Designation: D7315 – 12

Standard Test Method for Determination of Turbidity Above 1 Turbidity Unit (TU) in Static Mode[1]

This standard is issued under the fixed designation D7315; 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 test method covers the static determination of turbidity in water. Static refers to a sample that is removed from its source and tested in an isolated instrument. (See Section 4.)

1.2 This test method is applicable to the measurement of turbidities greater than 1.0 turbidity unit (TU). The upper end of the measurement range was left undefined because different technologies described in this test method can cover very different ranges. The round robin study covered the range of 0–4000 turbidity units because instrument verification in this range can typically be covered by standards that can be consistently reproduced.

1.3 Many of the turbidity units and instrument designs covered in this test method are numerically equivalent in calibration when a common calibration standard is applied across those designs listed in Table 1. Measurement of a common calibration standard of a defined value will also produce equivalent results across these technologies.

1.3.1 In this test method calibration standards are often defined in NTU values, but the other assigned turbidity units, such as those in Table 1 are equivalent. For example, a 1 NTU formazin standard is also a 1 FNU, a 1 FAU, a 1 BU, and so forth.

1.4 This test method does not purport to cover all available technologies for high-level turbidity measurement.

1.5 This test method was tested on different natural waters and wastewater, and with standards that will serve as surrogates to samples. It is the user's responsibility to ensure the validity of this test method for waters of untested matrices.

1.6 Depending on the constituents within a high-level sample, the proposed sample preparation and measurement methods may or may not be applicable. Those samples with the highest particle densities typically prove to be the most difficult to measure. In these cases, and alternative measurement method such as the process monitoring method can be considered.

1.7 *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. Refer to the MSDSs for all chemicals used in this procedure.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1129 Terminology Relating to Water

D1193 Specification for Reagent Water

D1889 Test Method for Turbidity of Water (Withdrawn 2007)[3]

D2777 Practice for Determination of Precision and Bias of Applicable Test Methods of Committee D19 on Water

D4411 Guide for Sampling Fluvial Sediment in Motion

D5847 Practice for Writing Quality Control Specifications for Standard Test Methods for Water Analysis

D6855 Test Method for Determination of Turbidity Below 5 NTU in Static Mode

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

2.2 *Other Referenced Standards:*

USEPA Method 180.1 Methods for Chemical Analysis of Water and Wastes, Turbidity[4]

ISO 7027 Water Quality—Determination of Turbidity[5]

United States Geological Survey (USGS) National Field

[1] This test method is under the jurisdiction of ASTM Committee D19 on Water and is the direct responsibility of Subcommittee D19.07 on Sediments, Geomorphology, and Open-Channel Flow.

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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.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Available from United States Environmental Protection Association (EPA), Ariel Rios Bldg., 1200 Pennsylvania Ave., NW, Washington, DC 20460, http://www.epa.gov.

[5] Available from International Organization for Standardization (ISO), 1 rue de Varembé, Case postale 56, CH-1211, Geneva 20, Switzerland, http://www.iso.ch.

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TABLE 1 Summary of Known Instrument Designs, Applications, Ranges, and Reporting Units

Design and Reporting Unit	Prominent Application	Key Design Features	Typical Instrument Range	Suggested Application Ranges
Nephelometric non-ratio (NTU)	White light turbidimeters. Comply with USEPA Method 180.1 for low level turbidity monitoring.	Detector centered at 90° relative to the incident light beam. Uses a white light spectral source.	0.0–40	0.0–40 Regulatory
Ratio White Light turbidimeters (NTRU)	Complies with ISWTR regulations and Standard Method 2130B. Can be used for both low and high level measurement.	Used a white light spectral source. Primary detector centered at 90°. Other detectors located at other angles. An instrument algorithm uses a combination of detector readings to generate the turbidity reading.	0–10 000	0–40 Regulatory 0–10 000 other
Nephelometric, near-IR turbidimeters, non-ratiometric (FNU)	Complies with ISO 7027. The wavelength is less susceptible to color interferences. Applicable for samples with color and good for low level monitoring.	Detector centered at 90° relative to the incident light beam. Uses a near-IR (780–900 nm) monochromatic light source.	0–1000	0–40 Regulatory (non-US) 0–1000 other
Nephelometric near-IR turbidimeters, ratio metric (FNRU)	Complies with ISO 7027. Applicable for samples with high levels of color and for monitoring to high turbidity levels.	Uses a near-IR monochromatic light source (780–900 nm). Primary detector centered at 90°. Other detectors located at other angles. An instrument algorithm uses a combination of detector readings to generate the turbidity reading.	0–10 000	0–40 Regulatory 0–10 000 other
Surface Scatter Turbidimeters (NTU)	Turbidity is determined through light scatter from or near the surface of a sample.	Detector centered at 90° relative to the incident light beam. Uses a white light spectral source.	10–10 000	10–10 000
Formazin Back Scatter (FBU)	Not applicable for regulatory purposes. Best applied to high turbidity samples. Backscatter is common with but not all only probe technology and is best applied in higher turbidity samples.	Uses a near-IR monochromatic light source in the 780–900 nm range. Detector geometry is between 90° and 180° relative to the incident light beam.	100–10 000+	100–10 000
Backscatter Unit (BU)	Not applicable for regulatory purposes. Best applied for samples with high level turbidity.	Uses a white light spectral source (400–680 nm range). Detector geometry is between 90° and 180° relative to the incident light beam.	10–10 000+	100–10 000+
Formazin attenuation unit (FAU)	May be applicable for some regulatory purposes. This is commonly applied with spectrophotometers. Best applied for samples with high level turbidity.	Detector is geometrically centered at 0° relative to incident beam (attenuation). Wavelength is 780–900 nm.	20–1000	20–1000 Regulatory
Light attenuation unit (AU)	Not applicable for some regulatory purposes. This is commonly applied with spectrophotometers.	Detector is geometrically centered at 0° relative to incident beam (attenuation). Wavelength is 400–680 nm.	20–1000	20–1000
Nephelometric Turbidity Multibeam Unit (NTMU)	Is applicable to EPA regulatory method GLI Method 2. Applicable to drinking water and wastewater monitoring applications.	Detectors are geometrically centered at 0° and 90°. An instrument algorithm uses a combination of detector readings, which may differ for turbidities varying magnitude.	0.02–4000	0–40 Regulatory 0–4000 other

Manual for the Collection of Water Quality Data[6]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method refer to Terminology D1129.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *turbidity, n*—An expression of the optical properties of a sample that causes light rays to be scattered and absorbed rather than transmitted in straight lines through the sample.

3.2.1.1 *Discussion*—turbidity of water is caused by the presence of matter such as clay, silt, finely divided organic matter, plankton, other microscopic organisms, organic acids, and dyes.

3.2.2 *turbidimeter, n*—An instrument that measures light scatter,caused by particulates within a sample and converts the measurement to a turbidity value.

3.2.2.1 *Discussion*—the detected light is quantitatively converted to a numeric value that is traced to a light-scatter standard. See Table 1 for examples of designs.

3.2.3 *reference turbidity standard, n*—A standard that is synthesized reproducibly from traceable raw materials by the user.

[6] Available from United Stated Geological Survey (USGS), 12201 Sunrise Valley Drive, Reston, VA 20192, http://www.usgs.gov.

3.2.3.1 *Discussion*—all other standards are traced back to this standard. The reference standard for turbidity is formazin (see 9.2.2).

3.2.4 *calibration turbidity standard, n*—A turbidity standard that is traceable and equivalent to the reference turbidity standard to within statistical errors; calibration turbidity standards include commercially prepared 4000 NTU Formazin, stabilized formazin (see 9.2.3), and styrenedivinylbenzene (SDVB) (see 9.2.4).

3.2.4.1 *Discussion*—these standards may be used to calibrate the instrument.

NOTE 1—Calibration standards may be instrument design specific.

NOTE 2—Calibration standards that exceed 10 000 turbidity units are commercially available.

3.2.5 *calibration verification standards, n*—Defined standards used to verify the accuracy of a calibration in the measurement range of interest.

3.2.5.1 *Discussion*—these standards may not be used to perform calibrations, only calibration verifications. Included standards are opto-mechanical light scatter devices, gel-like standards, or any other type of stable liquid standard.

NOTE 3—Calibration verification standards may be instrument design specific.

3.2.6 *nephelometric turbidity measurement, n*—The measurement of light scatter from a sample in a direction that is at 90° with respect to the centerline of the incident light path.

3.2.6.1 *Discussion*—units are NTU (Nephelometric Turbidity Units). When ISO 7027 technology is employed units are in FNU (Formazin Nephelometric Units).

3.2.7 *ratio turbidity measurement, n*—The measurement derived through the use of a nephelometric detector that serves as the primary detector and one or more other detectors used to compensate for variation in incident light fluctuation, stray light, instrument noise, or sample color.

3.2.8 *stray light, n*—All light reaching the detector other than that which is scattered by the sample.

3.2.8.1 *Discussion*—for example: ambient light leakage, internal reflections and divergent light in optical systems. For this test method stray light is likely to be negligible. The instrument design is intended to reduce or eliminate stray light.

3.2.9 *seasoning, v*—The process of conditioning labware with the standard to be diluted to a lower value.

3.2.9.1 *Discussion*—the process reduces contamination and dilution errors.

3.2.10 *attenuation, v*—The amount of incident light that is scattered and absorbed before reaching a detector, which is geometrically centered at 0° relative to the centerline of the incident light beam.

3.2.10.1 *Discussion*—attenuation is inversely proportional to transmitted signal.

$$\text{Attenuated Turbidity} = \text{Absorbed Light} + \text{Scattered Light}$$

NOTE 4—The application of attenuation in this test method is as a distinct means of measuring turbidity. When measuring in the FAU or AU mode, the turbidity value is a combination of scattered (attenuated) plus absorbed light. The scattered light is affected by particle size and is a positive response. The absorption due to color is a negative. The sum of these two entities results in the turbidity value in the respective units.

