Designation: E 185 – 98

Standard Practice for Conducting Surveillance Tests for Light-Water Cooled Nuclear Power Reactor Vessels, E 706 (IF)[1]

This standard is issued under the fixed designation E 185; 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 practice covers procedures for monitoring the radiation-induced changes in the mechanical properties of ferritic materials in the beltline of light-water cooled nuclear power reactor vessels. This practice includes guidelines for designing a minimum surveillance program, selecting materials, and evaluating test results.

1.2 This practice was developed for all light-water cooled nuclear power reactor vessels for which the predicted maximum neutron fluence (E > 1 MeV) at the end of the design lifetime exceeds 1×10^{17} n/cm^2 (1×10^{21} n/m^2) at the inside surface of the reactor vessel.

1.3 This practice does not provide procedures for monitoring the radiation induced changes in properties beyond the design life, but the procedure described may provide guidance for developing such a surveillance program.

2. Referenced Documents

2.1 *ASTM Standards:*

A 370 Test Methods and Definitions for Mechanical Testing of Steel Products[2]

A 751 Test Methods, Practices and Terminology for Chemical Analysis of Steel Products[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 23 Test Methods for Notched Bar Impact Testing of Metallic Materials[3]

E 208 Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels[3]

E 482 Guide for Application of Neutron Transport Methods for Reactor Vessel Surveillance, E 706 (IID)[4]

E 509 Guide for In-Service Annealing of Light-Water Cooled Nuclear Reactor Vessels[4]

E 560 Practice for Extrapolating Reactor Vessel Surveillance Dosimetry Results, E 706 (IC)[4]

E 636 Practice for Conducting Supplemental Surveillance Tests for Nuclear Power Reactor Vessels, E 706 (IH)[4]

E 706 Master Matrix for Light-Water Reactor Pressure Vessel Surveillance Standards, E 706 (O)[4]

E 844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IIC)[4]

E 853 Practice for Analysis and Interpretation of Light-Water Reactor Surveillance Results, E 706 (IA)[4]

E 900 Guide for Predicting Neutron Radiation Damage to Reactor Vessel Materials, E 706 (IIF)[4]

E 1214 Guide for Use of Melt Wire Temperature Monitors for Reactor Vessel Surveillance, E 706 (IIIE)[4]

E 1820 Standard Method for Measurement of Fracture Toughness[3]

E 1921 Test Method for the Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range[3]

2.2 *Other Document:*

American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Sections III and XI[5]

3. Terminology

3.1 *Definitions:*

3.1.1 *adjusted reference temperature (ART)*—the reference temperature adjusted for irradiation effects by adding to the initial RT_{NDT}, the transition temperature shift, and an appropriate margin.

3.1.2 *base metal (parent material)*—as-fabricated plate material or forging material other than a weldment or its corresponding heat-affected zone (HAZ).

3.1.3 *beltline*—the irradiated region of the reactor vessel (shell material including weld seams and plates or forgings) that directly surrounds the effective height of the active core, and adjacent regions that are predicted to experience sufficient neutron damage to warrant consideration in the selection of surveillance material.

3.1.4 *Charpy transition temperature curve*—a graphic presentation of Charpy data, including absorbed energy, lateral expansion, and fracture appearance as functions of test temperature, extending over a range including the lower shelf

---

[1] This practice is under the jurisdiction of ASTM Committee E-10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.02 on Behavior and Use of Structural Materials.

Current edition approved Jan. 10, 1998. Published May 1998. Originally published as E 185 – 61 T. Last previous edition E 185 – 82$^{\epsilon 2}$.

[2] *Annual Book of ASTM Standards*, Vol 01.03.

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

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

[5] Available from the American Society of Automotive Engineers, 345 E. 47th St., New York, NY 10017.

energy (5 % or less), transition region, and the upper-shelf energy (95 % or greater).

3.1.5 *correlation monitor*—any steel that has been characterized as to the sensitivity of its mechanical and fracture toughness properties to neutron radiation embrittlement.

