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Practice for use of a radiochromic film dosimetry system

Pratique de l'utilisation d'un système dosimétrique à film radiochromique

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ASTM International, 100 Barr Harbor Drive, PO Box C700,
West Conshohocken, PA 19428-2959, USA
Tel. +610 832 9634
Fax +610 832 9635
E-mail khooper@astm.org
Web www.astm.org

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75% of the member bodies casting a vote.

ASTM International is one of the world's largest voluntary standards development organizations with global participation from affected stakeholders. ASTM technical committees follow rigorous due process balloting procedures.

A project between ISO and ASTM International has been formed to develop and maintain a group of ISO/ASTM radiation processing dosimetry standards. Under this project, ASTM Subcommittee E10.01, Dosimetry for Radiation Processing, is responsible for the development and maintenance of these dosimetry standards with unrestricted participation and input from appropriate ISO member bodies.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. Neither ISO nor ASTM International shall be held responsible for identifying any or all such patent rights.

International Standard ISO/ASTM 51275 was developed by ASTM Committee E10, Nuclear Technology and Applications, through Subcommittee E10.01, and by Technical Committee ISO/TC 85, Nuclear Energy.

Standard Practice for Use of a Radiochromic Film Dosimetry System[1]

This standard is issued under the fixed designation ISO/ASTM 51275; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision.

1. Scope

1.1 This practice covers the procedures for handling, testing, and using a radiochromic film dosimetry system to measure absorbed dose in materials irradiated by photons or electrons in terms of absorbed dose in water.

1.2 This practice applies to radiochromic film dosimeters that can be used within part or all of the specified ranges as follows:

1.2.1 The absorbed dose range is 1 Gy to 100 kGy.

1.2.2 The absorbed dose rate is 1×10^{-2} to 1×10^{13} Gy/s **(1-4)**.[2]

1.2.3 The radiation energy range for both photons and electrons is 0.1 to 50 MeV.

1.2.4 The irradiation temperature range is –78 to +60°C.

1.3 This practice applies to radiochromic films of various formats, including small pieces used to measure a single dose value, strips used for one-dimensional dose-mapping, and sheets used for two-dimensional dose-mapping. Three-dimensional dose-mapping may be achieved by proper placement of any of these formats.

1.4 *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 and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced documents

2.1 *ASTM Standards:* [3]

E 170 Terminology Relating to Radiation Measurements and Dosimetry

E 668 Practice for Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices

2.2 *ISO/ASTM Standards:*

51261 Guide for Selection and Calibration of Dosimetry Systems for Radiation Processing[4]

51400 Practice for Characterization and Performance of a High-Dose Radiation Dosimetry Calibration Laboratory[4]

51707 Guide for Estimating Uncertainties in Dosimetry for Radiation Processing[4]

2.3 *International Commission on Radiation Units and Measurements (ICRU) Reports:*[5]

ICRU Report 14 Radiation Dosimetry: X–Rays and Gamma Rays with Maximum Photon Energies Between 0.6 and 50 MeV

ICRU Report 17 Radiation Dosimetry: X–Rays Generated at Potentials of 5 to 150 kV

ICRU Report 34 The Dosimetry of Pulsed Radiation

ICRU Report 35 Radiation Dosimetry: Electron Beams with Energies Between 1 and 50 MeV

ICRU Report 60 Fundamental Quantities and Units for Ionizing Radiation

3. Terminology

3.1 *Definitions:*

3.1.1 *analysis wavelength*—wavelength used in a spectrophotometric instrument for the measurement of optical absorbance or reflectance.

3.1.2 *calibration curve*—graphical representation of the dosimetry system's response function.

3.1.3 *dosimeter batch*—quantity of dosimeters made from a specific mass of material with uniform composition, fabricated in a single production run under controlled, consistent conditions and having a unique identification code.

3.1.4 *dosimetry system*—system used for determining absorbed dose, consisting of dosimeters, measurement instruments and their associated reference standards, and procedures for the system's use.