3.2.11 *surface scatter turbidimeter, n*—An instrument that determines the turbidity through incident light scatter that occurs at or slightly below the surface of a water sample with a detection angle that is at 90° relative to the incident light beam.

3.2.11.1 *Discussion*—interferences are not as substantial as nephelometric non-ratio measurements.

4. Summary of Test Method

4.1 The optical property expressed as turbidity is measured by the scattering effect that constituents within a sample have on light; the higher the quantity of scattered or attenuated incident light, the higher the turbidity. In samples containing particulate material, light scatter and attenuation will vary *(1)* due to size, shape and composition of the particles in the water, and *(2)* the wavelength of the incident light.

4.2 This test method is based upon a comparison of the amount of light scattered or attenuated by the sample with the amount of light scattered or attenuated by a reference suspension. Lower turbidity values are typically determined by a nephelometer, which measures light scatter from a sample in a direction that is at 90° with respect to the centerline of the incident light path. High-level turbidity determination can be performed using many different technologies. It is critical when reporting the measurement, traceability to the type of technology be used. Turbidity measurements are not often consistent among differing technologies.

5. Significance and Use

5.1 Turbidity at the levels defined in the scope of this test method are often monitored to help control processes, monitor the health and biology of water environments and determine the impact of changes in response to environmental events (weather events, floods, etc.). Turbidity is often undesirable in drinking water, plant effluent waters, water for food and beverage processing, and for a large number of other water-dependent manufacturing processes. Removal is often accomplished by coagulation, sedimentation, and various levels of filtration. Measurement of turbidity provides an indicator of contamination, and is a vital measurement for monitoring the characteristics and or quality within the sample's source or process.

5.2 This test method does overlap Test Method D6855 for the range of 1–5 TU. If the predominant measurement falls below 1.0 TU with occasional spikes above this value, Test Method D6855 may be more applicable. For measurements that are consistently above 1 TU, this test method is applicable.

5.3 This test method is suitable to turbidity such as that found in all waters that measure above 1 NTU. Examples include environmental waters (streams, rivers, lakes, reservoirs, estuaries), processes associated with water pollution control plants (wastewater treatment plants), and various industrial processes involving water with noticeable turbidity. For measurement of cleaner waters, refer to Test Method D6855.

5.4 The appropriate measurement range for a specific technology or instrument type that should be utilized is at or below

80 % of full-scale capability for the respective instrument or technology. Measurements above this level may not be dependable.

5.4.1 Dilutions of waters are not recommended, especially in the case of samples with rapidly settling particles (that is, sediments). It is recommended that an appropriate instrument design that covers the expected range be selected to avoid the need to perform dilutions.

5.5 Technologies described in this standard may not measure all aspects (absorption and scatter) of a sample. Some of the properties of the water, the suspended material, or both may interfere with the certain measured property of the sample, such as the scattering of light that the particular instrument is measuring.

5.6 Several different technologies are available for use in the measurement of high-level turbidity. Some technologies may be better suited for specific types of samples, depending on the application and measurement criteria. Please refer to Table 1 and Appendix X1 which is a flow chart to help assist in selecting the best technology for the specific application.

5.6.1 When measuring high levels of turbidity the samples will often contain significant interferences such as that from absorbing particles, absorbance in the matrix, and rapidly settling particles. These may have a significant impact on how one measurement technology responds to changes in turbidity. Often times it will be prudent to run a series of linear dilutions to determine if the measured response was expected relative to the dilution. In cases where the response to dilution ratio is linear, the technology may be adequately accounting for the interferences. If the response is not expected, another technology should be considered to determine if a more accurate measurement could be obtained.

5.7 When reporting the measured result, appropriate units should also be attached. The units are reflective of the technology used to generate the measurements. The intention is to provide traceability for the technology used to generate the measured result, and if necessary, provide more adequate comparison to historical data. Section 7 describes technology that each type of traceable reporting units is based.

5.7.1 Table 1 contains the list of technologies and respective reporting units that will be traceable to that technology.

5.7.1.1 The methods in Table 1 can be broken down into two distinct groups of designs which are based on the type of incident light source used. These are broad-band white light source or light sources that provide a spectral output in the 400–680 nm range. These include polychromatic light sources, such as those that are necessary to comply with regulatory method USEPA Method 180.1, but also can include monochromatic light sources if the respective wavelength falls within the specified range. The second group of instruments uses a near IR monochromatic light source that is in the range of 780 to 900 nm. These designs are distinguishable in the reporting units and will always begin with the letter F.

5.7.1.2 For a specific design that falls outside of these reporting ranges, the turbidity should be reported in turbidity units (TU) with a subscripted wavelength value to characterize the light source that was used. See 7.4.3.

5.7.1.3 Those designs listed in Table 1 cover those that were currently identified by the ASTM subcommittee. Future designs that are not covered in this document may be incorporated into a future revision after review by the method subcommittee.

5.7.1.4 See Section 7 for more details regarding instrument designs.

5.7.1.5 Section 16 contains precision and bias data that incorporates the different classifications of technologies. The precision and bias section includes the overall data set of all laboratories and smaller segments of this data set to provide comparisons across distinguishing technological features that are exhibited by those technologies that are represented in this test method.

5.8 This test method covers the measurement of samples collected from waters and analyzed using typical laboratory based or portable-based instruments.

6. Interferences

6.1 Bubbles, although they cause turbidity, may result in interferences in measured turbidity as determined by this test method. Bubbles cause a positive interference and color typically causes a negative interference. Dissolved material that imparts a color to the water may cause errors in pure nephelometric readings, unless the instrument has special compensating features to reduce these interferences. Certain turbulent motions also create unstable reading conditions of nephelometers.

6.2 Color is characterized by absorption of specific wavelengths of light. If the wavelengths of incident light are significantly absorbed, a negative interference will result unless the instrument has special compensating features. Depending on the application color may or may not be considered as an interference. Some instrument designs are intended to remove the effect that color imparts on a turbidity measurement. Other designs do not remove the effects of color.

6.2.1 Those designs where color effects can be reduced or eliminated include nephelometric-based designs with incident light sources in the 780–900 nm range. Those designs that have additional detectors, such as ratioing instruments also help to reduce the effects of color regardless of the light source. Single detector systems with light sources below 780 nm will be more impacted by the effects of color in the sample, that is, color visible to the naked eye. Color can have a significant impact on attenuation-based instruments if it has absorption spectrum that overlaps the spectral output of the incident light source.

6.3 Scratches, finger marks, or dirt on the walls of the sample cell may give erroneous readings, especially at lower turbidity levels. Sample cells should be kept scrupulously clean both inside and outside and discarded when they become etched or scratched. The sample cells must not be handled where the light strikes them when positioned in the instrument well.

6.4 Sample cell caps and liners must also be scrupulously clean to prevent contamination of the sample. Seasoning of the sample cells should be performed each time a new sample is measured.

6.5 The optical quality and geometry of the sample cells can also impact results. At all turbidity levels, sample cells that are not optically consistent can result in error. Errors greater than 10 % relative to the turbidity value can be reduced through indexing or replacement of the cells. See Section 16 for additional information.

6.5.1 Sample cells should be optically matched or a single cell should be used to perform calibrations and measurements.

6.6 Particle size and distribution will also impact turbidity and is sensitive to the different types of technologies used. Typically, small particles will more effectively scatter light in the nephelometric direction (at 90° relative to the incident light beam) than larger particles. Overall, however, it is the net aggregate scatter and attenuation of the available incident light by all particles that in the sample that contribute to the measurement.

6.7 The path-length of the sample cell or equivalent will impact the sensitivity of measurements. A shorter path length will extend the range and reduce the interference proportionally. However, use of a shorter path-length will reduce the sensitivity of the measurement.

6.8 Ideally, the same indexed sample cell should be used first for standardization followed by unknown (sample) determination. If this is not possible, then sample cells must be matched. Refer to the instrument manual or the standard's manufacturer for instructions regarding the matching of sample cells.

NOTE 5—Indexing of the sample cell to the instrument well is accomplished by placing a mark on the top of the sample cell and a similar mark on the upper surface of the well so that the sample cell can be placed in the well in an exact position each time.

6.9 Condensation on optical elements or sample cells can lead to severe errors in measurement.

6.10 Rapidly settling particles are also an interference. Particles such as sand can settle rapidly and cause false high or false low turbidity readings. The user of this test method must use care to ensure particles are suspended in solution the instant that the measurement is taken.

7. Apparatus

7.1 There are several technologies that are capable of measuring turbidity that exceeds 1.0 turbidity unit. A summary of these technologies is provided in Table 1. Within this table, suggested reporting units, which are representative to the technology, are included.

7.2 Several technologies for measuring high-level turbidity are discussed in this test method. They include nephelometer-based instruments (see Figs. 1-3), backscatter based instruments (see Fig. 4), and attenuation-based instruments (see Fig. 5). These are all discussed in more detail.

7.2.1 Nephelometers include the Photoelectric Nephelometer, Ratio Photoelectric Nephelometer with single beam design, and ratio photoelectric nephelometer in the dual beam design. The correlation between detector response and increasing turbidity levels is positive.

7.2.2 Backscatter turbidimeters typically employ similar light sources used in the photoelectric photometer but utilize a detection angle that is capable of detecting backscattered light from a sample. The correlation between detector response and increasing turbidity levels is positive.

7.2.3 Attenuation-based turbidimeters employ a detection angle that is 0° relative to the incident light beam.

7.3 The resolution of the instruments should permit detection of differences of at least 1 % of the range in which it is used. See Section 14 for rounding the reporting values of turbidity.

7.3.1 Consult the manufacturer to determine that your instrument meets any of the designs that are discussed in this test method.

