



Designation: E385 – 16

Standard Test Method for Oxygen Content Using a 14-MeV Neutron Activation and Direct-Counting Technique¹

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1. Scope

1.1 This test method covers the measurement of oxygen concentration in almost any matrix by using a 14-MeV neutron activation and direct-counting technique. Essentially, the same system may be used to determine oxygen concentrations ranging from under 10 $\mu\text{g/g}$ to over 500 mg/g , depending on the sample size and available 14-MeV neutron fluence rates.

NOTE 1—The range of analysis may be extended by using higher neutron fluence rates, larger samples, and higher counting efficiency detectors.

1.2 This test method may be used on either solid or liquid samples, provided that they can be made to conform in size, shape, and macroscopic density during irradiation and counting to a standard sample of known oxygen content. Several variants of this method have been described in the technical literature. A monograph is available which provides a comprehensive description of the principles of activation analysis using a neutron generator (1).²

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

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.* Specific precautions are given in Section 8.

2. Referenced Documents

2.1 ASTM Standards:³

¹ This test method is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.05 on Nuclear Radiation Metrology.

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² The boldface numbers in parentheses refer to a list of references at the end of the text.

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.

E170 Terminology Relating to Radiation Measurements and Dosimetry

E181 Test Methods for Detector Calibration and Analysis of Radionuclides

E496 Test Method for Measuring Neutron Fluence and Average Energy from ${}^3\text{H}(d,n){}^4\text{He}$ Neutron Generators by Radioactivation Techniques

2.2 U.S. Government Document:

Code of Federal Regulations, Title 10, Part 20⁴

3. Terminology

3.1 *Definitions* (see also Terminology E170):

3.1.1 *accelerator*—a machine that ionizes a gas and electrically accelerates the ions onto a target. The accelerator may be based on the Cockcroft-Walton, Van de Graaff, or other design types (1). Compact sealed-tube, mixed deuterium and tritium gas, Cockcroft-Walton neutron generators are most commonly used for 14-MeV neutron activation analysis. However, “pumped” drift-tube accelerators that use replaceable tritium-containing targets are also still in use. Reviews of operational characteristics, descriptions of accessory instrumentation, and applications of accelerators used as fast neutron generators for activation analysis are available (2,3).

3.1.2 *comparator standard*—a reference standard of known oxygen content whose specific counting rate ($\text{counts min}^{-1} [\text{mg of oxygen}]^{-1}$) may be used to quantify the oxygen content of a sample irradiated and counted under the same conditions. Often, a comparator standard is selected to have a matrix composition, physical size, density and shape very similar to the corresponding parameters of the sample to be analyzed.

3.1.3 *14-MeV neutron fluence rate*—the areal density of neutrons passing through a sample, measured in terms of neutrons $\text{cm}^{-2} \text{s}^{-1}$, that is produced by the fusion reaction of deuterium and tritium ions accelerated to energies of typically 150 to 200 keV in a small accelerator. Fluence rate has been commonly referred to as “flux density.” The total neutron fluence is the fluence rate integrated over time.

3.1.3.1 *Discussion*—The ${}^3\text{H}(d,n){}^4\text{He}$ reaction is used to

⁴ Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

produce approximately 14.7-MeV neutrons. This reaction has a Q -value of + 17.586 MeV.

3.1.4 *monitor*—any type of detector or comparison reference material that can be used to produce a response proportional to the 14-MeV neutron fluence rate in the irradiation position, or to the radionuclide decay events recorded by the sample detector. A plastic pellet with a relatively high oxygen content is often used as a monitor reference in dual sample transfer systems. It is never removed from the system regardless of the characteristics of the sample to be analyzed. It is important to distinguish that the monitor, whether an independent detector or an activated reference material, is not a standard used to scale the oxygen content of the samples to be measured, but rather is used to normalize the analysis system among successive analytical passes within the procedure.

