Designation: E185 – 02

Standard Practice for
Design of Surveillance Programs for Light-Water Moderated Nuclear Power Reactor Vessels[1]

This standard is issued under the fixed designation E185; 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 designing a surveillance program for monitoring the radiation-induced changes in the mechanical properties of ferritic materials in the beltline of light-water moderated nuclear power reactor vessels. This practice includes the minimum requirements for the design of a surveillance program, selection of vessel material to be included, and a schedule for evaluation of materials.

1.2 This practice was developed for all light-water moderated nuclear power reactor vessels for which the predicted maximum fast neutron fluence ($E > 1$ MeV) at the end of the design lifetime (EOL) 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 applies only to the planning and design of surveillance programs for reactor vessels designed and built after the effective date of this practice. Previous versions of Practice E185 apply to earlier reactor vessels.

1.4 This practice does not provide specific 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.

NOTE 1—The increased complexity of the requirements for a light-water moderated nuclear power reactor vessel surveillance program has necessitated the separation of the requirements into three related standards. Practice E185 describes the minimum requirements for a surveillance program. Practice E2215, "Standard Practice for the Evaluation of Surveillance Capsules from Light-Water Moderated Nuclear Power Reactor Vessels" describes the procedures for testing and evaluation of surveillance capsules removed from a surveillance program as defined in the current or previous editions of Practice E185. Another standard guide for supplementing existing light-water moderated nuclear power reactor vessel surveillance programs is under preparation. A summary of the many major revisions to Practice E185 since its original issuance is contained in Appendix X1.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A370 Test Methods and Definitions for Mechanical Testing of Steel Products

A751 Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products

E8 Test Methods for Tension Testing of Metallic Materials

E21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials

E23 Test Methods for Notched Bar Impact Testing of Metallic Materials

E170 Terminology Relating to Radiation Measurements and Dosimetry

E208 Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels

E399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials

E482 Guide for Application of Neutron Transport Methods for Reactor Vessel Surveillance, E706 (IID)

E560 Practice for Extrapolating Reactor Vessel Surveillance Dosimetry Results, E 706(IC)[3]

E636 Guide for Conducting Supplemental Surveillance Tests for Nuclear Power Reactor Vessels, E 706 (IH)

E693 Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements Per Atom (DPA), E 706(ID)

E844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706(IIC)

E853 Practice for Analysis and Interpretation of Light-Water Reactor Surveillance Results, E706(IA)

E900 Guide for Predicting Radiation-Induced Transition

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

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

Temperature Shift in Reactor Vessel Materials, E706 (IIF)
E1214 Guide for Use of Melt Wire Temperature Monitors for Reactor Vessel Surveillance, E 706 (IIIE)
E1253 Guide for Reconstitution of Irradiated Charpy-Sized Specimens
E1820 Test Method for Measurement of Fracture Toughness
E1921 Test Method for Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range
E2215 Practice for Evaluation of Surveillance Capsules from Light-Water Moderated Nuclear Power Reactor Vessels

2.2 *Other Documents:*

American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Sections III and XI [4]

ASME Boiler and Pressure Vessel Code Case N-629, Use of Fracture Toughness Test Data to Establish Reference Temperature for Pressure Retaining Materials, Section XI, Division 1[4]

ASME Boiler and Pressure Vessel Code Case N-631, Use of Fracture Toughness Test Data to Establish Reference Temperature for Pressure Retaining Materials Other Than Bolting for Class 1 Vessels, Section III, Division 1[4]

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 (for example, see Guide E900), and an appropriate margin to account for uncertainties.

3.1.2 *base metal (parent material)*—as-fabricated plate material or forging material other than a weld 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 sustain sufficient neutron damage to warrant consideration in the selection of surveillance material.

3.1.4 *Charpy transition region*—the region on the Charpy transition 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 a primarily shear (fibrous) fracture mode.

3.1.5 *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 energy (5 % or less shear fracture appearance), transition region, and the upper-shelf energy (95 % or greater shear fracture appearance).