7.4 *The Nephelometer:*

7.4.1 This instrument uses a light source for illuminating the sample and a single photodetector with a readout device to indicate the intensity of light scattered at right angle(s) (90°) to the centerline of the path of the incident light. The photoelectric nephelometer should be designed so that minimal stray light reaches the detector in the absence of turbidity and should

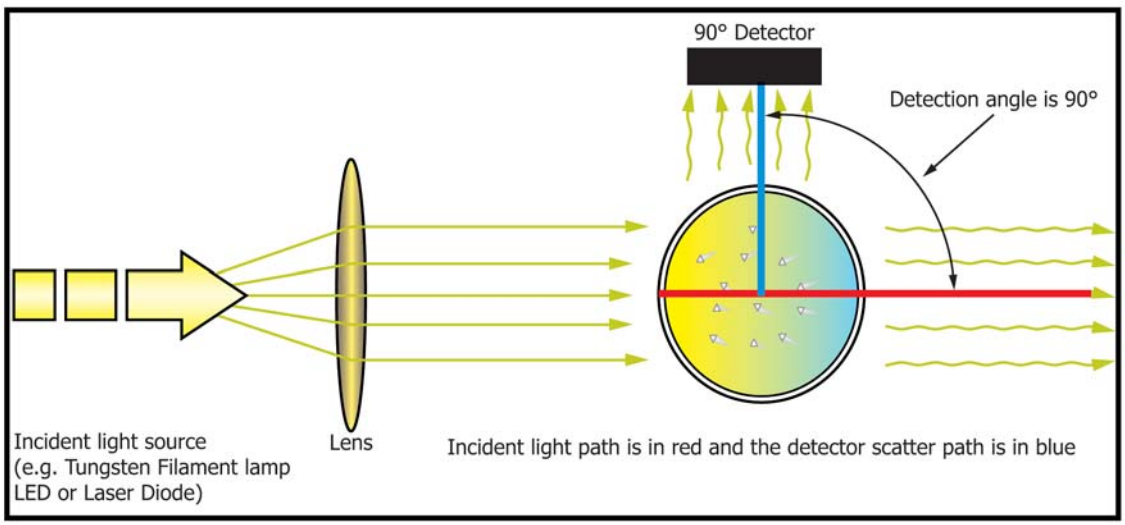

FIG. 1 Typical Nephelometer

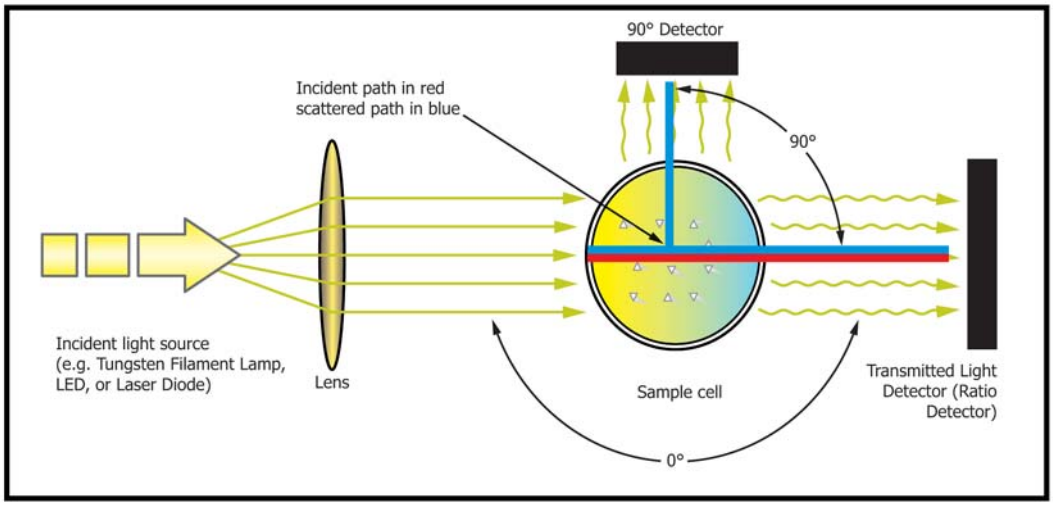

FIG. 2 Ratio Nephelometer (Single Beam Design)

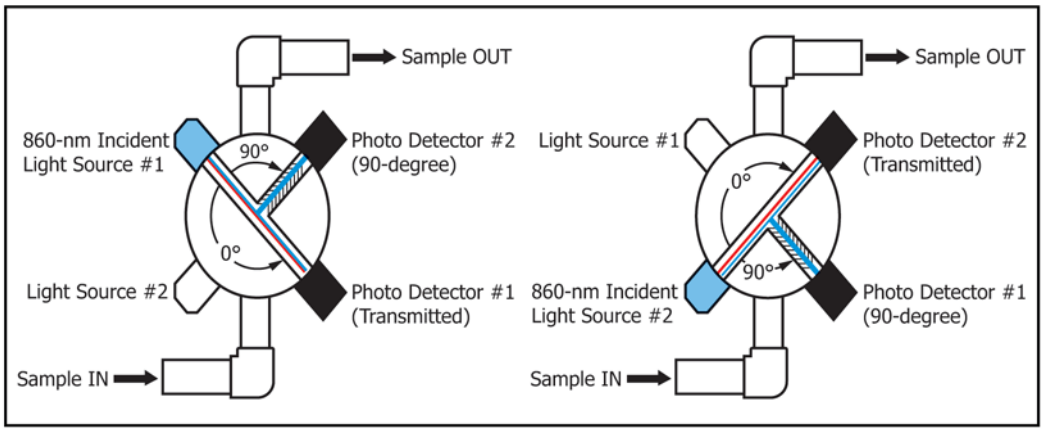

FIG. 3 Ratio Nephelometer (Multiple Beam Design)– The blue traces show the path of the scattered light.

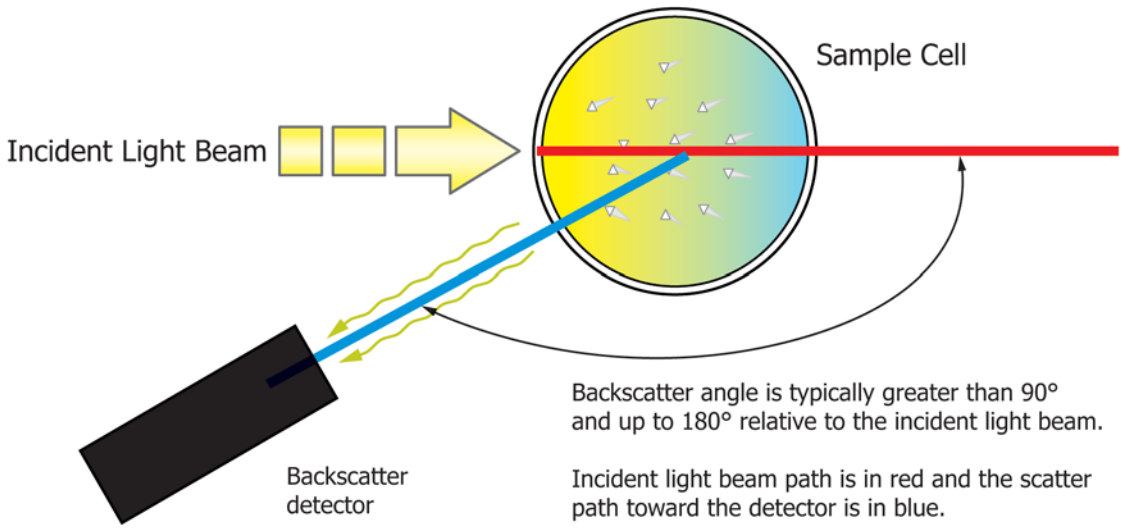

FIG. 4 Geometric Diagram of a Backscatter Measurement (<90°)-In the design shown, pathlength varies, depending on the turbidity of the sample.

be free from significant drift after a short warm-up period. The light source shall be a tungsten lamp operated at a color temperature between 2200 and 3000 K (USEPA Method 180.1). Light-emitting diodes (LEDs) or laser diodes in defined

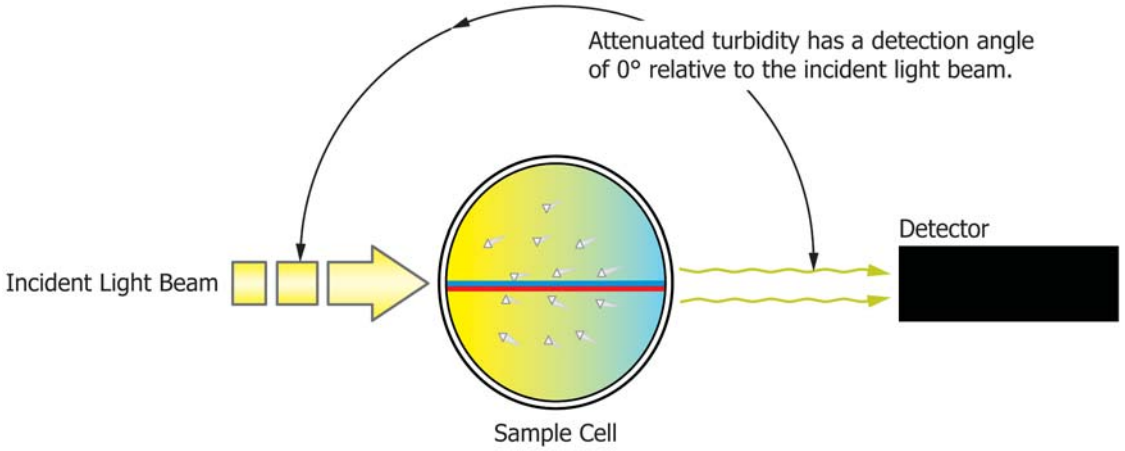

FIG. 5 Technology Diagram of an Attenuation Technology - The scatter and attenuation path is the same as the incident light path

wavelengths ranging from 400–680 nm and 780–900 nm may also be used if accurately characterized to be equivalent in performance to tungsten using the same type of calibration and calibration verification standards. It is important to note that new technologies may not be covered by this test method. If LEDs or laser diodes are used, then the LED or laser diode should be coupled with a monitor detection device to achieve a constant output. LEDs and laser diodes should be characterized by a wavelength of between 400 and 900 nm with a bandwidth of less than 60 nm. The total distance traversed by incident light and scattered light within the sample is not to exceed 10 cm. The angle of light acceptance to the detector shall be centered at 90° to the centerline of the incident light path and shall not exceed ±10° from the 90° scatter path centerline. The detector must have a spectral response that is sensitive to the spectral output of the incident light used.

