



Standard Practice for Evaluation of Surveillance Capsules from Light-Water Moderated Nuclear Power Reactor Vessels¹

This standard is issued under the fixed designation E2215; 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 the evaluation of test specimens and dosimetry from light water moderated nuclear power reactor pressure vessel surveillance capsules.

1.2 This practice is one of a series of standard practices that outline the surveillance program required for nuclear reactor pressure vessels. The surveillance program monitors the radiation-induced changes in the ferritic steels that comprise the beltline of a light-water moderated nuclear reactor pressure vessel.

1.3 This practice along with its companion surveillance program practice, Practice E185, is intended for application in monitoring the properties of beltline materials in any light-water moderated nuclear reactor.²

1.4 Modifications to the standard test program and supplemental tests are described in Guide E636.

1.5 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

2. Referenced Documents

2.1 ASTM Standards:³

A370 Test Methods and Definitions for Mechanical Testing of Steel Products

E8/E8M 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

E185 Practice for Design of Surveillance Programs for Light-Water Moderated Nuclear Power Reactor Vessels

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

E509 Guide for In-Service Annealing of Light-Water Moderated Nuclear Reactor Vessels

E560 Practice for Extrapolating Reactor Vessel Surveillance Dosimetry Results, E 706(IC)⁴

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

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

E900 Guide for Predicting Radiation-Induced Transition 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

2.2 ASME Standards:⁵

American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Sections III and XI⁵

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

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

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 Nuclear Structural Materials.

Current edition approved March 1, 2010. Published April 2010. Originally approved in 2002. Last previous edition approved in 2002 as E2215–02. DOI: 10.1520/E2215-10.

² Prior to the adoption of these standard practices, surveillance capsule testing requirements were only contained in Practice E185.

³ 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.

⁴ Withdrawn. The last approved version of this historical standard is referenced on www.astm.org.

⁵ Available from American Society of Mechanical Engineers, Third Park Avenue, New York, NY 10016.

3. Terminology

3.1 Definitions:

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

3.1.2 *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. Note that materials in regions adjacent to the beltline may sustain sufficient neutron damage to warrant consideration in the selection of surveillance materials.

3.1.3 *Charpy transition temperature curve*—a graphic or curve-fitted, or both, presentation of absorbed energy, lateral expansion, or fracture appearance as a function of test temperature, extending over a range including the lower shelf (5 % or less shear fracture appearance), transition region, and the upper shelf (95 % or greater shear fracture appearance).

3.1.4 *Charpy transition temperature shift*—the difference in the 40.7 J (30 ft-lbf) index temperatures for the best fit (average) Charpy absorbed energy curve measured before and after irradiation.

3.1.5 *Charpy upper-shelf energy level*—the average energy value for all Charpy specimen tests (preferably three or more) whose test temperature is at or above the Charpy upper-shelf onset; specimens tested at temperatures greater than 83°C (150°F) above the Charpy upper-shelf onset shall not be included, unless no data are available between the onset temperature and onset +83°C (+150°F).

3.1.6 *Charpy upper-shelf onset*—the test temperature above which the fracture appearance of all Charpy specimens tested is at or above 95 % shear.

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

3.1.8 *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.

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

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

3.1.10.1 *Discussion*—Changes in the reactor operating parameters and fuel management may cause the lead factor to change.

3.1.11 *limiting materials*—the weld and base material with the highest predicted transition temperature at EOL determined by adding the appropriate transition temperature shift to the unirradiated RT_{NDT} . The reference temperature shift can be determined from the relationship found in Guide E900. The basis for selecting the limiting material shall be documented.

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

3.1.13 *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 based on Charpy (Test Method E23) and drop weight tests (Test Method E208). ASME Code Cases N-629 and N-631 provide an alternative definition for the reference temperature (RT_{To}) based on fracture toughness properties (Test Method E1921).

3.1.14 *standby capsule*—a surveillance capsule meeting the recommendations of this practice that is in the reactor vessel irradiation location, but whose withdrawal is not required by this practice.

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 Neutron radiation effects are considered in the design of light-water moderated nuclear power reactors. Changes in system operating parameters may be made throughout the service life of the reactor to account for these effects. A surveillance program is used to measure changes in the properties of actual vessel materials due to the irradiation environment. This practice describes the criteria that should be considered in evaluating surveillance program test capsules.