3.1.5 *multichannel pulse-height analyzer*—an instrument that receives, counts, separates, and stores, as a function of their energy, pulses from a scintillation or semi-conductor gamma-ray detector and amplifier. In the 14-MeV instrumental neutron activation analysis (INAA) determination of oxygen, the multichannel analyzer may also be used to receive and record both the BF_3 neutron detector monitor counts and the sample gamma-ray detector counts as a function of stepped time increments (4-6). In the latter case, operation of the analyzer in the multichannel scaler (MCS) mode, an electronic gating circuit is used to select only gamma rays within the energy range of interest.

3.1.6 *transfer system*—a system, normally pneumatic, used to transport the sample from an injection port (sometimes connected to an automatic sample changer) to the irradiation station, and then to the counting station where the activity of the sample is measured. The system may include components to ensure uniform positioning of the sample at the irradiation and counting stations.

4. Summary of Test Method

4.1 The weighed sample to be analyzed is placed in a container for automatic transfer from a sample-loading port to the 14-MeV neutron irradiation position of a particle accelerator. After irradiation for a pre-selected time, the sample is automatically returned to the counting area. A gamma-ray detector measures the high-energy gamma radiation from the radioactive decay of the ^{16}N produced by the (n,p) nuclear reaction on ^{16}O . The number of counts in a pre-selected counting interval is recorded by a gated scaler, or by a multichannel analyzer operating in either the pulse-height, or gated multiscaler modes. The number of events recorded for samples and monitor reference standard are corrected for background and normalized to identical irradiation and counting conditions. If the sample and a monitor reference sample are not irradiated simultaneously, the neutron dose received during each irradiation must be recorded, typically by use of a BF_3 neutron proportional counter. The amount of total oxygen (all chemical forms) in the sample is proportional to the corrected and normalized sample count and is quantified by use of the corrected and normalized specific activity of the comparator standard(s).

4.1.1 ^{16}N decays with a half-life of 7.13 s by β -emission (7), thus returning to ^{16}O . From Ref (8), sixty seven percent of the decays are accompanied by 6.12863-MeV gamma rays, 4.9 % by 7.11515-MeV gamma rays, and 0.82 % by 2.7415-MeV gamma rays. Other lower intensity gamma rays are also observed. About 28 % of the beta transitions are directly to the ground state of ^{16}O . Useful elemental data including calculated sensitivities and reaction cross-sections for (14-MeV INAA) are provided in Refs (3) and (9). (See also Test Methods E181.)

5. Significance and Use

5.1 The conventional determination of oxygen content in liquid or solid samples is a relatively difficult chemical procedure. It is slow and usually of limited sensitivity. The 14-MeV neutron activation and direct counting technique provides a rapid, highly sensitive, nondestructive procedure for oxygen determination in a wide range of matrices. This test method is independent of the chemical form of the oxygen.

5.2 This test method can be used for quality and process control in the metals, coal, and petroleum industries, and for research purposes in a broad spectrum of applications.

6. Interferences

6.1 Because of the high energy of the gamma rays emitted in the decay of ^{16}N , there are very few elements that will produce interfering radiations; nevertheless, caution should be exercised. ^{19}F , for example, will undergo an (n,α) reaction to produce ^{16}N , the same indicator radionuclide produced from oxygen. Because the cross section for the $^{19}\text{F}(n,\alpha)^{16}\text{N}$ reaction is approximately one-half that of the $^{16}\text{O}(n,p)^{16}\text{N}$ reaction, a correction must be made if fluorine is present in an amount comparable to the statistical uncertainty in the oxygen determination. Another possible interfering reaction may arise from the presence of boron. ^{11}B will undergo an (n,p) reaction to produce ^{11}Be . This isotope decays with a half-life of 13.81 s, and emits several high-energy gamma rays with energies in the range of 4.67 to 7.98 MeV. In addition, there is Bremsstrahlung radiation produced by the high energy beta particles emitted by ^{11}Be . These radiations can interfere with the oxygen determination if the oxygen content does not exceed 1 % of the boron present.

6.2 Another possible elemental interference can arise from the presence of fissionable materials such as thorium, uranium, and plutonium. Many short-lived fission products emit high-energy gamma rays capable of interfering with those from ^{16}N .