3.1.5 *measurement quality assurance plan*—documented program for the measurement process that ensures on a continuing basis that the overall uncertainty meets the requirements of the specific application. This plan requires traceability to, and consistency with, nationally or internationally recognized standards.

3.1.6 *net absorbance*, ΔA—change in measured optical absorbance at a selected wavelength determined as the absolute difference between the pre-irradiation absorbance, A_0, and the post-irradiation absorbance, A, as follows:

$$\Delta A = |A - A_0|. \quad (1)$$

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[1] This guide is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.01 on Dosimetry for Radiation Processing, and is also under the jurisdiction of ISO/TC 85/WG 3.

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[2] The boldface numbers in parentheses refer to the bibliography at the end of this practice.

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

[5] Available from the International Commission on Radiation Units and Measurements, 7910 Woodmont Ave., Suite 800, Bethesda, MD 20814, USA.

3.1.6.1 *Discussion*—In practice, an average pre-irradiation absorbance may be used to determine net absorbance.

3.1.7 *radiochromic film-dosimeter*—specially prepared film containing ingredients that undergo change in optical absorbance under ionizing radiation. This change in optical absorbance can be related to absorbed dose in water.

3.1.8 *response function*—mathematical representation of the relationship between dosimeter response and absorbed dose for a given dosimetry system.

3.1.9 *specific net absorbance* (Δk)—Net absorbance, ΔA, at a selected wavelength divided by the optical pathlength, d, through the dosimeter material as follows:

$$\Delta k = \Delta A/d. \tag{2}$$

3.2 Definitions of other terms used in this standard that pertain to radiation measurement and dosimetry may be found in ASTM Terminology Standard E 170. Definitions in ASTM E 170 are compatible with ICRU 60; that document, therefore, may be used as an alternative reference.

4. Significance and use

4.1 The radiochromic film dosimetry system provides a means of determining absorbed dose in materials. Under the influence of ionizing radiation, chemical reactions take place in the radiochromic film creating or enhancing, or both, optical absorption bands. Absorbance is determined within these radiation-induced absorption bands using a spectrophotometer or photometer (See 5.1.2).

4.2 In the application of a specific dosimetry system, absorbed dose is determined by use of a calibration curve traceable to national or international standards.

4.3 The absorbed dose determined is usually specified in water. Absorbed dose in other materials may be determined by applying conversion factors. This is discussed in ISO/ASTM Guide 51261.

NOTE 1—For comprehensive discussion of various dosimetry methods applicable to the radiation types and energies discussed in this practice, see ICRU Reports 14, 17, 34, and 35.

4.4 Radiochromic film dosimetry systems are commonly applied in the industrial radiation processing of a variety of products, for example, sterilization of medical devices and processing of foods.

5. Dosimetry system

5.1 *Components of the Dosimetry System*—The following shall be used to determine absorbed dose with radiochromic film dosimetry systems:

5.1.1 *Radiochromic Film Dosimeters*

5.1.2 *Spectrophotometer or Photometer*, having documentation covering analysis wavelength range, accuracy of wavelength selection, absorbance determination, spectral bandwidth, and stray light rejection. Examples of appropriate wavelengths for analysis for specific dosimetry systems are provided by the manufacturer and in Refs **(3-14, 15)**.

5.1.3 *Holder*, to position the dosimeter reproducibly in and perpendicular to the analysis light beam.

5.1.4 *Thickness Gage*, with a precision of ±2 % of the film thickness (at a 95 % confidence level), if the film's thickness is to be measured.

NOTE 2—Documentation provided by the manufacturer of the radiochromic film dosimeter with regard to the film thickness and its variability may be substituted for direct measurement of thickness by the user. This information may be verified by the user by analyzing a representative sample of films.

NOTE 3—Some radiochromic film dosimeters contain a substrate which is not radiochromic. With such dosimeters the thickness is not measured; instead use the manufacturer's documentation of the thickness and/or variability of the film's radiation-sensitive layer.

5.1.5 Packaging materials for radiochromic films, where applicable, such as pouches or envelopes to protect from light or humidity variations.

