



Designation: **E2215–16** **E2215 – 18**

# Standard Practice for Evaluation of Surveillance Capsules from Light-Water Moderated Nuclear Power Reactor Vessels<sup>1</sup>

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 ( $\epsilon$ ) 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 Additionally, this practice provides guidance on reassessing withdrawal schedule for design life and operation beyond design life.

1.3 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 irradiation-induced changes in the ferritic steels that comprise the beltline of a light-water moderated nuclear reactor pressure vessel.

1.4 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.<sup>2</sup>

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

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

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

## 2. Referenced Documents

2.1 *ASTM Standards:*<sup>3</sup>

**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

**E636** Guide for Conducting Supplemental Surveillance Tests for Nuclear Power Reactor Vessels

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

**E844** Guide for Sensor Set Design and Irradiation for Reactor Surveillance

**E853** Practice for Analysis and Interpretation of Light-Water Reactor Surveillance Results

**E900** Guide for Predicting Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials

**E1214** Guide for Use of Melt Wire Temperature Monitors for Reactor Vessel Surveillance

**E1253** Guide for Reconstitution of Irradiated Charpy-Sized Specimens

**E1820** Test Method for Measurement of Fracture Toughness

<sup>1</sup> 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.

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

<sup>3</sup> 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.

**E1921 Test Method for Determination of Reference Temperature,  $T_o$ , for Ferritic Steels in the Transition Range**

2.2 ASME Standards:<sup>4</sup>

**Boiler and Pressure Vessel Code, Section III Subarticle NB-2000, Rules for Construction of Nuclear Facility Components, Class 1 Components, Materials**

**Boiler and Pressure Vessel Code, Section XI Nonmandatory Appendix A, Analysis of Flaws, and Nonmandatory Appendix G, Fracture Toughness Criteria for Protection against Failure**

### 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 presentation, or both, 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 41 J (30 ft-lbf) index temperatures for the best fit (average) Charpy absorbed energy curve measured before and after irradiation. Similar measures of temperature shift can be defined based on other indices in 3.1.3, but the current U.S. industry practice is to use 41 J (30 ft-lbf) and is consistent with Guide E900.

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 temperature at which the fracture appearance of all Charpy specimens tested is at or above 95 % shear.

3.1.7 *end-of-license (EOL) fluence*—the maximum predicted fluence at the inside surface of the ferritic pressure vessel (if clad, the interface between cladding and ferritic steel) corresponding to the end of the applicable 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 average neutron fluence ( $E > 1$  MeV) of the specimens in a surveillance capsule to the peak neutron fluence ( $E > 1$  MeV) of the corresponding material at the ferritic steel reactor pressure vessel inside surface calculated over the same time period.

#### 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*—typically, the weld and base material with the highest predicted transition temperature using the projected fluence at the end of design life of each material, determined by adding the appropriate transition temperature shift (TTS) to the unirradiated  $RT_{NDT}$ . Guide E900 describes a method for predicting the TTS. Regulators or other sources may describe different methods for predicting TTS.

3.1.12 *maximum design fluence (MDF)*—the maximum projected fluence at the inside surface of the ferritic pressure vessel at the end of design life (if clad, MDF is defined at the interface of the cladding to the ferritic steel).

3.1.13 *reference material*—any steel that has been characterized as to the sensitivity of its tensile, impact and fracture toughness properties to neutron radiation-induced embrittlement and is included in the Practice E185 surveillance program.

3.1.14 *reference temperature ( $RT_{NDT}$ )*—see subarticle NB-2300 of the ASME Boiler and Pressure Vessel Code, Section III, for the definition of  $RT_{NDT}$  for unirradiated material based on Charpy (Test Methods A370) and drop weight tests (Test Method E208). ASME Code Section XI, Appendices A and G provide an alternative definition for the reference temperature ( $RT_{To}$ ) based on fracture toughness properties (Test Method E1921).

<sup>4</sup> Available from American Society of Mechanical Engineers, Third Park Avenue, New York, NY 10016.

3.1.15 *standby capsule*—a surveillance capsule meeting the recommendations of this practice that is or has been in the reactor vessel irradiation location as defined by Practice E185, but the testing of which is not required by this practice during the applicable operating license period.

### 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 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 reactor pressure vessel are generally monitored by measuring the index temperatures, the 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.

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 irradiation response of the materials.