NOTE 2—Argon produces an interferent, ^{40}Cl , by the $^{40}\text{Ar}(n,p)^{40}\text{Cl}$ reaction. Therefore, argon should not be used for the inert atmosphere during sample preparation for oxygen analysis. ^{40}Cl ($t_{1/2} = 1.35$ m) has several high-energy gamma rays, including one at 5.8796 MeV with a yield of 4.1 %.

6.3 An important aspect of this analysis that must be controlled is the geometry during both irradiation and counting. The neutron source is usually a disk source. Hence, the fluence rate decreases as the inverse square at points distant from the target, and less rapidly close to the target. Because of these fluence rate gradients, the irradiation geometry should be reproduced as accurately as possible. Similarly, the positioning of the sample at the detector is critical and must be accurately

reproducible. For example, if the sample is considered to be a point source located 6 mm from a cylindrical sodium iodide (NaI) detector, a 1-mm change in position of the sample along the detector axis was found to result in a 3.5 to 5 % change in detector efficiency (10). Since efficiency is defined as the fraction of gamma rays emitted from the source that interact with the detector, it is evident that a change in efficiency would result in an equal percentage change in measured activity and in apparent oxygen content. The sample and monitor (if present) may be rotated during exposure or counting, or both, to ensure exposure and counting uniformity. See, for example, Ref (11). For counting, dual detectors at 180° can be used as an alternative to rotation to minimize positioning errors at the counting station.

6.4 Since ^{16}N emits high-energy gamma rays, determinations are less subject to effects of self-absorption than are determinations based on the use of indicator radionuclides emitting lower energy gamma rays. Corrections for gamma-ray attenuation during counting are usually negligible, except for large samples as may be needed in the highest sensitivity determinations.

6.5 The oxygen content of the transfer container (“rabbit”) must be kept as low as possible to avoid a large “blank” correction. Suggested materials that combine light weight and low oxygen content are polypropylene and high-density polyethylene (molded under a nitrogen atmosphere), high purity Cu, and high-purity nickel. A simple subtraction of the counts from the blank vial in the absence of the sample is not adequate for oxygen determinations below 200 $\mu\text{g/g}$, since large sample sizes may be required for these high-sensitivity measurements and gamma-ray attenuation may be important when the sample is present (12). If the total oxygen content of the sample is as low as that of the container (typically about 0.5 mg of oxygen), the sample should be removed from the irradiation container prior to counting. Statistical errors increase rapidly as true sample activities decrease, while container contamination activities remain constant. For certain shapable solids, it may be possible to use no container at all (13). This “containerless” approach provides optimum sensitivity for low-level determinations, but care must be taken to avoid contamination of the transfer system.

6.6 Although the discriminator is used to eliminate the signal originating from gamma rays of energy less than 4.5 MeV, it is possible when analyzing certain materials that very high matrix activities can result in multiple gammas of lower energy being summed, thereby generating a signal in the energy window. This effect can be minimized by reducing the specific activity of the interfering radionuclide or by altering the counting geometry to reduce the solid angle. Since the decay of these “coincidence” events are subject to the half-life of the radionuclide from which they are emitted, it may be possible to differentiate the interfering signal from oxygen counts by decay rate if using an MCS-based system (14).

7. Apparatus

7.1 *14-MeV Neutron Generator*—Typically, this is a high-voltage sealed-tube machine to accelerate both deuterium and

tritium ions onto a target to produce 14-MeV neutrons by the $^3\text{H}(d,n)^4\text{He}$ reaction. In the older “pumped” drift-tube accelerators, and also in some of the newer sealed-tube neutron generators, deuterium ions are accelerated into copper targets containing a deposit of titanium into which tritium is absorbed. Detailed descriptions of both sealed-tube and drift-tube machines have been published (1, 3).