4.2 Prior to the first issue date of this standard, the design of surveillance programs and the testing of surveillance capsules were both covered in a single standard, Practice E185. Between its provisional adoption in 1961 and its replacement linked to this standard, Practice E185 was revised many times (1966, 1970, 1973, 1979, 1982, 1993 and 1998). Therefore, capsules from surveillance programs that were designed and implemented under early versions of the standard were often tested after substantial changes to the standard had been adopted. For clarity, the standard practice for surveillance programs has been divided into the new Practice E185 that covers the design of new surveillance programs and this standard practice that covers the testing and evaluation of surveillance capsules. Modifications to the standard test program and supplemental tests are described in Guide E636.

4.3 This standard practice is intended to cover testing and evaluation of all light-water moderated reactor pressure vessel surveillance capsules. The practice is applicable to testing of capsules from surveillance programs designed and implemented under all previous versions of Practice E185.

4.4 The radiation-induced changes in the properties of the vessel are generally monitored by measuring the Charpy index temperatures, the Charpy upper-shelf energy and the tensile properties of specimens from the surveillance program capsules. The significance of these radiation-induced changes is described in Practice E185. The application of this data is the subject of Guide E900 and other documents listed in Section 2.

4.5 Alternative methods exist for testing surveillance capsule materials. Some supplemental and alternative testing methods are available as indicated in Guide E636. Direct measurement of the fracture toughness is also feasible using the T_o Reference Temperature method defined in Test Method E1921 or J-integral techniques defined in Test Method E1820. Additionally, hardness testing can be used to supplement

standard methods as a means of monitoring the radiation response of the materials.

4.6 The methodology to be used in the analysis and interpretation of neutron dosimetry data and the determination of neutron fluence is defined in Practice E853.

4.7 Guide E900 describes the bases used to evaluate the radiation-induced changes in Charpy transition temperature for reactor vessel materials and provides a methodology for predicting future values.

4.8 Guide E509 provides direction for development of a procedure for conducting an in-service thermal anneal of a light-water cooled nuclear reactor vessel and demonstrating the effectiveness of the procedure including a post-annealing vessel radiation surveillance program.

5. Determination of Capsule Condition

5.1 *Visual Examination*—A complete visual exam of the capsule condition should be completed upon receipt and during disassembly at the testing laboratory. External identification marks on the capsule shall be verified. Signs of damage or degradation of the capsule exterior shall be recorded.

5.2 *Capsule Content*—The specimen loading pattern should be compared to the capsule fabrication records and any deviations shall be noted. Any evidence of corrosion or other damage to the specimens shall also be noted. The condition of any thermal monitors shall be noted and recorded.

5.3 *Irradiation Temperature History*—The average capsule temperature during full power operation shall be estimated for each reactor fuel cycle prior to capsule removal. The local reactor coolant temperature may be used as a reasonable approximation. In a typical pressurized water reactor, the coolant inlet temperature may be used as an estimate of the capsule irradiation temperature using a time-weighted average (see Guide E900). In a typical boiling water reactor, the recirculation temperature may be used as an estimate of the capsule irradiation temperature.

5.4 *Peak Temperature*—Temperature monitors shall be examined and any evidence of melting shall be recorded in accordance with Guide E1214.

6. Measurement of Irradiation Exposure

6.1 The power history of the reactor for all cycles prior to capsule removal shall be recorded. Vessel dimensional information and capsule locations shall be provided for the evaluation of irradiation exposure.

6.2 The neutron fluence rate, neutron energy spectrum and neutron fluence of the surveillance specimens and the corresponding maximum values for the reactor vessel shall be determined in accordance with Practices E853 and E560.

6.3 Neutron fluence rate and fluence values ($E > 1$ MeV) and dpa rate and dpa values shall be determined and recorded using a calculated spectrum adjusted or validated by dosimetry measurements.

7. Measurement of Mechanical Properties

7.1 Tension Tests:

7.1.1 *Method*—Tension testing shall be conducted in accordance with Test Methods E8/E8M and E21.

