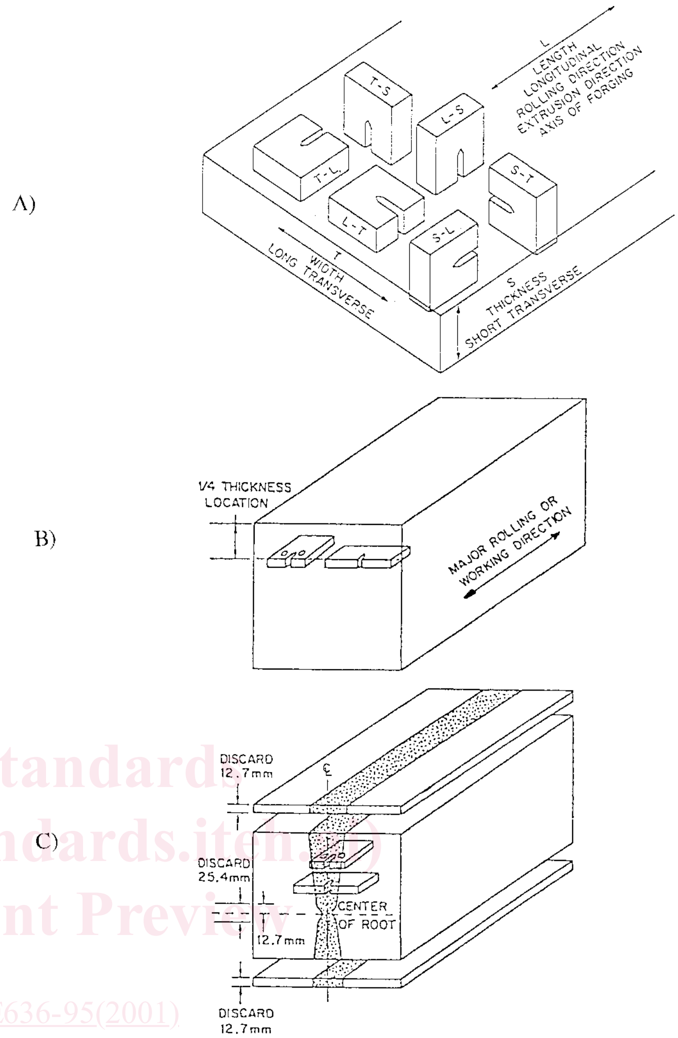

FIG. 1 Specimen Orientation and Location in Plate, Forging, and Weld Deposit Materials: A) Crack Plane Orientation Code; B) Plate and Forging Specimen Location and Orientation; C) Weld Specimen Location and Orientation

5.1.2.1 *Machining*—Specimens for irradiation should be finish machined on all sides to aid encapsulation in reactor experiments and to aid radiation temperature control and uniformity.

5.1.2.2 *Fatigue Precracking*—It is recommended that fatigue precracking of specimens, if required, should be accomplished prior to irradiation to avoid difficulties of precracking following irradiation. However, fatigue precracking of a specimen following irradiation is acceptable if a suitable means of following crack extension in the specimen is established.

5.1.2.3 *Fatigue Precracking of Postirradiation Heat-Treated Specimens*—Some postirradiation heat treatments at temperatures higher than the prior irradiation exposure can cause mechanical property recovery, including reductions in yield strength and tensile strength and an improvement in fracture toughness toward preirradiation levels. Compliance with Practice E 399 requires that fatigue precracking be accomplished in the final heat treatment condition. This may be impractical for irradiated specimens. Fatigue precracking before postirradiation heat treatment is acceptable for low temperature heat treatment typical of reactor vessel annealing. It is believed that heat treatments of ferritic materials below 900°F do not alter the test results and that the fatigue precracked tests represent the bulk material properties as intended.

5.2 *Specimen Irradiation*:

5.2.1 *General*—The recommendations of Practice E 185 concerning the encapsulation of specimens, temperature and neutron fluence monitoring, and irradiation exposure conditions should be followed. The larger size of some supplemental test specimens may require additional consideration of temperature gradients and neutron flux gradients within individual specimens and within the specimen capsules.

5.2.2 *Specimen Irradiation*—Supplemental test specimens may be irradiated in the same capsule as the specimens required by Practice E 185 when supplemental results are desired.

5.3 *Specimen Handling and Remote Test Equipment*:

5.3.1 *General*—For testing in a controlled area or in a hot cell facility, remote devices for accurately positioning the specimen in the test machine are generally required. For notched impact specimens, automatic devices to position the specimen on the test anvil are strongly recommended. Additional remote devices for specimen heating and cooling and for the attachment of measuring fixtures are also necessary. Remote testing equipment shall satisfy the tolerances and accuracy requirements of the applicable ASTM standards for the test method(s) employed.