6. Performance check of instrumentation

6.1 The performance of the photometer or spectrophotometer shall be checked as specified in Section 7.4, and documented. Use reference standards traceable to national or international standards.

6.1.1 When using a spectrophotometer, check and document the accuracy of the wavelength scale and absorbance scale at or near the analysis wavelength(s) at intervals not to exceed one month during periods of use and as specified by the end-user's internal procedures.

6.1.2 When using a photometer, check and document the accuracy of the absorbance scale at intervals not to exceed one month during periods of use and as specified by the end-user's internal procedures.

6.1.3 Compare the information obtained in 6.1.1 or 6.1.2 with the original instrument specifications to ensure adequate performance.

6.2 Check the thickness gage prior to first use and periodically thereafter to ensure reproducibility and lack of zero drift. Check and document the calibration of the gage at intervals not to exceed six months. Use gage blocks, traceable to national or international standards for this purpose.

7. Calibration of the dosimetry system

7.1 Prior to use, the dosimetry system (consisting of a specific batch of dosimeters and specific measurement instruments) shall be calibrated in accordance with the user's documented procedure that specifies details of the calibration process and quality assurance requirements. This calibration process shall be repeated at regular intervals to ensure that the accuracy of the absorbed dose measurement is maintained within required limits. Calibration methods are described in ISO/ASTM Guide 51261.

7.2 *Calibration Irradiation of Dosimeters*—Irradiation is a critical component of the calibration of the dosimetry system. Calibration shall be performed in one of three ways by irradiating the dosimeters at:

7.2.1 an accredited calibration laboratory that provides an absorbed dose (or an absorbed-dose rate) having measurement traceability to nationally or internationally recognized standards, or

7.2.2 an in-house calibration facility that provides an absorbed dose (or an absorbed-dose rate) having measurement traceability to nationally or internationally recognized standards, or

7.2.3 a production or research irradiation facility together with reference or transfer standard dosimeters that have measurement traceability to nationally or internationally recognized standards.

7.3 When the radiochromic film dosimeter is used as a transfer standard dosimeter, the calibration irradiation may be performed only as stated in 7.2.1, or in 7.2.2 at a facility that meets the requirements in ISO/ASTM 51400.

7.4 *Measurement Instrument Calibration and Performance Verification*—For the calibration of the instruments, and for the verification of instrument performance between calibrations, see ISO/ASTM Guide 51261 and/or instrument-specific operating manuals.

8. Procedure

8.1 *Examination and Storage Procedure*:

8.1.1 Ultraviolet radiation may cause the film to change color. Perform tests to ensure that the handling/reading environment does not cause measurable color development. If needed, place ultraviolet filters over fluorescent lights or windows to reduce color development (see also 9.3.1).

8.1.2 Handle dosimeters according to manufacturer's instructions. Avoid handling dosimeter surfaces with bare fingers.

8.1.3 Visually inspect the films for imperfections. Gently clean the dosimeters if necessary, for example with a soft brush or with air. Discard any dosimeters that show imperfections such as scratches that could give rise to erroneous readings.

8.1.4 Identify the dosimeters.

8.1.5 Store the dosimeters according to the manufacturer's written recommendations.

8.2 *Irradiation Procedure*:

8.2.1 Determine the pre-irradiation absorbance, A_0, for each dosimeter at the selected analysis wavelength. Alternatively, use an average ($\bar{A}_0$), determined by reading several dosimeters.

NOTE 4—If the orientation of the dosimeter has an effect on the absorbance reading, keep track of the dosimeter orientation (for example, by marking a corner or edge of the dosimeter).

8.2.2 If necessary, package the dosimeters to provide controlled environmental conditions during irradiation (see 9.3.1).