7.1.2 *Test Temperature*—In general, the test temperatures for each material shall include room temperature, service temperature, and, if a specimen is available, one intermediate temperature to define the strength versus temperature relationship. Specific consideration should be given to the specific temperatures at which unirradiated specimens have been tested.

7.1.3 *Measurements*—Determine yield strength, tensile strength, total and uniform elongation and reduction of area.

7.2 Charpy Tests:

7.2.1 *Method*—Charpy tests shall be conducted in accordance with Test Methods and Definitions A370 and Test Method E23. Instrumented tests are recommended and should be performed in accordance with Guide E636. Broken Charpy specimens may be reconstituted for supplemental testing in accordance with Guide E1253.

7.2.2 *Test Temperature*—Specimens for each material shall be tested at temperatures selected to define the full energy transition curve. Particular emphasis should be placed on defining the 40.7 J (30 ft-lbf) index temperature and the upper-shelf energy level. It is recommended that upper-shelf Charpy tests be conducted using at least three specimens tested and evaluated in accordance with 3.1.5 of this practice. Instrumented tests are recommended and should be performed in accordance with Guide E636.

7.2.3 *Measurements*—For each test specimen, measure the impact energy, lateral expansion, and percent shear fracture appearance.

7.3 *Hardness Tests (Optional)*—Hardness tests may be performed on irradiated Charpy specimens. The measurements shall be taken (prior to Charpy testing, if possible, to avoid sampling material deformed by the test) in areas away from the fracture zone or the edges of the specimens. The tests shall be conducted in accordance with Test Methods and Definitions A370.

7.4 Fracture Toughness Tests (Optional):

7.4.1 *Specimens*—Supplemental fracture toughness tests may be conducted following Guide E636 using either fracture mechanics specimens from the surveillance capsule or broken Charpy specimens that have been reconstituted. Procedures for reconstitution of Charpy specimens are given in Guide E1253.

7.4.2 *Upper-Shelf Fracture Toughness*—Testing to characterize upper-shelf toughness using the J-integral method should be conducted in accordance with Test Method E1820.

7.4.3 *Transition Fracture Toughness*—The reference temperature for ferritic steels in the transition range, T_o , can be established using the methodology provided in Test Method E1921.

7.5 *Retention of Broken Test Specimens*—It is recommended that all broken test specimens be maintained in good condition and retained in the event that additional analysis is required to explain anomalous results. Identification of broken test specimens should be maintained. Final disposition of specimens should only be performed after a thorough evaluation of the potential usefulness of the specimen materials. These specimens can provide materials that are useful for supporting reactor vessel license renewal or for verification of annealing.

8. Evaluation of Test Data

8.1 Tension Tests:

8.1.1 Determine the amount of radiation strengthening and loss of ductility by comparing irradiated test results with unirradiated data from the surveillance capsule documentation package.

8.2 Charpy Tests:

8.2.1 *Curve Fitting*—Average curves shall be drawn through the Charpy data to describe the Charpy impact energy, lateral expansion and percent shear fracture appearance as a function of the test temperature. A similar analysis of unirradiated Charpy data from the surveillance capsule documentation should also be performed. The preferred method for determining the average curves is statistical fitting to a hyperbolic tangent function.⁶

8.2.2 Occasionally a single data point will unduly influence the average curve. In this case, the test record and specimen should be examined for possible causes of discrepancy and its disposition documented.

8.2.3 *Index Temperatures*—Charpy index temperatures shall be determined for the 40.7 J (30 ft-lbf) energy level and 0.89 mm (35 mils) lateral expansion level. Optionally, the fracture appearance transition temperature corresponding to 50 % shear fracture can be determined. Radiation-induced shifts in the index temperatures shall be determined by comparing the measured values to values obtained from the analysis of the unirradiated data.

8.2.4 *Upper=Shelf Energy*—The Charpy upper-shelf energy should be determined according to the definition given in 3.1.5. The radiation-induced change in the upper-shelf energy shall be determined by comparing this data to unirradiated data from the surveillance capsule documentation.