7.1.1 Other nuclear reactions may be used, but the neutron energy must exceed 10.22 MeV (15) for the $^{16}\text{O}(n,p)^{16}\text{N}$ reaction to take place. The 14-MeV neutron output of the generator should be 10^9 to 10^{12} neutrons s^{-1} , with a usable fluence rate at the sample of 10^7 to 10^9 neutrons $\text{cm}^{-2} \text{s}^{-1}$. The 14-MeV fluence rate may be measured as described in Test Method E496.

7.1.2 The neutron output from targets in drift-tube machines decreases quite rapidly during use because of depletion of the tritium content of the target in the pumped system. Consequently, the target must be replaced frequently. The use of a sealed-tube-type neutron generator obviates the need to handle tritium targets and provides for longer stable operation.

7.2 *Sample Transfer System*—The short half-life (7.13 s) of the ^{16}N requires that the sample be transferred rapidly between the irradiation position and the counting station by a pneumatic system to minimize decay of the ^{16}N . If the oxygen content in the sample is low, it is desirable to use dry nitrogen, rather than air, in the pneumatic system to avoid an increase in radioactivity due to recoil of ^{16}N atoms produced in the air onto the sample surface or other transfer of irradiated air back to the counting station. The transfer system and data processing may be controlled directly by laboratory computers (16), or by programmable logic controllers (5,6). Dual transfer systems transport the sample and a monitor reference standard simultaneously. In this case, two independent counting systems are often used. Single sample transfer systems based on sequential irradiations of a sample and a comparator standard, are also used.

NOTE 3—As mentioned previously in 6.2, argon should be avoided in the transfer gas, as well as in sample packaging, because of the interferent ^{40}Cl produced.

7.3 *Monitor*—The number of counts obtained from any given irradiation is dependent upon the oxygen content of the sample, the length of irradiation, the neutron fluence rate, the neutron energy spectrum, the delay time between irradiation and counting, and the length of the count. It is desirable to make a measurement in which the result obtained is a function of only the oxygen content and independent of other variables. This can be achieved by standardizing the experimental conditions and use of a monitor.

7.3.1 In the dual sample transfer approach, the monitor is ordinarily a high-oxygen containing material that is irradiated with each sample in a position adjacent to the sample position, transferred to an independent detector, and counted simultaneously with the sample. The same monitor reference is used with each sample, and is never removed from the system. Since the sample and monitor reference are irradiated and counted simultaneously, and ^{16}N is measured in both, most changes in the experimental parameters affecting the sample counts will affect the monitor counts equally. One possible exception is

that changes in the neutron energy spectrum due to incident accelerator particle energy changes may affect the sample and monitor in different ways due to angular dependence factors. However, a relatively constant particle energy can usually be achieved. Therefore, while the number of counts obtained from any given sample may vary greatly from one irradiation to another, the ratio of sample counts to monitor reference counts will be a constant. To determine the oxygen content of a sample, it is necessary to irradiate a comparator standard of known oxygen content with physical and chemical properties similar to those of the sample and determine the ratio of its counts to that of the monitor reference as well.

7.3.2 If a single sample transfer system is used, it is necessary to measure the neutron fluence rate during both the irradiation of the sample and the irradiation of the comparator standard. Variations in fluence rate from a neutron generator are to be expected, not only with time, but also with position. Compensation for these variations must be provided. It is not necessary to make an absolute measurement of the fluence rate at the irradiation position, but only to obtain a value that is proportional to the neutrons $\text{cm}^{-2} \text{s}^{-1}$ passing through the sample. A wide variety of ingenious systems have been devised and used for this purpose (17). Probably the most commonly used and simplest system is a boron trifluoride (BF_3) counter coupled to a rate meter, scaler, or multichannel analyzer operating in the multichannel scaler mode to detect thermalized neutrons. The greatest difficulty with this system is that it detects thermal neutrons, while the oxygen reaction proceeds only with fast neutrons. Therefore, the BF_3 monitor, encased in a polyethylene cover to thermalize the fast neutrons from the generator, does not directly measure neutrons of the energy used for the analyses. Hence, the presumption of proportionality may not always be valid unless the neutron spectrum is constant. Fortunately, most newer sealed-tube generators provide consistent incident particle energies, reducing the likelihood of a variable energy spectrum during a single experiment. Another difficulty is that, if only a single scaler is used, total neutron fluence during the irradiation and not a representative fluence rate is measured. Since the length of irradiation is ordinarily at least as long as the half-life of the ^{16}N , any changes in fluence rate during irradiation will introduce an error. This error can be overcome by using a pulse-height analyzer operating in the multichannel scaler mode and recording the BF_3 monitor output and the induced ^{16}N activity on the same multiscaler pass (4-6, 18). Changes in beam intensity can then be precisely compensated for by mathematically treating each channel recording the relative neutron fluence rate as an individual irradiation and decay correcting its relative contribution to the oxygen counts over the remainder of the irradiation period. This produces a beam normalization value that is tailored to correct for beam variations during the irradiation as well as beam intensity differences between irradiations.