8.2.3 Mark the packaged dosimeters appropriately for identification.

8.2.4 Irradiate the dosimeters.

NOTE 5—The dosimeters may be irradiated in the product undergoing processing or in a medium of similar composition, or water, of appropriate dimensions so as to approximate electron equilibrium conditions. Such equilibrium conditions may not exist within dosimeters placed throughout the product under actual processing conditions. This particularly is the case near interfaces of different materials. Irradiation under nonequilibrium conditions, such as on the surface of a product package, is often used to monitor the absorbed dose delivered to the product and may be related to absorbed dose within the product by correction factors under certain conditions. For a detailed discussion of this subject, see ISO/ASTM Guide 51261.

8.3 *Analysis Procedure*:

8.3.1 Avoid any exposure to ultraviolet radiation that may induce coloration of the dosimeter (see 8.1.1).

8.3.2 Determine the post-irradiation absorbance, A, at the selected analysis wavelength(s).

8.3.3 If appropriate for the dosimeter being used, measure the thickness of each dosimeter, or use the average thickness and document the uncertainty of the measurement.

NOTE 6—Certain films may be too thin to allow the accurate determination of thickness using conventional gage technology. In such cases, statistical methods may be employed in order to provide the uncertainty values discussed in Section 12.

8.3.4 Calculate the absorbed dose based on the pre- and post-irradiation absorbances, the thickness, if appropriate, and the calibration curve or response function.

NOTE 7—Examples of radiochromic film dosimeter applications that employ reflectance techniques or alternative methods for determining net and specific net absorbance appear in the literature. The user may choose to refer to these techniques **(16, 17)**.

9. Characterization of each batch of dosimeters

9.1 *Repeatability of Specific Net Absorbance*:

9.1.1 For each batch of dosimeters, the repeatability of specific net absorbance should be obtained by analyzing the data from the sets of dosimeters irradiated during the calibration at each dose value.

9.1.2 Use the sample standard deviation (S_{n-1}) determined during calibration to calculate coefficients of variation (CV) for each absorbed dose value as follows:

$$CV = \frac{S_{n-1}}{\Delta k} \times 100\ (\%) \tag{3}$$

9.1.3 Document these coefficients of variation and note any that are unusually large.

NOTE 8—In general, if the coefficients of variation values are greater than 2 %, then a redetermination of the data should be considered.

9.2 *Post-Irradiation Characterization*:

9.2.1 Some types of dosimeters may fade or may continue color development after irradiation. This effect may depend on post-irradiation storage conditions such as temperature, humidity, or atmosphere. In order to determine if this is significant in a given application, measure the absorbance at the selected wavelength(s) over the period of anticipated analysis and over the range of expected storage conditions **(7, 8, 14, 16, 18)**.

9.2.2 If absorbances measured in 9.2.1 are found to vary significantly with post-irradiation storage time, then apply correction factors for such time-dependent variations, taking into account the calibration curve for that batch of dosimeters, in order to minimize dosimetric errors during routine application. Alternatively, control the post-irradiation storage and analysis so that correction factors are not needed..

9.2.3 For a given set of irradiation conditions, this procedure needs to be performed only once for a given batch of dosimeters.

9.3 *Other Factors*:

9.3.1 The effects of temperature, humidity, absorbed dose rate, incident energy spectrum, electron equilibrium and background ultraviolet radiation shall be taken into account. See Refs (**2-6**) and (**11-14, 16** and **19**) for examples of the types and magnitudes of the effects. Appropriate documented information regarding the magnitude and effect(s) upon the measurement made by the dosimetry system may be obtained from the scientific literature, dosimeter manufacturer, distributor, irradiation facility operator, or a qualified testing organization. Some effects may be reduced or eliminated with proper packaging.

10. Application of dosimetry system

10.1 The number of dosimeters required for the measurement of absorbed dose at a location on or within a material is determined by the precision of the dosimetry system and the required precision associated with the application. Appendix X3 of Practice E 668 describes a statistical method for determining this number.

10.2 For irradiating and analyzing the dosimeters, follow the procedures in accordance with 8.2 and 8.3.

10.3 Determine the absorbed dose from the mean specific net absorbance values and the system calibration curve that results from following the procedures in accordance with Section 7.