8.3 *Reference Material*—If reference material specimens are included in the surveillance capsule, they shall be tested and evaluated. The measured irradiation response of the reference material specimens should fall within the scatter band of the pre-existing database.⁷ In cases where the reference material test results exhibit excessive scatter relative to the available data, the source of the scatter should be investigated. Potential reasons that can be investigated include deviations from the expected surveillance capsule exposure conditions, a lack of uniformity of properties in the reference material itself, or both.

8.4 *Hardness Tests (Optional)*—The hardness data may be correlated to the yield or tensile strength of the material. Justification for any correlation used shall be provided with the report.

8.5 Fracture Toughness Tests (Optional):

8.5.1 *Upper-Shelf Fracture Toughness*—The resistance to crack initiation and extension on the upper shelf may be expressed in terms of the J-integral as described in Test Method E1820.

8.5.2 *Transition Fracture Toughness*—An appropriate reference temperature for fracture toughness in the transition region can be determined using the procedure in Test Method E1921. This reference transition temperature can be used to define an alternate reference temperature (RT_{To} in place of RT_{NDT}) as defined in ASME Code Cases N-629 and N-631.

9. Withdrawal Schedule Review

9.1 The primary consideration in the review of the withdrawal schedule shall be assuring that the vessel is appropriately monitored throughout its projected life. This should include a review of the original objectives of the surveillance program and the adequacy of the program to meet future needs. This practice provides guidelines to aid in that analysis. The circumstances of any particular reactor surveillance program may require considerations of factors beyond these guidelines.

9.2 The withdrawal schedule shall be reviewed upon completion of testing of each of the surveillance capsules. Proposed adaptations must accommodate the restrictions imposed by the design of the original surveillance program. The number and contents of the capsules included in a reactor vessel surveillance program will vary depending on the prevailing practice at the time the program was designed and the original perception of the radiation sensitivity of the vessel materials.

9.3 The withdrawal schedule is stated in terms of the end-of-license (EOL) fluences at the peak location on the vessel inner wall. Actual numbers will be determined by the effective capsule lead factors.

9.4 The withdrawal schedule from the companion version of Practice E185 is provided in Table 1.

9.4.1 The first step in the review of Table 1 is to update the estimated peak EOL vessel inside surface fluence (EOL ID) based on new dosimetry and current operating plans. These revised projections should be compared to the original basis.

9.4.2 The second step in the review of Table 1 is to update the projected transition temperature shift (ΔRT_{NDT}) for the most limiting vessel material based on any new material specific information or planned fuel management or other operation changes. ΔRT_{NDT} may be estimated using the equations provided in Guide E900. These revised projections should be compared to the original basis.

9.4.3 If a reactor vessel material is projected to exceed an EOL transition temperature shift (ΔRT_{NDT}) of 111°C (200°F), then a capsule with a target fluence of ½ peak EOL shall be withdrawn and tested. All plants for which the surveillance program was designed to Practice E185-09 are required to withdraw and test capsules at ¼ peak EOL, ¾ peak EOL and peak EOL target fluence.

TABLE 1 Suggested Withdrawal Schedule

Sequence	Target Fluence	Notes
First	¼ EOL ID	Testing Required
Second	½ EOL ID	Testing Required if projected $\Delta RT_{NDT} > 111^\circ\text{C}$ (200°F)
Third	¾ EOL ID	Testing Required
Fourth	EOL ID	Testing Required
Standby	< 2 EOL ID	Testing Not Required

⁶ Mager, T. R., Server, W. L., and Beaudoin, B. F., "Use of the Hyperbolic Tangent Function for Fitting Transition Temperature Toughness Data," WCAP-14370, Westinghouse Electric Corporation, May 1995.

⁷ See for example: ASTM DS54, July, 1974; NUREG/CR-4947 on HSST plates; and IAEA-TECDOC-1230, July, 2001, on the JRQ plate.

9.4.4 Capsules not required by the surveillance withdrawal schedule may be used to provide supplemental data. Supplemental testing may be required for plant license renewal or reactor vessel annealing programs following Guide E509. However, it is recommended that capsule fluence not exceed 2 times peak EOL. Supplemental testing may also be based on reconstitution of previously tested specimens following Guide E1253.

9.4.5 The schedule for capsule withdrawals is approximate and may be adjusted to coincide with a planned refueling outage.