7.3.3 Variations in the positions of the sample or monitor reference relative to the neutron generator will cause a variation in the ratio of sample counts to monitor counts. In order to avoid the effects of this nonuniformity, both the sample and the monitor reference standard can be rotated about an axis parallel

to the beam during irradiation. Selection of experimental irradiation and counting geometries normally can be done in such a way as to avoid significant errors (see 7.4.2).

7.3.4 The short half-life of ^{16}N imposes some restrictions on the timing of the various steps of the analysis. For maximum accuracy in a single sample transfer system, the entire cycle of irradiation, transfer, and counting should be controlled automatically so that all times are reproduced within a few hundredths of a second. Alternately, the entire irradiation and counting process may be recorded by a multichannel analyzer operating in the multichannel scaler mode and the parameters later normalized by use of a computer program (4-6). Precise control or measurements of time and fluence rate are not usually necessary when a monitor reference is irradiated simultaneously with the sample in a dual sample transfer and counting system.

7.4 Counting Equipment:

7.4.1 *Irradiation Container Receiver and Stopping Devices*—These are devices to accept the sample following irradiation, and to position it reproducibly for counting.

7.4.2 *Gamma Detector, or Detectors*—Detectors at least equal in sensitivity to a single 3 by 3-in. (76 by 76-mm) thallium-activated sodium iodide (NaI(Tl)) scintillation counter should be used. Both the sensitivity and reproducibility of the measurement will be affected by the choice of radiation detectors. Where energy discrimination is required, the superior resolution of a semi-conductor high-purity Ge (HPGe) detector may be desirable. However, use of an affordable HPGe detector may also result in some loss of efficiency, as compared to use of a NaI(Tl) detector. Systems based on use of a large well-type NaI(Tl) detector, or two 5 by 5-in. (127 by 127-mm) solid NaI(Tl) detectors mounted at 180°C are commonly used for higher efficiency counting. Bismuth germanate (BGO) scintillation detectors have higher efficiencies than NaI(Tl) detectors for the high-energy gamma rays from ^{16}N , but are also presently much more costly than equivalent-size NaI(Tl) crystals. BGO detectors also have poorer energy resolution than NaI(Tl) detectors and this could be a consideration in some types of analyses. In general, the sensitivity of oxygen analysis will be increased by increasing the volume of the detector, and analytical reproducibility will be increased by the use of multiple detectors. If a single detector is used, but not a well counter, the sample should be rotated during counting to minimize the effects of sample nonhomogeneity and positioning. An external radiation shield of heavy metal sufficient to reduce the detector background to an acceptable level should surround the detector assembly.

7.4.3 *Electronic Equipment*—Amplifiers, discriminators or multichannel analyzers, and data storage devices capable of taking the pulse from the detector, amplifying and shaping it, distinguishing it by its energy, and storing it are required.

7.4.4 *Scaler or Multichannel Pulse-Height Analyzer*—If a scaler is used for data collection, it should have a suitable speed to minimize dead-time losses and prevent pulse pileup. It should be preceded in the counting system by an energy analyzer. If a multichannel pulse-height analyzer is used, cognizance must be taken of the need for a dead-time correction. Very high counting rates with dead time may also result in