10.4 Record the calculated absorbed dose and all other relevant data as outlined in Section 11.

11. Minimum documentation requirements

11.1 Record the dosimeter manufacturer, type, and batch identification (code).

11.2 Record or reference the date of calibration, calibration source, and associated instruments used.

11.3 Record or reference the irradiation environmental conditions for the dosimeters, including temperature, pressure (if other than atmospheric), relative humidity, and composition of the surrounding atmosphere (if other than air).

11.4 Record the date of irradiation and the dates on which the non-irradiated and irradiated dosimeters are analyzed.

11.5 Record the absorbance and thickness data, if appropriate, and the resulting absorbed dose values.

11.6 Record or reference the uncertainty in the value of the absorbed dose.

11.7 Record or reference the measurement quality assurance plan used for the dosimetry system application.

12. Measurement uncertainty

12.1 To be meaningful, a measurement of absorbed dose shall be accompanied by an estimate of uncertainty.

12.2 Components of uncertainty shall be identified as belonging to one of two categories:

12.2.1 Type (*A*)—those evaluated by statistical methods, or

12.2.2 Type (*B*)—those evaluated by other means.

12.3 Other ways of categorizing uncertainty have been widely used and may be useful for reporting uncertainty. For example, the terms *precision* and *bias* or *random* and *systematic* (non-random) are used to describe different categories of uncertainty.

12.4 If this practice is followed, the estimate of the expanded uncertainty of an absorbed dose determined by this dosimetry system should be less than 6 % for a coverage factor k=2 (which corresponds approximately to a 95 % level of confidence for normally distributed data.

NOTE 9—The identification of Type A and Type B uncertainties is based on the methodology for estimating uncertainties published in 1995 by the International Organization for Standardization (ISO) in the Guide to the Expression of Uncertainty in Measurement (**20**). The purpose of this type of characterization is to promote an understanding of how uncertainty statements are developed and to provide a basis for the international comparison of measurement results.

NOTE 10—ISO/ASTM Guide 51707 defines possible sources of uncertainty in dosimetry performed in radiation processing facilities and offers procedures for estimating the magnitude of the resulting uncertainties in the measurement of absorbed dose using a dosimetry system. The document defines and discusses basic concepts of measurement, including estimation of the measured value of a quantity, "true" value, error and uncertainty. Components of uncertainty are discussed and methods are provided for estimating their values. Methods are also provided for calculating the combined standard uncertainty and estimating expanded (overall) uncertainty.

13. Keywords

13.1 absorbed dose; dose measurement; dosimeter; dosimetry; electron beam; gamma radiation; ionizing radiation; quality control; radiation processing; radiochromic dosimetry; radiochromic film; ICS 17.240

Bibliography

(**1**) Chappell, S. E. and Humphreys, J. C. "The Dose Response of a Dye-Polychlorostyrene Film Dosimeter," *Transactions of Nuclear Science*, Vol 19, 1972, pp. 175–180.

(**2**) Gehringer, P., Eschweiler, H., and Proksch, E., "Dose and Humidity Effects on the Radiation Response of Nylon-Based Radiochromic Film Dosimeters," *International Journal of Applied Radiation and Isotopes*, Vol 31, No. 10, 1980, pp. 595–605.

(**3**) McLaughlin, W. L., Humphreys, J. C., Levine, H., Miller, A., Radak, B. B., and Rativanich, N., "The Gamma-Ray response of Radiochromic Dye Films at Different Absorbed Doses," *Radiation Physics and Chemistry*, Vol 18, 1981, pp. 987–999.

(**4**) McLaughlin, W. L., Humphreys, J.C., Radak, B. B., Miller, A., and Olejnik, T. A., "The Response of Plastic Dosimeters to Gamma Rays and Electrons at High Dose Rates," *Radiation Physics and Chemistry*, Vol 14, 1979, pp. 535–550.

(**5**) Levine, H., McLaughlin, W. L., and Miller, A., "Temperature and Humidity Effects on the Gamma-Ray Response and Stability of Plastic and Dyed Plastic Dosimeters," *Radiation Physics and Chemistry*, Vol 14, 1979, pp. 551–574.