3.1.6 *Charpy transition temperature shift*—the difference in the 30 ft-lbf (41J) index temperatures for the best fit (average) Charpy curve measured before and after irradiation.

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

3.1.8 *Charpy upper shelf onset*—the test temperature above which the fracture appearance of all Charpy specimens tested is nominally 100 % shear. Specimens with 95 % or greater shear may be included in this determination.

3.1.9 *end-of-life (EOL)*—the design lifetime in terms of years corresponding to the operating license period.

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

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

3.1.12 *heat-affected-zone (HAZ)*—plate material or forging material extending outward from, but not including, the weld fusion line in which the microstructure of the base metal has been altered by the heat of the welding process.

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

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

NOTE 2—Changes in the reactor operating parameters and fuel management may cause the lead factor to change.

3.1.15 *nil-ductility transition temperature (T_{NDT})*—the maximum temperature at which a standard drop weight specimen breaks when tested in accordance with Test Method E208.

3.1.16 *reference material*—any steel that has been characterized as to the sensitivity of its mechanical and fracture toughness properties to neutron radiation embrittlement.

3.1.17 *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. ASME Code Cases N-629 and N-631 provide an alternative definition for the reference temperature (RT_{To}).

3.2 *Neutron Exposure Terminology:*

3.2.1 Definitions of terms related to neutron dosimetry and exposure are provided in Terminology E170.

4. Significance and Use

4.1 Predictions of neutron radiation effects on pressure vessel steels are considered in the design of light-water

[4] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Three Park Ave., New York, NY 10016-5990, http://www.asme.org.

moderated nuclear power reactors. Changes in system operating parameters often are made throughout the service life of the reactor vessel to account for radiation effects. Due to 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 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 estimation of neutron exposure obtained for reactor vessel surveillance programs is defined in Guide E482, which establishes the bases to be used to evaluate both the design and future condition 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 radiation effects.

5. Surveillance Program Design

5.1 This section describes the minimum requirements for the design of a surveillance program for monitoring the radiation-induced changes in the mechanical properties of ferritic materials in the reactor vessel beltline region.

5.2 *Test Materials*

5.2.1 *Materials Selection*:

5.2.1.1 Surveillance test materials shall be full thickness samples taken from each of the actual materials used in fabricating the beltline of the reactor vessel or from weldments fabricated to match the reactor vessel weld(s). These surveillance test materials shall include a minimum of one heat of the base metal and one weld.

NOTE 3—If there is no weld in the beltline, then there is no requirement to include weld material in the surveillance program. However, it may be prudent to include the weld with the highest projected EOL ΔRT_{NDT} value.

5.2.1.2 The base metal and weld metal materials included in the program shall be those predicted to be most limiting 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 E900. The base metal and the weld with the highest adjusted reference temperature at end-of-life shall be selected for the surveillance program.

5.2.1.3 The adjusted reference temperature of each material in the reactor vessel beltline shall be determined by adding the appropriate value of transition temperature shift to the reference temperature of the unirradiated material plus an appropriate margin. The reference temperature shift can be determined from the relationship found in Guide E900.

5.2.2 *Material Sampling*—A minimum test program shall consist of the material selected in 5.2.1, taken from the following locations: (*1*) base metal from each plate or forging used in the beltline, and (*2*) each weld metal made with the same heat of weld wire and lot of flux and by the same welding procedure as that used for each of the beltline welds. The base metal used to fabricate the weldment shall be one of the base metals included in the surveillance program.

NOTE 4—Experience has shown that it is no longer necessary to include the heat-affected zone material in the surveillance program. However, it is recommended that the heat-affected-zone material be included with the archives (see 5.2.5).

5.2.3 *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.

5.2.4 *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), silicon (Si), manganese (Mn), 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 Method A751 and verified by analyzing samples selected from the base metal and the as-deposited weld metal.

5.2.5 *Archive Materials*—Test stock to fill up to six 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 stock should be in the form of full-thickness sections of the original materials (plates, forgings, and welds). It is recommended that the heat-affected-zone material associated with the archive weld material be retained to provide supplemental data.