7.4.2 Differences in physical design of nephelometers may cause differences in measured values for turbidity even though the same suspension is used for calibrations. Comparability of measurements made using instruments differing in optical and physical designs is not recommended. To minimize initial differences, the following design criteria should be observed (see Fig. 1).

7.4.3 Report in units of NTU if a white light source was used or in units of FNU if a 780–900 nm light source was used.

7.5 *Ratio Nephelometer:*

7.5.1 *Ratio Nephelometer* (see Fig. 2 for single beam design; see Fig. 3 for multiple beam design)—This instrument uses the measurement derived through the use of a nephelometric detector that serves as the primary detector and one or more other detectors used to compensate for variation in incident light fluctuation, stray light, instrument noise, or sample color. As needed by the design, additional photodetectors may be used to detect the intensity of light scattered at other angles. The signals from these additional photodetectors may be used to compensate for variations in incident light fluctuation, instrument stray light, instrument noise, sample color, or combinations thereof. The ratio photoelectric nephelometer should be so designed that minimal stray light reaches the detector(s), and should be free from significant drift after a short warm-up period. The light source should be a tungsten lamp, operated at a color temperature between 2200 and 3000 K (USEPA Method 180.1). LEDs and laser diodes in defined wavelengths ranging from 400 to 900 nm may also be used. If an LED or a laser diode is used in the single beam design, then the LED or laser diode should be coupled with a monitor detection device to achieve a consistent output. The distance traversed by incident light and scattered light within the sample is not to exceed 10 cm. The angle of light acceptance to the nephelometric detector(s) should be centered at 90° to the centerline of the incident light path and should not exceed ±10° from the scatter path centerline. The detector must have a spectral response that is sensitive to the spectral output of the incident light used. The instrument calibration (algorithm) must be designed such that the scaleable reading is from the nephelometric detector(s), and other detectors are used to compensate for instrument variation described in 7.4.1.

7.5.2 Differences in physical design of ratio photoelectric nephelometers may cause differences in measured values for turbidity even when the same suspension is used for calibrations. Comparability of measurements made using instruments differing in optical and physical design is not recommended. To minimize initial differences, the following design criteria should be observed (see Figs. 2 and 3).

7.5.3 Report in the appropriate units using Table 1 as guidance.

7.5.3.1 FNRU, and FNMU signify the use of an incident light wavelength between 780–900 nm. NTRU and NTMU signify the use of an incident light in the wavelength range of 400–680 nm for a ratio technology.

7.6 *Backscatter Turbidimeters:*

7.6.1 The instrumentation contains a light source that meets or exceeds the criteria specified in 7.4.1 for illumination of the sample.

7.6.2 The response curve of the detector should be such that it overlaps the output of the light source.

7.6.3 The detection angle for backscatter is between 90° and 180° relative to the centerline of the incident light beam. See Fig. 4.

7.6.4 When reporting turbidity, report in units that best fit the light source and detector in Table 2. Report in BU (white light source) or FBU (if a 780–900 nm light source was used).

TABLE 2 Reporting of Results for High Level Static Turbidity Measurements

NOTE 1—New developments in technologies may allow instruments to extend beyond range.

Measured Value In Appropriate Units	Report to Nearest
1.0* < 9.9	0.1
10 < 99	1
100–999	5
1000 <	50

7.7 *Attenuation-Based Turbidimeters:*

7.7.1 The instrument contains a light source that meets or exceeds the criteria specified in 7.4.1 for illumination of the sample. Examples include monochromatic light such as those generated in spectrophotometers.

7.7.2 The detector response curve should overlap the incident light source.

7.7.3 The detection angle for attenuation is to be set at 0° relative to the centerline of the incident light beam. See Fig. 5.

7.7.4 When reporting turbidity, report in units that best fit the light source and detector in Table 1. Report in AU (white light source) or FAU (if a 780–900 nm light source was used).

7.8 *Sample Cells* (if used with typical benchtop or portable instruments):

7.8.1 The sample cells used in calibration and sample measurement must be the following:

7.8.1.1 Clear, colorless glass or optically clear plastic, be kept scrupulously clean, both inside and out, and discarded when it becomes etched or scratched (see non-mandatory Appendix X3 for sample cell cleaning procedure).

7.8.1.2 Index marked so that repeated exact placements into the instrument sample cell compartment for measurement can be made. The location of the index mark should be such that the window of movement is less than 10° of rotation where the measurement is consistent. See 11.4.2.1.

7.8.1.3 Cells should be handled where the light path does not pass during measurement. Provision should be made in design to give the sample cell a proper place in which to handle the cell during calibration or sample measurement procedure.

7.8.1.4 The outside surface of a glass sample cell may be oiled, using silicone oil and a soft cloth, or a lint free laboratory tissue to minimize imperfections that could cause light to scatter off the surface of this sample cell, or wiped with alcohol. See the manufacturer's recommendations for sample cell preparation.

7.8.1.5 Preferably matched sample cells that provide consistent readings to within 10 % on filtered DI water should be used.

7.9 *Sample Chambers:*

7.9.1 For those instruments not using sample cells, the sample is placed directly into the sample chamber. For those units, the sample chamber must be the following:

7.9.1.1 Sample chambers should be kept scrupulously clean. Scratches, fingerprints and dirt on the walls of the sample chamber may give erroneous results. See the manufacturer's recommendations for sample chamber maintenance.

7.9.1.2 Sample chambers should be designed in such a way as to negate any influence from external light sources, and to minimize stray light interference with readings.

8. Purity of Reagents

8.1 *Purity of Reagents*—Reagent grade chemicals shall be used in all tests. All reagents shall conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society, where such specifications are available.[7]

8.1.1 ACS grade chemicals of high purity (99+%) shall be used in all tests. Unless otherwise indicated, it is intended that all reagents shall conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society, where such specifications are available. Other grades may be used providing it is first ascertained that the reagent is of sufficiently high purity to permit its use without lessening the accuracy of the determination.

NOTE 6—Refer to product MSDS for possible health exposure concerns.

8.2 Reverse osmosis (RO) water is acceptable and preferred in this test method. Standard dilution waters and rinse waters should be prepared by filtration through a 0.22 µm or smaller membrane filter or any other suitable filter within 1 h of use to reduce background turbidity. Type III water is also acceptable (See Specification D1193). These types of water should be used in preparation of turbidity standards for calibration or verification.

9. Reagents

9.1 *Dilution and Final Rinsing Water,* see 8.2.

9.2 *Turbidity Standards:*

NOTE 7—A standard with a turbidity of 1.0 NTU is the lowest formazin turbidity standard that should be produced on the bench. Skilled laboratory personnel with experience in quantitative analysis shall perform preparation of formazin standards. Close adherence to the instructions within this section is required in order to accurately prepare low-level turbidity standards.

NOTE 8—Equivalent, commercially available, calibration standards may be used. These standards, such as stabilized formazin (StablCal®) and styrenedivinylbenzene (SDVB), have a specified turbidity value and accuracy. Such standards must be referenced (traceable) to bench-synthesized formazin (see 9.2.2). Follow specific manufacturer's calibration procedures.

9.2.1 All volumetric glassware must be scrupulously clean. The necessary level of cleanliness can be achieved by performing all of the following steps: washing glassware with laboratory detergent followed by 3 tap water rinses; then rinse with portions of 1:4 HCl followed by at least 3 tap water rinses; finally, rinse with rinse water as defined in 8.2.

9.2.2 *Reference Formazin Reference Turbidity Standard, 4000 NTU*—This standard is synthesized in the lab.

[7] *Reagent Chemicals, American Chemical Society Specifications*, American Chemical Society, Washington, DC. For Suggestions on the testing of reagents not listed by the American Chemical Society, see *Annual Standards for Laboratory Chemicals,* BDH Ltd., Poole, Dorset, U.K., and the *United States Pharmacopeia and National Formulary,* U.S. Pharmacopeial Convention, Inc. (USPC), Rockville, MD.

9.2.2.1 Quantitatively transfer 5.000 g of reagent grade hydrazine sulfate (99.5%+ purity) ($N_2H_4 \cdot H_2SO_4$) into approximately 400 mL of dilution water (see 8.2) contained in a 1-L Class A volumetric flask; stopper and completely dissolve by swirling.

NOTE 9—To quantitatively transfer this powdered reagent, transfer the hydrazine sulfate into the flask containing the dilution water. Rinse the weighing bowl with dilution water, adding the rinsings to the flask. Repeat the rinsing again adding the second rinsings to the flask.

9.2.2.2 Quantitatively transfer 50.000 g of reagent grade hexamethylenetetramine (99%+ purity) in approximately 400 mL of dilution water (see 8.2) contained in a clean flask; stopper and completely dissolve by swirling. Filter this solution through a 0.2 µm filter into a clean flask.

9.2.2.3 Quantitatively transfer the filtered hexamethylenetetramine into the flask containing the hydrazine sulfate. Dilute this mixture to 1 L using dilution water (see 8.2). Stopper and mix for at least 5 min, and no more than 10 min.

NOTE 10—To quantitatively transfer this liquid mixture, transfer the hexamethylenetetramine into the flask containing the hydrazine sulfate. Rinse this flask two times using 50 mL aliquots of dilution water, adding each rinsing to the flask containing the hydrazine sulfate.

9.2.2.4 Allow the solution to stand for at least 24 h at 25 ± 1°C. The 4000 NTU Formazin suspension develops during this time.

NOTE 11—This suspension, if stored at 20–25°C in amber polyethylene bottles, is stable for 1 year; it is stable for 1 month if stored in glass at 20–25°C.