4.6 Practice E853 describes a methodology that may be used in the analysis and interpretation of neutron dosimetry data and the determination of neutron fluence. Regulators or other sources may describe different methods.

4.7 Guide E900 describes a method for predicting the TTS. Regulators or other sources may describe different methods for predicting TTS.

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 temperature 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 experienced by the capsule. The local reactor coolant temperature may be used as a reasonable approximation, although gamma-ray heating should be considered if it leads to a significant temperature difference. 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 monthly power history of the reactor for all cycles prior to capsule removal shall be recorded. Other data that are needed on a fuel-cycle-specific basis include: assembly-wise core power distributions, including enrichments and burnups, axial core

power distributions, axial core void distributions (BWRs only), and core and downcomer water temperatures. Other key changes that need to be recorded include the addition or removal of flux suppression rods or shield rods, uprates or derates of reactor power, and other reactor modifications such as adding neutron shielding or the removal or addition of structures such as a thermal shield. Fuel assembly, reactor internals, and reactor pressure vessel dimensional information also need to be recorded. Surveillance capsule locations and movements: including storage periods outside the reactor, shall be provided for the evaluation of irradiation exposure.

6.2 Practice **E853** describes practices for determining the neutron fluence rate, neutron energy spectrum and neutron fluence of the surveillance specimens and the corresponding maximum values for the reactor vessel. Regulators or other sources may describe different methods.

6.3 Neutron fluence rate and fluence values ( $E > 1$  MeV) and dpa rate and dpa values per Practice **E693** (or alternatives in regulatory guidance or prescribed by regulations) shall be determined and recorded using a calculated spectrum adjusted or validated by dosimetry measurements.

## 7. Measurement of Mechanical Properties

7.1 Generally, all the materials contained in the capsule except the HAZ specimens (if included) should be tested. Testing of the HAZ specimens is optional.<sup>(1)</sup><sup>5</sup>

### 7.2 Tension Tests:

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

7.2.2 *Test Temperature*—In general, the test temperatures for each material shall include room temperature and reactor vessel service temperature. Other specimens should be retained for tension testing at possible future fracture toughness test temperature(s). Specific consideration should be given to the specific temperatures at which unirradiated specimens have been tested.

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

### 7.3 Charpy Tests:

7.3.1 *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**.

7.3.2 *Test Temperature*—Specimens for each material shall be tested at temperatures selected to define the full Charpy energy transition curve. Particular emphasis should be placed on defining the 41 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**.

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

7.4 *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**.

### 7.5 Fracture Toughness Tests (Optional):

7.5.1 *Specimens*—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 and precracked. Procedures for reconstitution of Charpy specimens are given in Guide **E1253**.

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

7.5.3 *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**.

7.6 *Retention of Test Specimens*—It is recommended that all broken and unbroken test specimens be maintained in good condition and retained. These test specimens may be useful in the event that additional analysis is required to explain anomalous results. Identification of all test specimens shall be maintained. After it is determined that additional testing or analysis to explain anomalous results is not required, then it is recommended that specimens be either retained or used for appropriate research to increase understanding of embrittlement or for direct use or potential reconstitution to support reactor vessel material surveillance programs during extended operating periods. Final disposition of specimens should only be performed after a thorough evaluation of the potential usefulness of the specimen materials.

<sup>5</sup> Troyer, Greg and Erickson, Marjorie, "Empirical Analyses of Effects of the Heat Affected Zone and Post Weld Heat Treatment on Irradiation Embrittlement of Reactor Pressure Vessel Steel," Effects of Radiation on Nuclear Materials: 26th Volume, STP 1572, Mark Kirk and Enrico Lucero, Eds., ASTM International, West Conshohocken, PA, 2014, pp. 155-170. The boldface numbers in parentheses refer to a list of references at the end of this standard.



## 8. Evaluation of Test Data

### 8.1 Tension Tests:

8.1.1 Determine the amount of radiation-induced 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 display 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~~ as discussed in Appendix X1.

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 41 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 subtracting the measured unirradiated index temperatures from the irradiated index temperatures. If the differences among these three shift measurements exceed 15°C, then the test records and specimens should be examined for possible causes of discrepancy and the outcome of the examination documented.

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.<sup>6</sup> 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, or other parameters. 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 Section XI, Appendices A and G.