(**6**) McLaughlin, W. L., Miller, A., Uribe, R. M., Kronenburg, S., and Siebentritt, C. R., "Energy Dependence of Radiochromic Dosimeter Response to X and Gamma Rays," *High Dose Dosimetry, Proceedings of the International Symposium*, Vienna, 1985, pp. 397–424.

(**7**) Danchenko, V. and Griffin, G. F., "Delayed Darkening of Radiation-Exposed Radiochromic Dye Dosimeters," *Transactions of Nuclear Science*, Vol NS-25, No. 6, December 1981, pp. 4156–4160.

(**8**) Chappas, W. J., "Accelerated Color Development Irradiated Radiochromic Dye Films," *Transactions of Nuclear Science*, Vol NS-28, No. 2, April 1981, pp. 1784–1785.

(**9**) Patel, G. N., "Diacetylenes as Radiation Dosage Indicators," *Radiation Physics and Chemistry*, Vol 18, 1981, pp. 913–925.

(**10**) McLaughlin, W. L., Wei-Zhen, B., and Chappas, W. J., "Cellulose Diacetate Film Dosimeters," *Radiation Physics and Chemistry*, Vol 31, 1988, pp. 481–490.

(**11**) Schaffer, H. L., and Garcia, R. D., "Practical Application of Dosimetry Systems Utilized in Radiation Processing of Medical Devices," *Radiation Physics and Chemistry*, Vol 31, 1988, pp. 497–504.

(**12**) Miller, A., Batsberg, W., and Karman, W., "A New Radiochromic Thin-Film Dosimeter System," *Radiation Physics and Chemistry*, Vol 31, 1988, pp. 491–496.

(**13**) McLaughlin, W. L., Humphreys, J. C., Hocken, D., and Chappas, W. J., "Radiochromic Dosimetry for Validation and Commissioning of Industrial Radiation Processes," *Radiation Physics and Chemistry*, Vol 31, 1988, pp. 505–514.

(**14**) Saylor, M. C., Tamargo, T. T., McLaughlin, W. L., Kahn, H. M., Lewis, D. F., and Schenfele, R. D., "A Thin Film Recording Medium for Use in Food Irradiation," *Radiation Physics and Chemistry*, Vol 31, 1988, pp. 529–536.

(**15**) McLaughlin, W. L., Chen, Y. D., Soares, C. G., Miller, A., Vay Dyk, G. and Lewis, D. F., "Sensitometry of the Response of a New Radiochromic Film Dosimeter to Gamma Radiation and Electron Beams," *Nucl. Instrum. Methods Phys. Res.* A302, 1991, pp. 165–176

(**16**) Prusik, T., and Montesalvo, M., and Wallace, T., "Use of Polydiacetylenes in an Automated Label Dosimetry System," *Radiation Physics and Chemistry*, Vol 31, Second Edition, 1997, pp. 441–447.

(**17**) "Absorbed Dose Determination in Photon and Electron Beams," IAEA Technical Report Series No. 277, Vienna, Second Edition, 1997.

(**18**) McLaughlin, W. L., Puhl, J. M., Al-Sheikhly, M., Christou, C. A. Miller, A., Kovacs, A., Wojnarovits, L., and Lewis, D F., "Novel. Radiochromic Films for Clinical Dosimetry," *Radiation Protection Dosimetry*, Vol. 66, Nos. 1–4, 1996, pp. 263–268.

(**19**) Janovsky, I. and Mehta, K., "The Effects of Humidity on the Response of Radiochromic Film Dosimeters FWT-60–00 and Gafchromic-DM-1260," *Radiat. Phys. Chem.*, 43, 1994, pp. 407–409.

(**20**) "Guide to the Expression of Uncertainty in Measurement," International Organization for Standardization, 1995, ISBN 92-67-10188-9. (Available from International Organization for Standardization, 1 rue de Varembé, Case Postale 56, CH-1211, Geneva 20, Switzerland.)