9.2.3 Stabilized formazin turbidity standards (StablCal®) are prepared stable suspensions of the formazin polymer. Preparation is limited to inverting the container to re-suspend the formazin polymer. These standards require no dilution and are used as received from the manufacturer.

9.2.4 SDVB standards are prepared stable suspensions of copolymer microspheres which are used as received from the manufacturer or distributor. These standards exhibit calibration performance characteristics that are specific to instrument design.

NOTE 12—Sealed or solid samples should not be used to standardize turbidimeters for the turbidity measurement of water or waste; they may only be used for calibration verification. These two methods (sealed or solid examples) neglect the zeroing out of the sample cell prior to making water measurement in the cell.

9.2.5 *Formazin Turbidity Suspension, Standard (40 NTU)*—This is an example on how to prepare a calibration standard of a specific turbidity value. All labware shall be seasoned (see Appendix X3). Invert 4000 NTU stock suspension 25 times to mix (1 s inversion cycle); immediately pipette, using a Class A pipette, 10.00 mL of mixed 4000 NTU stock into a 1000-mL Class A volumetric flask and dilute with water to mark. The turbidity of this suspension is defined as 40 NTU. This 40-NTU suspension must be prepared weekly.

9.2.6 *Other Formazin Calibration Standards*—Using a similar procedure as in 9.2.5, prepare the appropriate standards as required to calibrate the instrument as instructed by the instrument calibration protocol.

9.2.7 *Dilute Formazin Turbidity Suspension Standard (1.0 NTU)*—Prepare this standard daily by inverting the 40 NTU (9.2.5) stock suspension 25 times to mix (1 s inversion cycle) and immediately pipet a volume of 40 NTU standard. All glassware shall be seasoned (see Appendix X3).

NOTE 13—The instructions below result in the preparation of 200 mL of a formazin standard. Users of this test method will need different volumes of the standard to meet their instrument's individual needs; glassware and reagent volumes shall be adjusted accordingly.

9.2.7.1 Within one day of use, rinse both a glass Class A 5.00 mL pipette and a glass Class A200 mL volumetric flask with laboratory glassware detergent or 1:1 hydrochloric acid solution. Follow with at least ten rinses with rinse water. Cap and store in a clean environment until use.

9.2.7.2 Using the cleaned glassware, pipet 5.00 mL of well-mixed 40.0 NTU formazin suspension (9.2.5) into the 200 mL flask and dilute to volume with the dilution rinse water. Stopper and invert (1 s inversion cycle) 25 times to mix. The turbidity of this standard is 1.0 NTU.

9.2.8 *Miscellaneous Dilute Formazin Turbidity Suspension Standard*—Prepare all turbidity standards with values below 40 NTU daily. Standards ≥ 40 NTU have a useful life of one week. All labware shall be seasoned (See Appendix X3). Use Class A glassware that has been cleaned per the instructions in 9.2.1 and prepare each dilution by pipetting the volume of 40 NTU (9.2.5) into a 100-mL volumetric flask and diluting to mark with dilution water (8.2). For example, prepare the solution so that 50.0 mL of 40 NTU diluted to 100 mL is 20.0 NTU and 10.0 mL of 40 NTU diluted to 100 mL is 4.00 NTU.

9.2.8.1 Prepare standards at the turbidity concentrations that are required to meet the specific calibration requirements for the instrument that is to undergo calibration.

9.2.9 Stable turbidity standards are commercially available. These standards, such as stabilized formazin and styrenedivinylbenzene (SDVB), have a specific turbidity value and accuracy. Such standards must be traceable to the reference turbidity standard.

10. Safety

10.1 Wear appropriate personal protection equipment at all times.

10.2 Follow all relevant safety guidelines.

10.3 Refer to instrument manuals for safety guidelines when installing, calibrating, measuring or performing maintenance with any of the respective instrumentation.

10.4 Refer to all Material Safety Data Sheets (MSDSs) prior to preparing or using standards and before calibrating or performing instrument maintenance.

11. Sampling and Sample Preservation

11.1 *Collection of Sample*—Collect the sample in accordance with the applicable standard, Specification and Practices. See Guide D4411 for the collection of samples in moving waters.

11.2 *Storage of Sample*—Analyze the sample immediately. Do not store the sample.

11.3 *Sample Handling*—Samples should be measured expeditiously after collection to prevent changes in particle characteristics due to temperature changes and settling. Temperature can effect particles either by changing their behavior or

creating new particles, if precipitates are created. Dilution water may dissolve particles or change their characteristics. Operators should draw samples only when turbidimeters are ready for operation. Do not draw a sample and allow it to sit while the turbidimeter is being readied.

11.4 *Other Important Sampling Techniques:*

11.4.1 Minimize agitation of samples as particles can be altered or air may be entrained into the sample. Gentle agitation or swirling is recommended to reduce particle settling. Swirling may not be appropriate for rapidly settling particles.

11.4.2 Sample cells should only be used with the instrumentation for which they were intended.

11.4.2.1 Prior to each measurement inspect the filled sample cell and ensure that there are no bubbles in the sample, and that the cell is free of scratches.

NOTE 14—If degassing is necessary, a non-intrusive procedure for removing bubbles can be used. Examples include the application of a vacuum or the use of an ultra-sonic bath. Caution must be exercised not to alter the composition of the samples.

11.4.2.2 Sample cells should be evaluated with a low turbidity water (after cleaning) to determine if cells remain matched. If the evaluation determines that a cell is corrupted, discard the cell. This check should be performed on a weekly basis.

11.4.2.3 If a sample cell's condition is questionable, discard the cell and replace with a new sample cell.

11.5 *Sample Preparation for Measurement:*

11.5.1 Rinse the clean sample cell or chamber twice with the sample that is to be measured, and discard the rinsings.

11.5.2 Fill the sample cell or chamber to a level at which the top air/liquid interface will not interfere with the subsequent reading. Follow manufacturer recommendations as to sample cell or chamber filling.

11.5.3 After the sample cell is filled, use a lint-free tissue to remove all traces of dirt or fingerprints. Tissue alone does not clean dirty sample cells and one of the common nonabrasive glass cleaners may be necessary.

11.5.4 The cleaned sample cell is handled by its very top and placed in an indexed manner in the instrument.

12. Calibration and Calibration Verification

12.1 Determine if the instrument requires any maintenance such as cleaning the sample cell or sample chamber, etc. Follow the manufacturer's instructions for any required instrument maintenance prior to calibration.

12.2 *Calibration:*

12.2.1 Follow the manufacturer's instructions for calibration and operation. Calibrate the instrument to assure proper operation for the range of interest with appropriate standards. See standard or instrument manufacturers for the preparation and use of calibration or verification standards.

12.2.2 Formazin-based calibration standards should be re-suspended through inversion (1 s inversion cycle) 25 times followed by a 2 to 10 min wait to allow for bubble removal. Standards of 40 NTU or below will remain suspended for up to 30 min; standards greater than 40 NTU may require more frequent re-suspension.

NOTE 15—A Calibration Turbidity Standard is a turbidity standard that is traceable and equivalent to the reference turbidity standard to within statistical errors, including commercially prepared 4000 NTU Formazin, stabilized formazin, and styrenedivinylbenzene (SDVB). These standards may be used to calibrate the instrument.

12.2.3 Verify instrument calibration accuracy in the expected measurement area using a calibration verification standard. The calibration verification standard used should have a defined value with known accuracy. The calibration verification standard should allow the instrument to perform to within its defined performance specifications. Verification should be conducted at timely intervals between calibrations. (Consult instrument manufacturer's recommendations, standard's manufacturers recommendations, or both for guidance associated with verification methods and devices.)

NOTE 16—Some regulatory agencies may have specific requirements or guidelines regarding the calibration of turbidimeters. Consult those authorities if reporting to specific regulatory agencies.

12.2.4 In case of verification failure clean the instrument to reduce stray light levels or contamination. Follow with a recalibration (instrument adjustment) according to manufacturer's calibration instructions, using a calibration standard (see 3.2.4), or at a minimum on a quarterly basis.

12.2.5 Close adherence to the calibration procedure and to the rinsing/seasoning techniques is very important to ensure data quality.

12.2.6 Proper sample handling and preparation procedures must be followed to assure data quality (see Section 11).

12.2.7 Proper care and maintenance of sample cells and sample chambers must be performed in a timely manner (see 7.7).

13. Procedure for the Measurement of High-Level Static Turbidity

13.1 Identify the technology to be used and determine the most appropriate turbidity unit. See Table 1 and Appendix X2 for guidance and application of the technologies offered in this test method.

13.2 *Turbidity Greater than 1.0 NTU*—Gently invert the sample several times (1 s inversion cycle) to thoroughly suspend any solids. Rinse a clean sample cell several times with sample. Fill the sample cell with sample and cap the cell. Clean outside surfaces of the sample cell (see non-mandatory Appendix X3). Invert again and immediately place the sample cell into the instrument at the index mark and measure at a consistent distinct time interval, not to exceed 15 s, after inserting the vial. Repeat a minimum of 2 more times with new sample. Average the values to generate the reported result.

NOTE 17—Care must be taken to ensure the sample does not settle when transferring from the sample container to a sample vial. See 13.5.1.

NOTE 18—If the instrument has a long measurement-averaging interval, the interval should be as short as possible to minimize error due to particle settling. Even with extremely short intervals (for example, <1 s) rapidly settling particles may still lead to erroneous results. Under such conditions, a different measurement practice, such as an in-situ measurement my produce better data quality.

NOTE 19—If the measurement is to be performed with an in-situ probe,

follow the instructions for maintenance of the measurement chamber. Place the probe into the sample chamber immediately after mixing and perform measurements using the same timelines that are suggested in this section.

13.2.1 If the measured sample exceeds the highest calibration point, dilute the sample using quantitative techniques until a measured value is below the highest calibration point. For real-world samples, if the measurement is above 80 % of the maximum range, the operator should use dilution to ensure the measurement is valid.

