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Standard Guide for Benchmark Testing of Light Water Reactor Calculations[1]

This standard is issued under the fixed designation E2006; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers general approaches for benchmarking neutron transport calculations for pressure vessel surveillance programs in light water reactor systems. A companion guide (Guide E2005) covers use of benchmark fields for testing neutron transport calculations and cross sections in well controlled environments. This guide covers experimental benchmarking of neutron fluence calculations (or calculations of other exposure parameters such as dpa) in more complex geometries relevant to reactor pressure vessel surveillance. Particular sections of the guide discuss: the use of well-characterized benchmark neutron fields to provide an indication of the accuracy of the calculational methods and nuclear data when applied to typical cases; and the use of plant specific measurements to indicate bias in individual plant calculations. Use of these two benchmark techniques will serve to limit plant-specific calculational uncertainty, and, when combined with analytical uncertainty estimates for the calculations, will provide uncertainty estimates for reactor fluences with a higher degree of confidence.

1.2 Although this guide and the companion guide, Guide E2005, are focused on power reactors, the principle of this guide is also applicable to non-power light water reactor pressure vessel surveillance programs.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *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:*[2]

E170 Terminology Relating to Radiation Measurements and Dosimetry
E261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques
E262 Test Method for Determining Thermal Neutron Reaction Rates and Thermal Neutron Fluence Rates by Radioactivation Techniques
E706 Master Matrix for Light-Water Reactor Pressure Vessel Surveillance Standards
E844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance
E944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance
E1006 Practice for Analysis and Interpretation of Physics Dosimetry Results from Test Reactor Experiments
E1018 Guide for Application of ASTM Evaluated Cross Section Data File
E2005 Guide for Benchmark Testing of Reactor Dosimetry in Standard and Reference Neutron Fields

3. Terminology

3.1 *Definitions*—definitions of terms used in this guide may be found in Terminology E170.

4. Significance and Use

4.1 This guide deals with the difficult problem of benchmarking neutron transport calculations carried out to determine fluences for plant specific reactor geometries. The calculations are necessary for fluence determination in locations important for material radiation damage estimation and which are not accessible to measurement. Typically, the most important application of such calculations is the estimation of fluence within the reactor vessel of operating light water reactors (LWR) to provide accurate estimates of the irradiation embrittlement of the base and weld metal in the vessel. The benchmark procedure must not only prove that calculations

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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.

give reasonable results but that their uncertainties are propagated with due regard to the sensitivities of the different input parameters used in the transport calculations. Benchmarking is achieved by building up data bases of benchmark experiments that have different influences on uncertainty propagation. For example, in simple vessel wall mockups where measurements are made within a simulated reactor vessel wall, the integral effect of uncertainties in iron cross sections (absorption and elastic and inelastic scattering) are dominant and have been bounded by the agreement between calculation and measurement. For more complicated integral benchmarks, other factors such as: uncertainties in the distribution of fission sources, geometry, the energy-dependent cross sections, and the angular scattering distribution for elemental components of major materials in the neutron field (such as water and iron) may all be important uncertainty contributors. This guide describes general procedures for using neutron fields with known characteristics to corroborate the calculational methodology and nuclear data used to derive neutron field information from measurements of neutron sensor response.

4.2 The bases for benchmark field referencing are usually irradiations performed in standard neutron fields with well-known energy spectra and intensities. There are, however, less well known neutron fields that have been designed to mockup special environments, such as pressure vessel mockups in which it is possible to make dosimetry measurements inside of the steel volume of the "vessel". When such mockups are suitably characterized, they are also referred to as benchmark fields. A benchmark is that against which other things are referenced, hence the terminology "to benchmark reference" or "benchmark referencing". A variety of benchmark neutron fields, other than standard neutron fields, have been developed, or pressed into service, to improve the accuracy of neutron dosimetry measurement techniques. Some of these special benchmark experiments are discussed in this standard because they have identified needs for additional benchmarking or because they have been sufficiently documented to serve as benchmarks.

4.3 One dedicated effort to provide benchmarks whose radiation environments closely resemble those found outside the core of an operating reactor was the Nuclear Regulatory Commission's Light Water Reactor Pressure Vessel Surveillance Dosimetry Improvement Program (LWR-PV-SDIP) (**1**)[3]. This program promoted better monitoring of the radiation exposure of reactor vessels and, thereby, provided for better assessment of vessel end-of-life conditions. An objective of the LWR-PV-SDIP was to develop improved procedures for reactor surveillance and document them in a series of ASTM standards (see Matrix E706). The primary means chosen for validating LWR-PV-SDIP procedures was by benchmarking a series of experimental and analytical studies in a variety of fields (see Guide E2005).

5. Particulars of Benchmarking Transport Calculations

5.1 Benchmarking of neutron transport calculations involves several distinct steps that are detailed below.

5.1.1 Nuclear data used for transport calculations are evaluated using differential data or a combination of integral and differential data. This process results in a library of cross sections and other needed nuclear data (including fission spectra) that, in the opinion of the evaluator, gives the best fit to the available experimental and theoretical results. Some of the information used in evaluating the cross sections may be the same as that used directly for benchmarking transport calculations for LWR systems (see 5.1.2). The cross section benchmarking itself is not addressed in this standard. It is assumed that the cross-section set is derived in this fashion to be applicable to a variety of calculational geometries and may not give the most accurate answer for LWR geometries. Thus further benchmarking in LWR geometries is required.

5.1.2 Transport calculations in LWR geometries may be benchmarked using measurements made in well-defined and well-characterized facilities that each mock-up part of an LWR-type system. These facilities have the advantage over operating plants that the dimensions and material compositions can be more accurately defined, the neutron source can be well characterized, and measurements can be made in a large number of locations that would not be accessible in actual systems.

5.1.2.1 In power reactors, one is interested in the transport of neutrons from the distributed source in the fuel, through the reactor internals and water to the vessel, and through the vessel to the reactor cavity. Three mockups that together encompass this entire transport problem are described in 6.1. Modeling and calculating of neutron transport in these various geometries can be expected to identify any bias in specific parts of the calculations. Biases that can be detected include those due to modeling the irregular fuel geometry and distributed neutron source, those due to errors in the cross-sections or neutron spectra, and those due to calculational approximations.

5.1.2.2 In non-power reactors, the objective is the same in that the purpose is to characterize the transport of neutrons from the distributed source in the fuel to and through the pressure vessel. However, in many non-power reactors, the geometries between the reactor core and the pressure vessel are significantly different from those represented by the mockups described in Section 6. In this case the evaluator must justify the validity of using the benchmarks discussed in Section 6. If these benchmarks cannot be justified, other benchmarks must be identified and their use justified.

5.1.3 The benchmarking described above does not provide checks on geometries identical to actual plants and does not include bias that may exist in the definition of a specific plant model. Identification of these types of bias can only be accomplished using actual plant measurements. Benchmarking using these measurements is described in 6.2 and 6.3.

5.1.4 The final aspect of benchmarking is the benchmarking of the dosimetry results. This aspect is treated in Guide E2005. It is assumed that the measurements in the benchmarked facilities and in the actual operating plants are carried out using benchmarked reactions and dosimeters. This involves using

[3] The boldface numbers given in parentheses refer to a list of references at the end of the text.