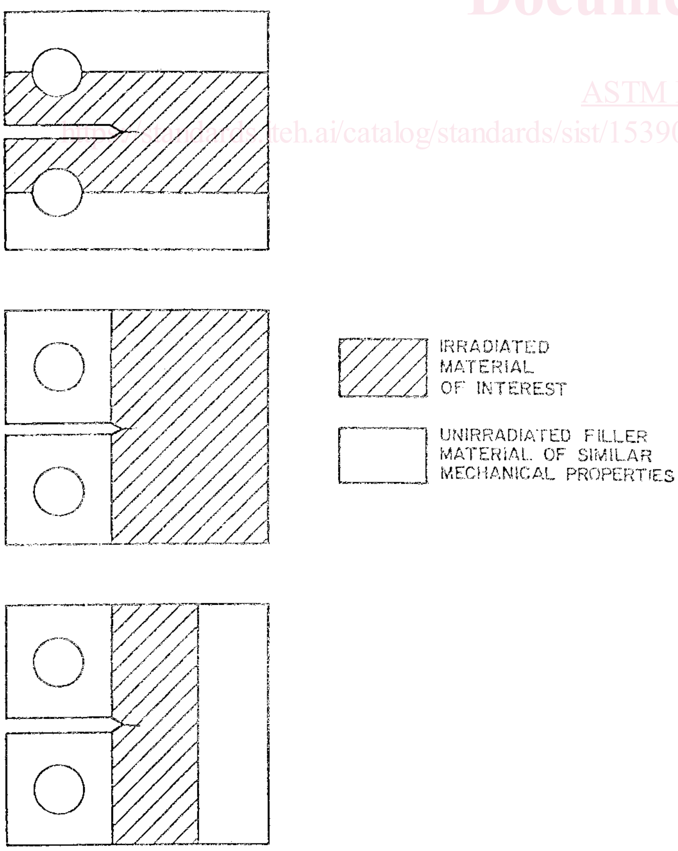

FIG. 2 Various Forms of End-Tab Welded (Compound) Specimens

5.4 *Specimen Testing*—It is recommended that postirradiation Charpy V-notch impact and tensile tests be performed in accordance with Practice E 185 prior to supplemental specimen testing to establish a basis for selecting test temperatures for the supplemental specimens provided under this method.

5.5 *Documentation*:

5.5.1 The report shall include the reporting requirements on material identification and irradiation history required by Practice E 185. Emphasis should be placed on the reporting of tensile properties with compact specimen and precracked charpy impact test results (see 6.1.3.2 and 7.2.1).

5.5.2 Names and models of testing and monitoring equipment, and the accuracy to which they operate, will be reported. Any special modifications (for example, load damping equipment, etc.) to the testing equipment must be indicated. Pertinent testing procedures used also shall be reported.

5.5.3 To aid in the interpretation of these supplemental surveillance results, data developed in accordance with Practice E 185, including data from reference correlation monitor material or data from other supplemental surveillance test methods, should be included in the report or should be referenced suitably.

6. Compact Specimen Test

6.1 *Specimen Design and Possible Modifications*:

6.1.1 *Specimen*—The compact specimen of dimensions outlined in Test Method E 399 or Test Method E 813, allowing for design modification (see 6.1.2) for surveillance capsules, will be used for testing. Other specimen designs including the disk-shaped compact specimen or others described in Ref **(1)**[5] also can be used.

6.1.2 *Possible Design Modification*—Modified specimens are useful when test stock or irradiation space is limited, or when gamma heating or neutron flux gradients must be minimized. An example of a modified specimen design is a compound specimen with welded end-tabs as illustrated in Fig. 2. Specimens have also been modified after irradiation to improve their measuring capabilities. For example, many early PWR reactors contain 1-X WOL size fracture mechanics specimens. These specimens originally were intended for testing in the brittle fracture regimen. For ductile material, bending can occur in the loading arms of these specimens and the tests become invalid. However, techniques have been developed to make these specimens useful for testing under ductile conditions. These include extension of the fatigue precrack length or modification of the specimen dimensions, or both **(2)**. Modified compact specimen designs may be employed for irradiation provided that it is shown in advance that their use will not significantly diminish the accuracy of the test or alter test results.

6.1.2.1 The pinhole spacings recommended in Test Method E 399 and Test Method E 813 are different. However, this difference does not significantly affect the stress field at the crack tip and therefore either pinhole spacing is acceptable for surveillance testing **(3)**.

[5] The boldface numbers in parentheses refer to a list of references at the end of this guide.

6.1.3 *Fatigue Precracking*—Fatigue precracking shall be performed in accordance with either Test Method E 399 or Test Method E 813, as discussed in 6.1.3.1-6.1.3.3.

NOTE 1—Since the referenced standards for fracture toughness testing were designated for upper-shelf fracture toughness evaluations or for high-strength materials, their precracking requirements may be too liberal for testing pressure vessel steels in the transition range. Care should be exercised to ensure that the maximum K value at the finish of precracking is significantly less than the anticipated level of fracture toughness.

6.1.3.1 *Elastic and Elastic-Plastic Fracture Behavior*—When testing is expected to be performed at temperatures where the specimen fractures by cleavage, the crack length-to-width ratio, *a/W*, should range between 0.45 and 0.55, and precracking should be accomplished in accordance with Test Method E 399.