13.3 *Sample Verification*—It is prudent to carefully dilute samples that contain significant color or turbidity. Ensure that there is not active settling of particles within the sample when performing dilutions. For such samples, perform at least three dilutions at approximately 80, 50, and 20 % of the original concentration. Determine the turbidity of each dilution and determine if they are linear and correlate positively with the dilutions (that is, a 50 % dilution should read ½ the turbidity value of the concentrated sample). If a dilution was used to generate the result, it should be reported that it was performed.

13.3.1 Dilutions of samples on a routine basis are not recommended, especially in the case of samples with fast settling particles (those with high densities). It is recommended that an appropriate instrument design that covers the expected measurement range be selected to avoid dilutions.

13.3.1.1 Aliquots for the dilution should be withdrawn from the original sample in such a way as to ensure that an aliquot contains the original concentration and particle size distribution of all suspended material. (see Section 5.1.1 in United States Geological Survey (USGS), National Field Manual for the Collection of Water Quality Data).

13.3.2 Dilution of samples with colorless and filtered water should be performed if the desired application treats color as part of turbidity. However, if the desired application does not consider color as part of the turbidity measurement, then the sample dilution should be made using water that is less than 1 TU as read by the instrument being used.

13.4 *Stability*—To better assure stability in reading, do not shake the samples, but place the sample in the meter as rapidly as possible after inverting the sample vial several times (approximately 1 inversion per s) to ensure all suspended material is in suspension. If after the placement of the sample vial in the measurement chamber for measurement, the reading does not become stable and decreases more than 10 % over a short period of time (for example, 20 s) it is likely due to rapid settling. In this case, re-invert the sample gently, immediately insert into the instrument and record the highest measurement. Repeat at least two more times to collect a minimum of three measurements. Average the values together to generate the recorded result as greater than the average of the three reading.

13.5 Measurement variability that is unsatisfactory due to settling may warrant the use of other technologies such as in-situ turbidimeters.

13.5.1 If the response for the dilution curve is non-linear, it is typically due to the impacts of color absorbance in the sample matrix or particle absorbance. Typically, as dilutions become more significant, the impacts of matrix absorbance will eventually be reduced to project a linear portion of the response curve at lower turbidity levels (1–40 TU range). Multiply the turbidity value by the dilution factor to generate the reported result.

13.5.2 If interferences are severe (see 13.5), an alternative technology that may better compensate for the interference should be considered.

14. Report

14.1 Report results as presented in Table 2.

15. Quality Control/Quality Assurance

15.1 In order to be certain that analytical values obtained using this test method are valid and accurate within the confidence limits of the test, the following QC procedures must be followed when running the test.

15.2 *Calibration and Calibration Verification:*

15.2.1 Determine if the instrument requires any maintenance such as replacing the lamp, cleaning the sample cells, sample chamber, or optics etc. Follow the manufacturer's instructions for any required instrument maintenance prior to calibration.

15.2.2 Follow the manufacturer's instruction for calibration and operation of instrumentation. Refer to the standard's manufacturer for the preparation and use of calibration or verification standards. Calibrate the instrument to assure proper operation for the range of interest with the appropriate standards.

15.2.2.1 Verify instrument calibration by analyzing calibration or calibration verification standards that is within the range of interest. These standards must be run prior to and after any sample determinations. The recommended frequency for determining calibration verification is more than or equal to every 10 samples or upon the arrival of a new measurement site.

NOTE 20—Consult instrument or standards manufacturers for recommended and available sources for verification standards.

15.2.3 The round robin study resulted in the generation of a precision and bias section. The values obtained upon analysis of calibration or calibration verification standards will fall within the acceptance limits presented in Tables 3-7, as determined from single operator standard deviation (S_O), as determined by Practice E691.

15.3 Alternative to 15.2.3:

15.3.1 The values obtained upon analysis of calibration or calibration verification standards must fall within the acceptance criteria generated after sufficient data is generated for each of the standards, typically 20 to 30 results. Control charts must be developed from the mean recovery (x) and the standard deviation (S) of the percent recovery for the standards. These data are used to establish upper and lower control limits as follows:

$$\text{Upper control limit} = x + 3S$$
$$\text{Lower control limit} = x - 3S$$

15.3.2 After each five to ten new recovery measurements, new control limits must be calculated using the most recent 20 to 30 data points. If these calculated control limits exceed those established in the method, corrective action must be taken. If

TABLE 3 ASTM E691 Data Analysis: Comparison Across All Technologies

Reporting: ASTM High Level Turbidity Measurement in the Static Mode—Round Robin Study—October 2005
All Laboratories Reporting: NTU, NTRU, AU, FNU, FNRU, FAU, and FBU

	Material	All Laboratories Average TU	Within Laboratory Repeatability TU	Between Laboratories Reproducibility TU	Single Operator S_o^* Repeatability TU	Expected TU	Overall Bias TU	Test Sequence	Number of Labs Reporting
Surrogates	SDVB #2 2 NTU	2.4294	0.2938	0.6326	0.1049	2.000	0.4294	6	17
	Formazin A	81.2500	2.4466	5.7671	0.8738	83.800	–2.5500	1	18
	StablCal B286	278.5141	4.5804	194.0931	1.6359	286.000	–7.4859	4	17
	Formazin B	487.4812	7.6308	72.5012	2.7253	507.100	–19.6188	2	17
	SDVB #2 800 NTU	687.0938	3.4369	833.7638	1.2275	800.000	–112.9062	7	15
	Formazin C	1383.3800	8.6869	508.4925	3.1025	1433.000	–49.6200	3	10
Real World Samples	Acid Mine 1	105.7830	10.8195	64.7087	3.8641			8	18
	Acid Mine Dup	107.0219	19.5133	80.2707	6.9690			9	18
	Alk Glac Flr 100%	1373.3424	112.2216	2381.2417	40.0791			10	11
	Alk Glac Flr 100% Dup	1165.6667	842.0044	980.2578	300.7158			11	10
	Alk Glac Flr 50%	753.0642	59.9148	711.1709	21.3981			12	12
	Alk Glac Flr 25%	372.2931	78.1192	291.3120	27.8997			13	17
	Kansas 100%	1573.1733	59.5038	1828.6915	21.2514			14	10
	Kansas 100% Dup	1641.3037	151.4506	1853.3339	54.0895			15	9
	Kansas 50%	873.7083	42.2894	716.8163	15.1034			16	14
	Kansas 50% Dup	873.7083	31.0279	755.4455	11.0814			17	12
	Kansas 25%	408.6984	63.4992	338.3758	22.6783			18	17
	Kansas 4.2%	62.3828	3.9393	53.9633	1.4069			19	19
	Reston Pond No Filt	34.1472	7.7058	25.1033	2.7521			20	19
USGS QC	USGS QC #1	12.6296	2.6517	7.9051	0.9470			21	19
	USGS QC #2	40.1219	6.2935	35.0466	2.2477			22	18
	USGS QC #3	161.8663	18.7592	115.5199	6.6997			23	17
	USGS QC #4	142.1513	20.8887	106.4929	7.4603			24	18
	USGS QC #5	349.6522	37.8965	263.1686	13.5345			25	17

TABLE 4 ASTM E691 Data Analysis: Comparison Across Ratio Technologies

Reporting: ASTM High Level Turbidity Measurement in the Static Mode—Round Robin Study—October 2005
Finalized for All Laboratories Using Ratio Technologies: NTRU and FNRU

	Material	All Laboratories Average TU	Within Laboratory Repeatability TU	Between Laboratories Reproducibility TU	Single Operator S_o^* Repeatability TU	Expected TU	Overall Bias TU	Test Sequence	Number of Labs Reporting
Surrogates	SDVB #2 2 NIL	2.4560	0.4527	0.6064	0.1617	2.000	0.4560	6	
	Formazin A	81.2400	0.4025	5.3856	0.1438	83.800	–2.5600	1	5
	StablCal B286	280.9200	2.6097	29.2805	0.9320	286.000	–5.0800	4	5
	Formazin B	490.8000	5.3126	34.5131	1.8974	507.100	–16.3000	2	5
	SDVB #2 800 NTU	646.8000	2.2862	693.8744	0.8165	800.000	–153.2000	7	5
	Formazin C	1489.5000	12.1244	165.5437	4.3301	1433.000	56.5000	3	4
Real World Samples	Acid Mine 1	110.4933	13.5129	43.0844	4.8260			8	5
	Acid Mine Dup	111.4200	10.3837	49.7262	3.7085			9	5
	Alk Glac Flr 100%	2290.2222	164.8040	545.8287	58.8586			10	3
	Alk Glac Flr 100% Dup	1165.6667	842.0044	980.2578	300.7158			11	3
	Alk Glac Flr 50%	903.6667	50.3222	478.0769	17.9722			12	4
	Alk Glac Flr 25%	406.7733	25.3835	204.8961	9.0655			13	5
	Kansas 100%	2111.1111	64.9120	808.5700	23.1828			14	3
	Kansas 100% Dup	2127.6667	250.0201	815.8910	89.2929			15	3
	Kansas 50%	963.1667	36.2110	633.9762	12.9325			16	4
	Kansas 50% Dup	963.1667	16.6437	664.1603	5.9442			17	4
	Kansas 25%	449.6667	13.8121	294.2140	4.9329			18	5
	Kansas 4.2%	61.7800	3.5777	19.3406	1.2778			19	5
	Reston Pond No Filt	30.5867	3.0885	28.6735	1.1030			20	5
USGS QC	USGS QC #1	12.8733	2.3202	5.9592	0.8287			21	5
	USGS QC #2	39.1667	6.6154	20.0112	2.3626			22	5
	USGS QC #3	157.1733	17.2458	105.9137	6.1592			23	5
	USGS QC #4	138.7600	22.5074	93.6608	8.0384			24	5
	USGS QC #5	372.4200	30.3104	269.2088	10.8252			25	5

calibration cannot be verified because standards are determined to be outside acceptance limits, recalibrate the instrument.