3.1.6 *end-of-life (EOL)*—the design lifetime in terms of years, effective full power years, or neutron fluence.

3.1.7 *fracture strength—in a tensile test*, the load at fracture divided by the initial cross-sectional area of the test specimen.

3.1.8 *fracture stress—in a tensile test*, the load at fracture divided by the cross-sectional area of the test specimen at time of fracture.

3.1.9 *heat-affected zone (HAZ)*—plate material or forging material in which the microstructure of the base metal has been altered by the heat of the welding process, and which extends outward from, but does not include any of, the weld fusion zone.

3.1.10 *index temperature*—that temperature corresponding to a selected level of absorbed energy, lateral expansion, or fracture appearance obtained from the best fit (average) Charpy transition curve.

3.1.11 *lead factor*—the ratio of the neutron fluence rate (E > 1 MeV) of the specimens in a surveillance capsule to the neutron fluence rate (E > 1 MeV) at the reactor pressure vessel inside surface peak fluence.

3.1.12 *margin*—an addition included in the adjusted reference temperature to account for uncertainties in the data.

3.1.13 *nil-ductility transition temperature* (T_{NDT})—the maximum temperature at which a standard drop weight specimen breaks when tested in accordance with Test Method E 208.

3.1.14 *onset of upper-shelf*—the test temperature above which the fracture appearance of all Charpy specimens tested is nominally 100 % shear. Specimens with 5 % or less cleavage may be included in this determination.

3.1.15 *reference temperature* (RT_{NDT})— See subarticle NB-2300 of the ASME Boiler and Pressure Vessel Code, Section III, ′′Nuclear Power Plant Components" for the definition of RT_{NDT} for unirradiated material.

3.1.16 *transition region*—the region on the Charpy transition temperature curve in which toughness increases rapidly with rising temperature; in terms of fracture appearance, it is characterized by a change from a primarily cleavage (crystalline) fracture mode to primarily shear (fibrous) fracture mode.

3.1.17 *transition temperature shift* (ΔRT_{NDT})—the difference in the 30 ft·lbf (40.7 J) index temperatures for the best fit (average) Charpy curve measured before and after irradiation.

3.1.18 *upper-shelf energy level*—the average energy value for all Charpy specimen tests (normally three) whose test temperature is above the onset of upper-shelf behavior; specimens tested at temperature greater than 150°F (83°C) above the onset of upper-shelf need not be included.

3.1.18.1 *Discussion*—The range of test temperatures for which energy values were averaged must be reported as well as the individual energy values. For specimens tested in sets of three at each test temperature, the set having the highest average may be regarded as defining the upper-shelf energy.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 The following definitions are intended for application to this standard and may not be in agreement with definitions of the same parameters given in other standards:

3.2.1.1 *neutron fluence*— the time integrated neutron fluence rate, expressed in neutrons per square meter or neutrons per square centimeter.

3.2.1.2 *neutron fluence rate*—a measure of the intensity of neutron radiation within a given range of neutron energies; the product of the neutron density and velocity, expressed in neutrons per square meter-second or neutrons per square centimeter-second.

3.2.1.3 *neutron spectrum*— the distribution by energy levels of neutrons impinging on a surface, as determined from analysis of multiple neutron dosimeter measurements or from a calculation of the neutron energy distribution.

4. Significance and Use

4.1 Predictions of neutron radiation effects on pressure vessel steels are considered in the design of light-water cooled nuclear power reactors. Changes in system operating parameters are made throughout the service life of the reactor vessel to account for radiation effects. Because of the variability in the behavior of reactor vessel steels, a surveillance program is warranted to monitor changes in the properties of actual vessel materials caused by long-term exposure to the neutron radiation and temperature environment of the given reactor vessel. This practice describes the criteria that should be considered in planning and implementing surveillance test programs and points out precautions that should be taken to ensure that: (*1*) capsule exposures can be related to beltline exposures, (*2*) materials selected for the surveillance program are samples of those materials most likely to limit the operation of the reactor vessel, and (*3*) the tests yield results useful for the evaluation of radiation effects on the reactor vessel.