10. Report

10.1 *Surveillance Program Description*—Descriptions of the surveillance capsule and materials should be included with the documentation of the original surveillance program. The surveillance capsule report should reference the original documentation and provide any relevant supplementary material.

10.2 The report shall contain the following information and shall consist of the following elements. Where applicable, both SI and conventional units shall be reported.

10.3 *Test Specimen and Environmental Sensor Design*—Description of the test specimens (tension, Charpy, and any other types of specimens used), neutron dosimeters, and temperature monitors.

10.4 Test Results:

10.4.1 Tension Tests:

10.4.1.1 Trade name and model of the testing machine, gripping devices, extensometer, and recording devices used in the test,

10.4.1.2 Speed of testing and method of measuring the controlling testing speed,

10.4.1.3 Complete stress-strain curve (if a group of specimens exhibits similar stress-strain curves, a typical curve may be reported for the group), and

10.4.1.4 Test data from each specimen as follows:

- (1) Specimen identification,
- (2) Material identification,
- (3) Test temperature,
- (4) Yield strength or yield point and method of measurement,
- (5) Ultimate Tensile Strength,
- (6) Fracture strength and fracture stress,
- (7) Total elongation,
- (8) Reduction of area, and
- (9) Location of fracture.

10.4.2 Charpy Tests:

10.4.2.1 Trade name and model of the testing machine, available hammer energy capacity and striking velocity, temperature conditioning and measuring devices,

10.4.2.2 Test Data from each specimen as follows:

- (1) Specimen identification,
- (2) Material identification,
- (3) Temperature of test,
- (4) Energy absorbed by the specimen in breaking,
- (5) Fracture appearance, and
- (6) Lateral expansion.

10.4.2.3 Procedures used to analyze Charpy data should be described. Any excluded data shall be justified and fixing of lower and/or upper shelves should be reported.

10.4.2.4 Test data for each material as follows:

- (1) Material identification,
- (2) Charpy 40.7 J (30 ft-lbf) index temperature,
- (3) 0.89 mm (35 mil) lateral expansion index temperature, and
- (4) Upper-shelf energy (USE).

10.4.3 Hardness Tests (Optional):

10.4.3.1 Trade name and model of testing machine,

10.4.3.2 Test methods and scale, and

10.4.3.3 Hardness data.

10.4.4 *Fracture Toughness Tests*—If fracture toughness tests are performed, the test data shall be reported together with the procedures used for conducting the tests and analysis of the data.

10.4.5 Temperature and Neutron Radiation Environment Determinations:

10.4.5.1 Temperature monitor results,

10.4.5.2 Estimate of capsule exposure temperature, and

10.4.5.3 Summary of reactor power history for cycles of capsule exposure including for each cycle:

- (1) Cycle number,
- (2) Number of effective full power days of operation, and
- (3) Estimated capsule temperature (per 5.3).

10.4.5.4 Neutron dosimeter measurements and analysis techniques,

10.4.5.5 Calculated results for the specimens using a spectrum adjusted or validated by dosimetry measurements, including the following:

- (1) Neutron fluence rate ($E > 1$ MeV),
- (2) Neutron fluence ($E > 1$ MeV),
- (3) dpa rate, and
- (4) dpa.

10.4.5.6 Complete neutron spectrum including thermal energy levels, if calculated. If an adjustment procedure is used both the adjusted and unadjusted spectra shall be reported.

10.4.5.7 Descriptions of the methods used to verify the procedures, including calibrations, cross sections, and other pertinent nuclear data.

10.5 Application of Test Results:

10.5.1 Extrapolation of the neutron fluence rate and fluence results to the inside surface and $1/4$ -thickness and $3/4$ -thickness locations of the reactor vessel at the peak fluence location,

10.5.2 Comparison of fluence determined from the dosimetry analysis with original predicted values, and

10.5.3 Extrapolation of Charpy index temperature shifts to the surface, $1/4$ - and $3/4$ -T locations of the reactor vessel at the peak fluence location.

10.6 *Deviations*—Deviations, or anomalies, in procedure from this practice shall be identified and described fully in the report.

11. Keywords

11.1 irradiation; nuclear reactor vessels (light water moderated); radiation exposure; surveillance (of nuclear reactor vessels)

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