## 9. Withdrawal Schedule Review

9.1 The primary consideration in the review of the withdrawal schedule shall be ensuring that the vessel is appropriately monitored throughout its projected design 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 shall also include monitoring the neutron exposure of the reactor vessel throughout its projected design life using a combination of neutron fluence tracking analysis methods and fluence measurements. The fluence measurements may consist of both in-vessel and ex-vessel neutron dosimetry. 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 and reactor type.

9.2.1 Consideration should be given to adjusting withdrawal schedules to permit surveillance capsule withdrawals during extended operating periods, to the degree possible given the number of capsules and the lead factors available in the original surveillance program.

### 9.3 Withdrawal Schedule Review for Design Life:

9.3.1 Update the MDF based on new dosimetry, fluence analysis and current operating plans.

9.3.2 Update the projected transition temperature shift (TTS) for the most limiting vessel material based on any new material specific information.

<sup>6</sup> See for example: ASTM D554, July, 1974; Data Series DS54(2); NUREG/CR-4947(3) on HSST plates; and IAEA-TECDOC-1230; IAEA-TECDOC-1230(4), July, 2001, on the JRQ plate.

9.3.3 Adjust the withdrawal schedule to meet the recommendations in [Table 1](#).

9.4 *Anticipated Operation Beyond Design Life:*

9.4.1 When operation beyond design life is anticipated, a plan for reactor vessel surveillance should be developed to ensure that the vessel beltline is appropriately monitored throughout the period of operation. This may include fabrication and insertion of a new capsule, moving an existing capsule to a higher lead factor location, a change in status of a standby capsule to one scheduled for withdrawal and testing, or participation in an integrated surveillance program.

9.4.2 Update EOL fluence, TTS, EOL reactor vessel material property projections and limiting material for the operating period beyond design life.

9.4.3 The goal is to have limiting beltline material (or a surrogate material, if this is not practical) index temperature measurements at a fluence greater than the projected EOL renewal fluence, but less than twice the EOL renewal fluence. The testing should be performed before the limiting material vessel fluence reaches the fluence of the previous highest fluence surveillance measurement.

9.5 Standby capsules 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 twice MDF, or twice EOL fluence if operating beyond design life. Supplemental testing may also be based on reconstitution of previously tested specimens following [Guide E1253](#).

9.6 The schedule for capsule withdrawals is approximate and may be adjusted to coincide with a planned outage. A fluence higher than the target is preferred to a lower value.

9.7 Long periods of operation without any dosimetry measurements can leave errors in the inputs or errors in the application of the fluence calculation methodology undetected. Therefore, dosimetry measurement(s) may be advisable between specimen capsule withdrawals. See [Practice E185](#) for further information.

9.8 If no surveillance capsules remain in the reactor, some method should be considered to periodically make dosimetry measurements to monitor radiation conditions.

9.9 Generally, the preferred location for additional dosimetry is the air gap between the reactor pressure vessel reflective insulation and the biological shield surrounding the reactor. Dosimetry in this location can monitor the neutron exposure of the reactor vessel; both axially and azimuthally. In addition, dosimetry with various azimuthal locations can monitor changes in the core azimuthally, whereas the surveillance capsule dosimeters cannot detect core changes away from the surveillance capsule location. Operationally, dosimetry in this location is more easily removed and replaced than dosimetry located within the vessel. Neutron dosimeters shall be selected according to [Guide E844](#).

**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 including latest assessments of previous surveillance capsule test results.

10.1.1 Each material heat identification.

10.1.2 Copper (Cu), nickel (Ni), manganese (Mn), phosphorus (P), sulfur (S), silicon (Si), carbon (C), and vanadium (V) as well as all other alloying and residual elements for which data is available for each surveillance material tested.

10.1.3 Heat treatment of each surveillance material.

10.2 *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.

10.3 *Test Results:*

10.3.1 *Tension Tests:*

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

**TABLE 1 Suggested Withdrawal Schedule<sup>A,B</sup>**

Sequence	Target Fluence	Notes
First	¼ MDF	Testing Required
Second	½ MDF	Testing Required
Third	¾ MDF	Testing Required
Fourth	MDF	Testing Required
Standby	< 2 MDF	Testing Not Required

<sup>A</sup> If the original surveillance program contained less than 5 capsules, adjust the withdrawal schedule to provide monitoring through the period of operation attempting to meet the general intent of this guidance.

<sup>B</sup> See [9.4](#) for anticipated operation beyond design life.