4.2 The methodology to be used in the analysis and interpretation of neutron exposure data obtained from reactor vessel surveillance programs as defined in Practice E 853 establishes the bases to be used to evaluate both the present and future conditions of the reactor vessel.

4.3 The design of a surveillance program for a given reactor vessel must consider the existing body of data on similar materials in addition to the specific materials used for that reactor vessel. The amount of such data and the similarity of exposure conditions and material characteristics will determine their applicability for predicting the radiation effects. As a large amount of pertinent data becomes available, it may be possible to reduce the surveillance effort for selected reactors by integrating their surveillance programs.

5. Test Materials

5.1 *Materials Selection*:

5.1.1 Surveillance test materials shall be full thickness samples taken from the actual materials used in fabricating the beltline of the reactor vessel. These surveillance test materials shall include a minimum of one heat of the base metal and one butt weld. The base metal and weld metal materials included in the program shall be those predicted to be most limiting with regard to setting pressure-temperature limits for operation of the reactor to compensate for radiation effects during its lifetime. The beltline materials shall be evaluated on the basis of adjusted reference temperature. The predicted changes in the initial properties as a function of chemical composition and the neutron fluence during reactor operation shall be determined in accordance with Guide E 900. The base metal and the weld with the highest adjusted reference temperature at end-of-life shall be selected for the surveillance program. If the Charpy upper-shelf energy of any of the beltline materials is predicted to drop to a marginal level (currently considered to be 50 ft·lb (67.8 J) at the quarter thickness (¼ *T*) location) during the operating lifetime of the vessel, provisions shall be made to also include that material in the surveillance program. It is recommended that the selected material be in the form of fracture toughness specimens (Practice E 636).

5.1.2 The adjusted reference temperature of each material in the reactor vessel beltline shall be determined by adding the value of transition temperature shift to the reference temperature of the unirradiated material plus an appropriate margin. The reference temperature shift and Charpy upper-shelf energy drop can be determined from relationships of fluence and chemical composition. A procedure for making this determination is described in Guide E 900.

5.2 *Material Sampling*—A minimum test program shall consist of the material selected in 5.1, taken from the following locations: (*1*) base metal from one plate or forging used in the beltline, and (*2*) weld metal made with the same heat of weld wire and lot of flux and by the same welding procedure as that used for the selected beltline weld. The base metal used to fabricate the weldment shall be one of the base metals included in the surveillance program.

NOTE 1—Experience has shown that it is no longer necessary to include the weld heat-affected zone material in the surveillance program. However, it is recommended that the heat-affected-zone material be included with the archives (see 5.3) and that the material qualification test results be evaluated for anomalous or unusual results, for example, from new or unique fabrication procedures that may yield degraded heat-affected-zone properties.

5.3 *Archive Materials*—Sufficient test stock to fill at least two additional capsules with test specimens of the base metal and weld materials used in the program shall be retained with full documentation and identification. This test stock should be in the form of full-thickness sections of the original materials (plates, forgings, and welds). It is recommended that the designated heat-affected-zone materials be retained to provide supplemental data.

5.4 *Fabrication History*—The fabrication history (austenitizing, quench and tempering, and post-weld heat treatment) of the test materials shall be fully representative of the fabrication history of the materials in the beltline of the reactor vessel and shall be recorded.

5.5 *Chemical Analysis Requirements*—The chemical analysis required by the appropriate product specifications for the surveillance test materials (base metal and as-deposited weld metal) shall be recorded and shall include phosphorus (P), sulfur (S), copper (Cu), vanadium (V), and nickel (Ni), as well as all other alloying and residual elements commonly analyzed for in low-alloy steel products. The product analysis shall be as described in Test Methods, Practices and Terminology A 751 and verified by analyzing a minimum of three samples randomly selected from both the base metal and the as-deposited weld metal.