15.4 *Duplicate:*

TABLE 5 ASTM E691 Data Analysis: Comparison Across Single Detector Technologies

Reporting: ASTM High Level Turbidity Measurement in the Static Mode—Round Robin Study—October 2005
Finalized for All 1-Detector Labs: NTU, AU, FNU, FAU, FBU

	Material	All Laboratories Average TU	Within Laboratory Repeatability TU	Between Laboratories Reproducibility TU	Single Operator S_o* Repeatability TU	Expected TU	Overall Bias TU	Test Sequence	Number of Labs Reporting
Surrogates	SDVB #2 2 NTU	2.4183	0.1920	0.6599	0.0686	2.000	0.4183	6	12
	Formazin A	81.2538	2.8680	6.1086	1.0243	83.800	–2.5462	1	13
	StablCal B286	277.5117	5.1850	229.5469	1.8518	286.000	–8.4883	4	12
	Formazin B	486.0983	8.4102	84.5842	3.0036	507.100	–21.0017	2	12
	SDVB #2 800 NTU	707.2407	3.8865	925.6199	1.3880	800.000	–92.7593	7	10
	Formazin C	1312.6333	5.2698	575.5349	1.8821	1433.000	–120.3667	3	6
Real	Acid Mine 1	103.9713	9.5841	72.1389	3.4229			8	13
World	Acid Mine Dup	105.3303	22.0397	90.5792	7.8713			9	13
Samples	Alk Glac Flr 100%	1029.5125	84.4463	2032.0846	30.1594			10	8
	Alk Glac Flr 100% Dup	1165.6667	842.0044	980.2578	300.7158			11	7
	Alk Glac Flr 50%	677.7629	64.1756	737.6383	22.9199			12	8
	Alk Glac Flr 25%	357.9264	91.5253	319.3609	32.6876			13	12
	Kansas 100%	1342.6286	57.0293	1782.4962	20.3676			14	7
	Kansas 100% Dup	1398.1222	56.1330	1885.3905	20.0475			15	6
	Kansas 50%	828.9792	44.4888	752.7435	15.8889			16	10
	Kansas 50% Dup	828.9792	36.1330	808.6572	12.9046			17	8
	Kansas 25%	391.6283	75.0514	355.6457	26.8041			18	12
	Kansas 4.2%	62.5981	4.0607	62.5680	1.4502			19	14
	Reston Pond No Filt	35.4188	8.7852	23.7970	3.1376			20	14
USGS	USGS QC #1	12.5426	2.7604	8.6631	0.9859			21	14
QC	USGS QC #2	40.4892	6.1652	40.0012	2.2019			22	13
	USGS QC #3	163.8217	19.3549	123.2921	6.9125			23	12
	USGS QC #4	143.4556	20.2317	114.2947	7.2256			24	13
	USGS QC #5	340.1656	40.6415	267.7663	14.5148			25	12

TABLE 6 ASTM E691 Data Analysis: Comparison Across IR Light Source Based Technologies

Reporting: ASTM High Level Turbidity Measurement in the Static Mode—Round Robin Study—October 2005
Finalized for All Laboratories That Utilize IR light Sources Between 780–900 nm: FNU, FNRU, FAU, and FBU

	Material	All Laboratories Average TU	Within Laboratory Repeatability TU	Between Laboratories Reproducibility TU	Single Operator S_o* Repeatability TU	Expected TU	Overall Bias TU	Test Sequence	Number of Labs Reporting
Surrogates	SDVB #2 2 NTI	12.3452	0.3635	0.6000	0.1298	2.000	0.3452	6	11
	Formazin A	81.1590	2.7862	5.5747	0.9951	83.800	–2.64101	1	13
	StablCal B286	276.3672	5.3713	49.8787	1.9183	286.000	–9.63284	4	12
	Formazin B	483.9317	4.7082	79.8551	1.6815	507.100	–23.1683	2	12
	SDVB #2 800 NTU	759.7642	3.9538	826.6066	1.4121	800.000	–40.2358	7	11
	Formazin C	1366.2571	9.5591	614.8087	3.4140	1433.000	–66.7429	3	7
Real	Acid Mine 1	115.4354	12.5496	46.0717	4.4820			8	13
World	Acid Mine Dup	118.3123	22.6772	64.9024	8.0990			9	13
Samples	Alk Glac Flr 100%	1257.0481	113.6384	2511.1350	40.5851			10	9
	Alk Glac Flr 100% Dup	1165.6667	842.0044	980.2578	300.7158			11	8
	Alk Glac Flr 50%	745.3448	67.6794	820.6508	24.1712			12	9
	Alk Glac Flr 25%	384.6931	87.0719	306.5319	31.0971			13	12
	Kansas 100%	1512.7583	64.9420	2016.6404	23.1936			14	8
	Kansas 100% Dup	1589.3429	169.9017	2095.3183	60.6792			15	7
	Kansas 50%	867.9815	44.7673	788.7334	15.9883			16	11
	Kansas 50% Dup	867.9815	32.1095	855.9333	11.4677			17	9
	Kansas 25%	413.4617	73.7887	345.2275	26.3531			18	12
	Kansas 4.2%	66.4082	3.9546	52.1435	1.4123			19	13
	Reston Pond No Filt	36.9844	8.9659	24.7738	3.2021			20	13
USGS	USGS QC #1	13.6815	2.8589	6.2732	1.0210			21	13
QC	USGS QC #2	43.9431	6.8357	33.0671	2.4413			22	13
	USGS QC #3	171.7133	19.3790	114.0778	6.9211			23	12
	USGS QC #4	148.3633	22.4063	113.6330	8.0022			24	13
	USGS QC #5	362.5628	44.1518	263.0593	15.7685			25	12

15.4.1 To check the precision of sample analyses, analyze a sample in duplicate with each batch of samples. The recommended frequency for determining precision is more than or equal to 5 % of all samples determined for each batch of samples.

15.4.2 Calculate the standard deviation of the duplicate values and compare it to the single operator precision data found in Table 3 of this procedure by using a one-sided *F* test at the $\alpha = 0.01$ significance level.

TABLE 7 ASTM E691 Data Analysis: Comparison Across Laboratories Reporting with Broad-Band Light Sources from 400–700 nm

Reporting: ASTM High Level Turbidity Measurement in the Static Mode—Round Robin Study—October 2005
Finalized for All EPA (400–600 nm Light Source) Labs Analysis: NTU, NTRU, and AU

	Material	All Laboratories Average TU	Within Laboratory Repeatability TU	Between Laboratories Reproducibility TU	Single Operator S_o^* Repeatability TU	Expected TU	Overall Bias TU	Test Sequence	Number of Labs Reporting
Surrogates	SDVB #2 2 NTU	2.5839	0.0476	0.4532	0.0170	2.000	0.5839	6	6
	Formazin A	81.4867	1.1680	6.7434	0.4171	83.800	–2.3133	1	5
	StablCal B286	283.6667	1.4459	29.1836	0.5164	286.000	–2.3333	4	5
	Formazin B	496.0000	12.0324	48.1558	4.2973	507.100	–11.1000	2	5
	SDVB #2 800 NTU	487.2500	1.1431	630.2388	0.4082	800.000	–312.7500	7	4
	Formazin C	1423.3333	6.1910	49.6191	2.2111	1433.000	–9.6667	3	3
Real	Acid Mine 1	80.6867	3.4551	53.4877	1.2340			8	5
World	Acid Mine Dup	77.6667	5.8049	54.7076	2.0732			9	5
Samples	Alk Glac Flr 100%	1896.6667	105.6111	994.6820	37.7183			10	2
	Alk Glac Flr 100% Dup	1165.6667	842.0044	980.2578	300.7158			11	2
	Alk Glac Flr 50%	776.2222	24.8519	279.7650	8.8757			12	3
	Alk Glac Flr 25%	342.5333	50.5295	255.9977	18.0462			13	5
	Kansas 100%	1814.8333	28.8731	694.7446	10.3118			14	2
	Kansas 100% Dup	1823.1667	46.7413	679.8899	16.6933			15	2
	Kansas 50%	890.8889	31.5820	473.9575	11.2793			16	3
	Kansas 50% Dup	890.8889	27.5294	450.2106	9.8319			17	3
	Kansas 25%	397.2667	25.3345	356.9925	9.0480			18	5
	Kansas 4.2%	53.6611	3.9061	53.8016	1.3950			19	6
	Reston Pond No Filt	28.0000	3.7234	16.0483	1.3298			20	6
USGS	USGS QC #1	10.3506	2.1348	7.3748	0.7624			21	6
QC	USGS QC #2	30.1867	4.5935	23.9715	1.6405			22	5
	USGS QC #3	138.2333	17.1807	97.4127	6.1360			23	5
	USGS QC #4	126.0000	16.2946	74.8351	5.8195			24	5
	USGS QC #5	318.6667	14.2955	270.3274	5.1056			25	5

15.4.2.1 Appendix X4 is the Table X2.1 from Practice D5847 for the critical values of F at the 1 % significance (99 % confidence) level (one-sided). Also, reference Practice D5847 if necessary to see an example of how the calculation utilizes both the single operator standard deviation (S_O) and the standard deviation of the duplicate sample analysis values (SA).

15.4.2.2 The result from $(S_A)^2/(S_O)^2$ = (standard deviation of sample reps)^2/(single operator standard deviation)^2 = calculated value versus (> or <) critical value from table. The result will determine if the duplicate values are acceptable.

15.4.3 If the result exceeds the precision limit as derived from the F test, the batch must be reanalyzed or the results must be qualified with an indication that they do not fall within the performance criteria of the test procedure.

15.5 *Independent Reference Material (IRM):*

15.5.1 In order to verify the quantitative value produced by the test procedure, analyze an IRM submitted as a regular sample to the laboratory at least once per quarter. The value of the IRM should be in the range of the determinations that the lab normally determines during the analyses of samples. The value obtained must fall within the control limits specified by the provider of the IRM.