6.1.3.2 *Fully Plastic Behavior*—When testing is expected to be performed in the region characteristic of fully plastic fracture behavior, compliance with Test Method E 813 requires the *a/W* ratio to be equal to or greater than 0.50 and that the specimen thickness, B, and the initial remaining ligament, b_o, be greater than the value of $J/25\ \sigma_{flow}$, where σ_{flow} is the average of the yield strength and the tensile strength of the material at the test temperature.

6.1.3.3 *a/W ratio*—It is noted that *a/W* values between 0.50 and 0.55 will comply with both the requirements of Test Method E 399 for testing elastic fracture behavior (see 6.1.3.1) and Test Methods E 813 and E 1152 for testing elastic-plastic and plastic behavior (see 6.1.3.2).

6.2 *Special Requirements for Surveillance Application*—For a given neutron exposure level, it is recommended that sufficient specimens be provided for establishing fracture toughness properties at temperatures corresponding to elastic, elastic-plastic, and fully plastic (upper shelf) behavior. For a better properties definition when specimen numbers are limited, single tests at multiple temperatures are preferred to duplicate tests at one given temperature.

NOTE 2—If transition temperature data are of primary interest, multiple specimen testing at a single test temperature and appropriate statistical analysis methods should be considered **(4, 5)**.

NOTE 3—The specimens for characterization of elastic fracture behavior need not be of the same thickness as those required for elastic-plastic or fully plastic fracture behavior. See Test Methods E 399 and E 813 for size requirements.

6.2.1 *Tensile Data*—Yield and ultimate tensile strength properties for the material are requirements for the evaluation of fracture toughness test results.

6.2.2 *Postirradiation Preparation of Specimens*:

6.2.2.1 If end-tab welding (compound specimens) is to be performed (see Fig. 2), it must be verified that the temperature in the test region does not reach or exceed the irradiation temperature. Additionally, the procedure should minimize residual stresses that will affect the experimental results. To minimize the temperature in the notch region during welding, electron beam welding (two passes per weld, one on each side of the specimen) and the use of copper chill blocks are recommended. The irradiated material shall be of sufficient size to fully contain the plastic zone developed at maximum load. For information about determining the dimensions of irradiated material see Refs **(6)** and **(7)**. A compound specimen fabrication procedure should not be used unless previously proven to have no significant influence on the fracture toughness test result.

6.2.2.2 If additional fatigue crack extension is performed after irradiation, the conditions outlined in 6.1.3 should be satisfied.

6.2.2.3 Side grooving of specimens, if required, may be performed after irradiation but should be performed following final fatigue crack extension.

6.2.3 *Postirradiation Specimen Testing*—If the recommendations of 6.2 on the sufficiency of test specimens cannot be satisfied, a decision on testing emphasis will have to be made taking into consideration the results of the surveillance program described in Practice E 185 and other available information.

6.2.3.1 *Test Temperature Selection*—If fracture toughness properties in the transition region are of greatest need for measurements and correlations with the radiation-induced Charpy V-notch 41-J temperature shift, tests should be selected to define the temperature for a fracture toughness level (K) of 100 MPa $\sqrt{m}$ (or J-integral equivalent). In general, this fracture toughness level corresponds to current practice for measuring the radiation-induced 41-J temperature shift. If fracture toughness in the upper shelf region is of greatest need, J-integral tests should be performed at temperatures effecting fully plastic fracture behavior in the specimen.

6.2.3.2 *Loading Rates*—Test Method E 399 for plane strain fracture toughness testing defines a static test as one carried out at a stress intensity rate, $\mathring{K}$, between 0.55 and 2.75 MPa $\sqrt{m}$ /s (0.5 and 2.5 ksi $\sqrt{in.}$ /s). Test Method E 813 specifies that specimen loading to 40 % of the estimated maximum load must be completed in 0.1 to 10.0 min in static J_{Ic} tests.

6.3 *Data Development and Computational Procedures*:

6.3.1 *Elastic Behavior*—Test Method E 399 data development methods, computational procedures, and test validity criteria are to be applied for fully elastic test behavior.

6.3.2 *Elastic-Plastic and Plastic Behavior*—The J-integral method or the J-R curve technique, or both, shall be applied as appropriate for the computation of fracture toughness when the material demonstrates elastic-plastic or fully plastic fracture behavior (Test Methods E 813 and E 1152). Although these methods do not apply to the case of cleavage fracture, the J-integral value, J_c, at the onset of cleavage can be calculated and an elastic-plastic estimate of fracture toughness can be calculated from:

$$K_{Jc} = \sqrt{E\,J_c} \tag{1}$$

where:
E = the elastic modulus.

6.4 *Report*:

6.4.1 *Data*—In addition to the reporting requirements of 5.5 and Test Methods E 399, E 813, and E 1152, the following shall be reported: load-deflection curve, specimen type and dimensions, method and location of displacement measurements, test temperature, specimen identification and orientation, measured fatigue precrack crack length, amount of stable ductile tearing, and specimen loading rate (or stress-intensity