5.3 *Test Specimens*

5.3.1 *Type of Specimens*—Charpy V-notch specimens corresponding to the Type A specimen described in Test Methods A370 and E23 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 A370 and E8 are recommended. Fracture toughness test specimens shall be consistent with the guidelines provided in Test Methods E1820 and E1921.

5.3.2 *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 base metal 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.

5.4 *Quantities of Specimens*

5.4.1 *Unirradiated Baseline Specimens*—It is recommended that a minimum of 15 Charpy specimens shall be tested to establish a full transition temperature and upper- shelf curve for each material. It is recommended that at least six tension test specimens be provided to establish the unirradiated tensile properties for both the base metal and the weld metal. A minimum of two specimens at room temperature and two specimens at reactor vessel beltline operating temperature should be tested. The remainder of the specimens may be tested at intermediate temperatures as needed to define the effects of temperature on the tensile properties. It is recommended that a minimum of 8 fracture toughness specimens be tested to establish the reference temperature, T_o, per Test Method E1921 for the limiting beltline material and/or other fracture toughness tests be performed following Test Method E1820.

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

Material	Charpy	Tension	Fracture Toughness
Each Base Metal	15	3	8^A
Each Weld Metal (if required)	15	3	8^A

^{A} Only fracture toughness specimens from the limiting material are required. It is suggested that a greater quantity of specimens be included in the irradiation capsules whenever possible.

5.5 *Irradiation Requirements*

5.5.1 *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 matches, 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 at 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.

5.5.2 *Location of Capsules*:

5.5.2.1 *Vessel 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 (see 3.1.14) be greater than one and less than or equal to three. This range of lead factors has been selected to minimize the calculational uncertainties in extrapolating the surveillance measurements from the specimens to the reactor vessel wall and to optimize the ability of the program to monitor material property changes throughout the life of the reactor vessel. 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.

5.5.2.2 *Accelerated Irradiation Capsules (Optional)*—The design of some reactor vessel or core internals may not allow the positioning of all surveillance capsules in low lead factor locations. Additional test specimens may be positioned at locations closer to the core than those described in 5.5.2.1 for accelerated irradiation. Plants with lead factors greater than five should provide a method of verifying the validity of the accelerated irradiation data. This verification may be accomplished by the inclusion of a reference material (see 5.6).

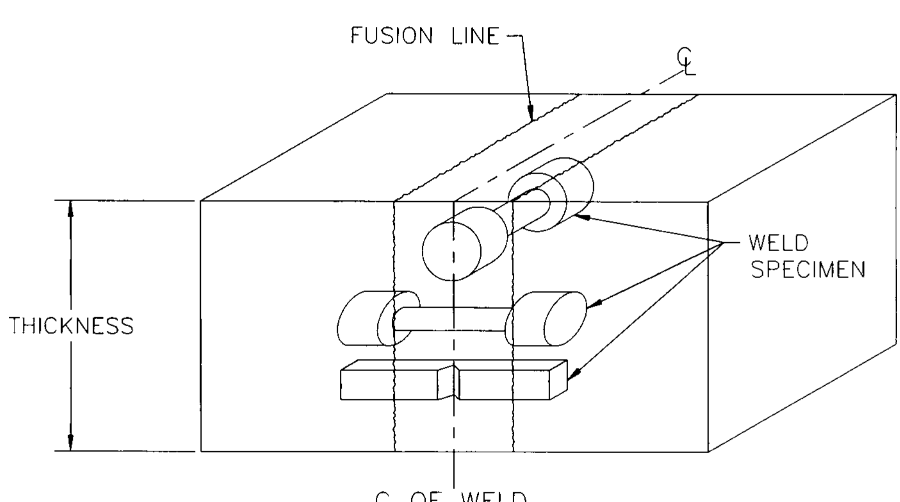

FIG. 1 Location of Test Specimens Within Weld Material