6. Test Specimens

6.1 *Type of Specimens*—Charpy V-notch specimens corresponding to the Type A specimen described in Test Methods A 370 and E 23 shall be used. The gage section of irradiated and unirradiated tension specimens shall be of the same size and shape. Tension specimens of the type, size, and shape described in Test Methods A 370 and E 8 are recommended. Additional fracture toughness test specimens shall be employed to supplement the information from the Charpy V-notch specimens if the surveillance materials are predicted to exhibit marginal properties (see Practice E 636).

6.2 *Specimen Orientation and Location*—Tension and Charpy specimens representing the base metal shall be removed from about the quarter-thickness (¼ *T*) locations. Material from the mid-thickness of the plates shall not be used for test specimens. Specimens representing weld metal may be removed from any location throughout the thickness with the exception of locations within 12.7 mm (½ in.) of the root or surfaces of the welds. Special attention must be given to defining the root of the weld in order to avoid taking weld metal that is different in composition from the surveillance weld metal. The tension and Charpy specimens from base metal shall be oriented so that the major axis of the specimen is parallel to the surface and normal to the principal rolling direction for plates, or normal to the major working direction for forgings as described in Section III of the ASME Code. The axis of the notch of the Charpy specimen for base metal and weld metal shall be oriented perpendicular to the surface of the material. The recommended orientation of the weld metal specimens is shown in Fig. 1. Weld metal tension specimens may be oriented in the same direction as the Charpy specimens provided that the gage length consists entirely of weld metal.

6.3 *Quantities of Specimens*:

6.3.1 *Unirradiated Baseline Specimens*—It is recommended that 18 Charpy specimens be provided, of which a minimum of 15 specimens shall be tested to establish a full transition temperature and upper-shelf curve for each material (base metal, weld metal, and correlation monitor material). The three remaining Charpy specimens should be reserved to provide supplemental data for conditions such as excessive data scatter. It is recommended that at least six tension test specimens shall be provided to establish the unirradiated tensile properties for both the base metal and the weld metal. A minimum of two specimens should be tested at room temperature and at reactor vessel beltline operating temperature. The remainder of the specimens may be tested at intermediate temperatures as needed to define the effects of temperature on the tensile properties.

6.3.2 *Irradiated Specimens*—The minimum number of test specimens for each irradiation exposure set (capsule) shall be as follows:

Material	Charpy	Tension
Base Metal	12	3
Weld Metal	12	3
Correlation Monitor	12	0

It is suggested that a greater quantity of the above specimens

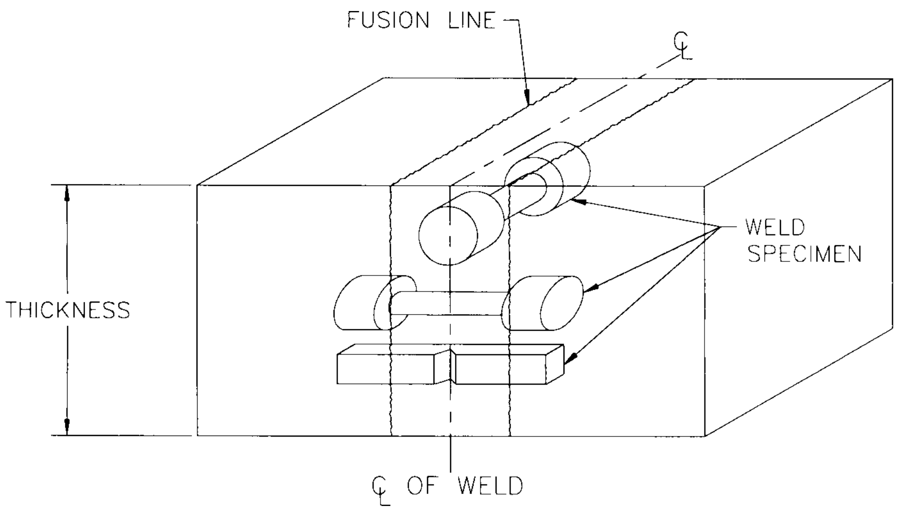

FIG. 1 Location of Test Specimens Within Weld Test Material

be included in the irradiation capsules whenever possible.

7. Irradiation Requirements

7.1 *Encapsulation of Specimens*—Specimens should be maintained in an inert environment within a corrosion-resistant capsule to prevent deterioration of the surface of the specimens during radiation exposure. Care should be exercised in the design of the capsule to ensure that the temperature history of the specimens duplicates, as closely as possible, the temperature experienced by the reactor vessel. Surveillance capsules should be sufficiently rigid to prevent mechanical damage to the specimens and monitors during irradiation. The design of the capsule and capsule attachments shall also permit insertion of replacement capsules into the reactor vessel if required at a later time in the lifetime of the vessel. The design of the capsule holder and the means of attachment shall (*1*) preclude structural material degradation by the attachment welds, (*2*) avoid interference with in-service inspection required by ASME Code Section XI, and (*3*) ensure the integrity of the capsule holder during the service life of the reactor vessel.

7.2 *Location of Capsules*:

7.2.1 *Vessel Wall Capsules (Required)*—Surveillance capsules shall be located within the reactor vessel so that the specimen irradiation history duplicates as closely as possible, within the physical constraints of the system, the neutron spectrum, temperature history, and maximum neutron fluence experienced by the reactor vessel. It is recommended that the surveillance capsule lead factors be no greater than five. The lead factors shall be selected to reduce the calculational uncertainties in extrapolating the surveillance measurements from the specimens to the reactor vessel wall and maximize the ability of the program to monitor material property changes throughout the life of the reactor vessel. The design of the internals of some reactor vessels may not allow the positioning of surveillance capsules in low fluence locations. Plants with lead factors greater than five should provide for a method of verifying the validity of the data. This may be accomplished by the inclusion of one of the correlation monitor materials (see 7.4) or a similarly characterized material. It should be recognized that during the service life of the reactor vessel the lead factors for individual capsules may change as a result of changes in fuel management.

7.2.2 *Accelerated Irradiation Capsules (Optional)*—Additional test specimens may be positioned at locations closer to the core than those described in 7.2.1 for accelerated irradiation.

7.3 *Neutron Dosimeters*:

7.3.1 *Selection of Neutron Dosimeters*—Neutron dosimeters for the surveillance capsules shall be selected in accordance with Guides E 482 and E 844. The group of dosimeters selected shall be capable of providing information about fast neutron fluence, fluence rate, energy spectrum, thermal neutron fluence and fluence rate information (see 8.2.3), displacements per atom (dpa), and dpa rate in iron.

7.3.2 *Location of Neutron Dosimeters*—Dosimeters shall be located within each vessel wall capsule (see 7.2.1) and each accelerated capsule (see 7.2.2) if used.

7.3.3 Separate dosimeter capsules should also be used to monitor radiation conditions independent of the specimen capsules if it is expected that the withdrawal schedule will otherwise result in a delay in obtaining timely fluence data.

7.4 *Correlation Monitors*:

7.4.1 *Credibility of Surveillance Data*—Correlation monitors[6] provide an independent check on the measurement of irradiation conditions for the surveillance materials. A criterion for the credibility of surveillance data is that the transition temperature shift data for the correlation monitor material in the capsule should fall within the scatter band for the data base for the material.[7]

7.4.2 *Selection of Correlation Monitor Materials*—Correlation monitor materials should be well characterized in

[6] Information regarding the availability of correlation monitors can be obtained from ASTM Committee E-10. See also ASTM DS54, July 1974.

[7] Stallmann, F. W., *Analysis of the A302B and A533B Standard Reference Materials in Surveillance Capsules of Commercial Power Reactors*, NUREG/CR-4947, ORNL, Oak Ridge, TN, January 1988; and Wallin, K., Valo, M. J., Rintamaa, R., Torronen, K., and Ahlstrand, R., "Characteristics of the IAEAA Correlation Monitor Material for Surveillance Programs," *Radiation Embrittlement and Surveillance of Nuclear Reactor Pressure Vessel Steels: An International Review, Third Volume*, ASTM STP 1011, L. E. Steele, ed., February 1989, p. 91.