16. Precision and Bias[8]

16.1 This test method was tested on 21 different laboratories that were assembled at a common site. Each laboratory consisted of an operator and an instrument (turbidimeter) that operated using a specific technology and traceable reporting unit that was listed in Table 1. Testing was conducted over a two-day period. Fig. 6 is a breakdown of the different laboratories.

16.1.1 *Samples*—24 samples were analyzed in this round robin. These were broken down into surrogates, real world environmental samples, and United States Geological Survey Quality Control Samples (USGS QC).

16.1.1.1 Surrogate samples were samples of a defined turbidity value and prepared from turbidity standard materials. Specifically, these were formazin, stabilized formazin, and styrene divinylbenzene (SDVB) materials. Surrogate samples were prepared at defined values, but were run as unknowns during the round robin study. A total of six surrogate samples were run.

16.1.1.2 Real world environmental samples were samples that were collected in the field and shipped to the round robin test site. No preservation action was taken with these samples. Samples were prepared immediately before and during dispensation to each of the laboratories. Real world samples included samples from streams and ponds. A total of 13 real world environmental samples were analyzed.

16.1.1.3 USGS QC samples were samples that were prepared by the USGS branch of quality systems immediately prior to analysis. These samples had defined quantities of sands and fines. A total of five different samples were run through this round robin.

16.2 *Sample Preparation and Measurement*—Each bulk sample was mixed using a churn splitter, which is designed to maintain particulate suspensions and homogeneity throughout the bulk sample. Samples were dispensed to each laboratory at

[8] Supporting data for the precision and bias statements have been filed at ASTM Headquarters. Request RR:D19-1179.

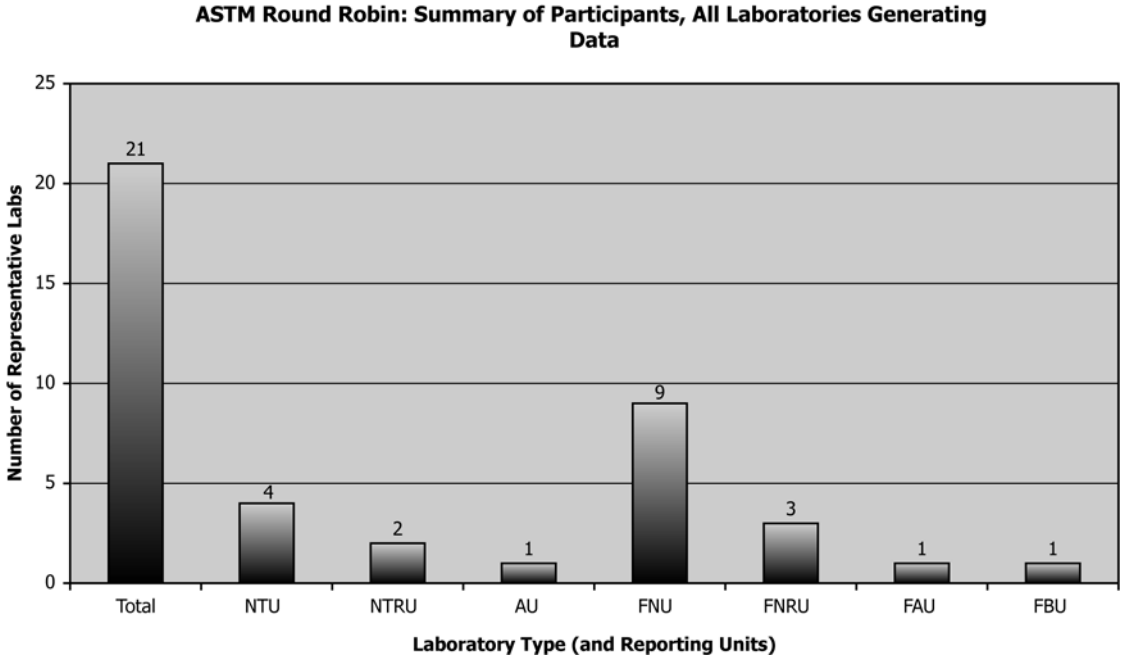

FIG. 6 Breakdown of Technologies Represented for this Test Method's Round Robin

the same time and were mixed throughout the dispensation process. Once the samples were dispensed, they were prepared for measurement as prescribed in Section 13 of this test method. A total of three measurements were made of each sample. A measurement included a new dispensation, preparation, and measurement in the respective measurement. These triplicate measurements were then recorded and used in the Practice E691 data analysis methods.

16.3 *Results*—Results from this study were expressed in Tables 3-7. One of the objectives of this round robin was to demonstrate that different technologies can deliver different results on the same sample. Thus, results have been grouped to show several different comparisons among technologies. Within each table, a generic unit of "TU" is displayed, which is to infer that depending on the technology used, a specific reporting unit would be displayed.

16.3.1 *All Laboratories*—Table 3 shows the Practice E691 comparison across all laboratories. Laboratories include: ratio and non-ratio technologies, different light sources (white light, IR, defined wavelengths), and different detection angles (attenuated, nephelometric, backscatter). For certain samples, the turbidity value may have been outside the measurement range for that specific laboratory. For example, some laboratories are only capable of measuring samples at or below 40 turbidity units and for these laboratories, any sample that has a value above 40 turbidity units will be above the measurement range of the respective technology for that laboratory (that is, the instrument). Thus, depending on the sample, the number of the laboratories participating will vary. The same condition is also true for Tables 4-7.

16.3.2 The analysis of data that was generated by ratio technologies is represented in Table 4. A ratio laboratory has a nephelometric detector plus one or more detectors at other angles. All detectors work together to determine the turbidity value of the sample. The reporting units represented in this table are NTRU, and FNRU.

16.3.3 Table 5 represents the analysis of data that was generated using only 1-detector technologies. These include nephelometric, backscatter, and attenuated measurement technologies. The reporting units would be NTU, FNU, FAU, FBU, and AU.

16.3.4 Table 6 represents the analysis of data that was generated from technologies that use an IR light source as the incident light. These laboratories utilized light sources that were in the 780 to 900-nm range. This includes all FNU, FNRU, FAU, and FBU reporting units.

16.3.5 Table 7 represents the analysis of data that was generated from technologies that use a "white light" incident light source. More specifically, these light sources emit light that is in the wavelength range of 400 to 700-nm. These are represented by the units: NTU, NTRU, and AU.

16.4 The samples that were analyzed in this collaborative study may not be typical of results for matrices other than those studied. A broad range of samples was collected and this data should help guide the user of this test method to the type of technology(ies) that would be applicable for the analysis of their respective sample.

16.5 Precision and bias were determined in accordance to Practice E691 statistical methods. Only surrogate samples were used for the determination of bias. All other samples could be used for determining precision, as long as the minimum number of laboratories was represented for the calculation. This number of laboratories is seven. Thus, in Tables 3-7, if the number of reporting laboratories is below 7, then that precision values between laboratories should be discarded.

16.6 Because Youden Pair samples were not feasible in this study, So was calculated in accordance with the repeatability

measure of Practice E691. This is the exact equivalent of single operator precision as defined in Practice D2777 when Youden pairs are not utilized.

16.6.1 Only a statement of single operator precision is required. The modification of this study was allowed according to Section 1.3.2 in D2777.

16.6.2 *Discussion of Results*—Due to the length of the round robin results, a brief discussion has been provided in Appendix X1. This discussion was presented at the 2006 National Water Quality Monitoring Conference and represents the analysis of data that was performed by some of the round robin participants. The summary is non-mandatory information.

17. Keywords

17.1 calibration; calibration turbidity standard; calibration verification; measurement; nephelometric turbidity; ratio turbidity; turbidimeter; turbidity; turbidity standards

APPENDIXES

(Nonmandatory Information)

X1. DISCUSSION OF ROUND ROBIN RESULTS

X1.1 Introduction

X1.1.1 Due to the length of the round robin results section, a brief discussion has been provided in this appendix. The discussion includes conclusions from this study. This appendix also provides suggestions to improve data quality when measuring environmental samples.

X1.1.2 This information was presented at the 2006 National Water Quality Monitoring Conference and represents the analysis of data that was performed by some of the round robin participants. The summary is non-mandatory information.

X1.2 Study Conclusions

X1.2.1 Formazin and stabilized formazin standards compared well across most technologies.

X1.2.1.1 SDVB (styrene divinylbenzene) standards are designed for individual models of turbidity meters and need to be matched with the correct instrument type, or errors will develop.

X1.2.2 Different technologies can produce significantly different results from identical environmental samples.

X1.2.3 Within a given technology, results varied less than between technologies.

X1.2.4 Duplicate samples agree quite well within technologies (that is, results are repeatable if using the same technology.

X1.2.5 *Dilutions*—Although the average of all technologies resulted in a reasonable error range, individual technologies, with the exception of FAU and FBU, had at least double-digit differences when compared to original sample readings.

X1.3 Suggestions to Improve Data Quality in Turbidity Measurement of Environmental Samples

X1.3.1 Understand the expected range of measurements prior to technology selection.

X1.3.1.1 Technologies with ratio techniques have greater ranges and better consistency across sample types.

X1.3.2 Traceable reporting units are necessary.

X1.3.3 Diluting samples should be avoided if possible.

X1.3.4 Practice consistency in sub-sample dispensation, preparation, and measurement.

X1.3.5 The static mode of measuring turbidity should be avoided if the sample has a significant amount of rapidly settling material.

X2. SELECTION CRITERIA FLOWCHART FOR HIGH-LEVEL TURBIDITY MEASUREMENT

X2.1 Selection Criteria Flowchart for High-Level Turbidity Measurement

X2.1.1 This criteria was developed as a cooperative effort between the ASTM sub-committee on high-level turbidity measurement and the USGS. (See 2.2.)

NOTE X2.1—The technologies listed in this flowchart are those that are best applied for static turbidity measurements. Other technologies may be available but may not be suitable for static turbidity measurement applications. Change IR light sources to 780–900-nm.

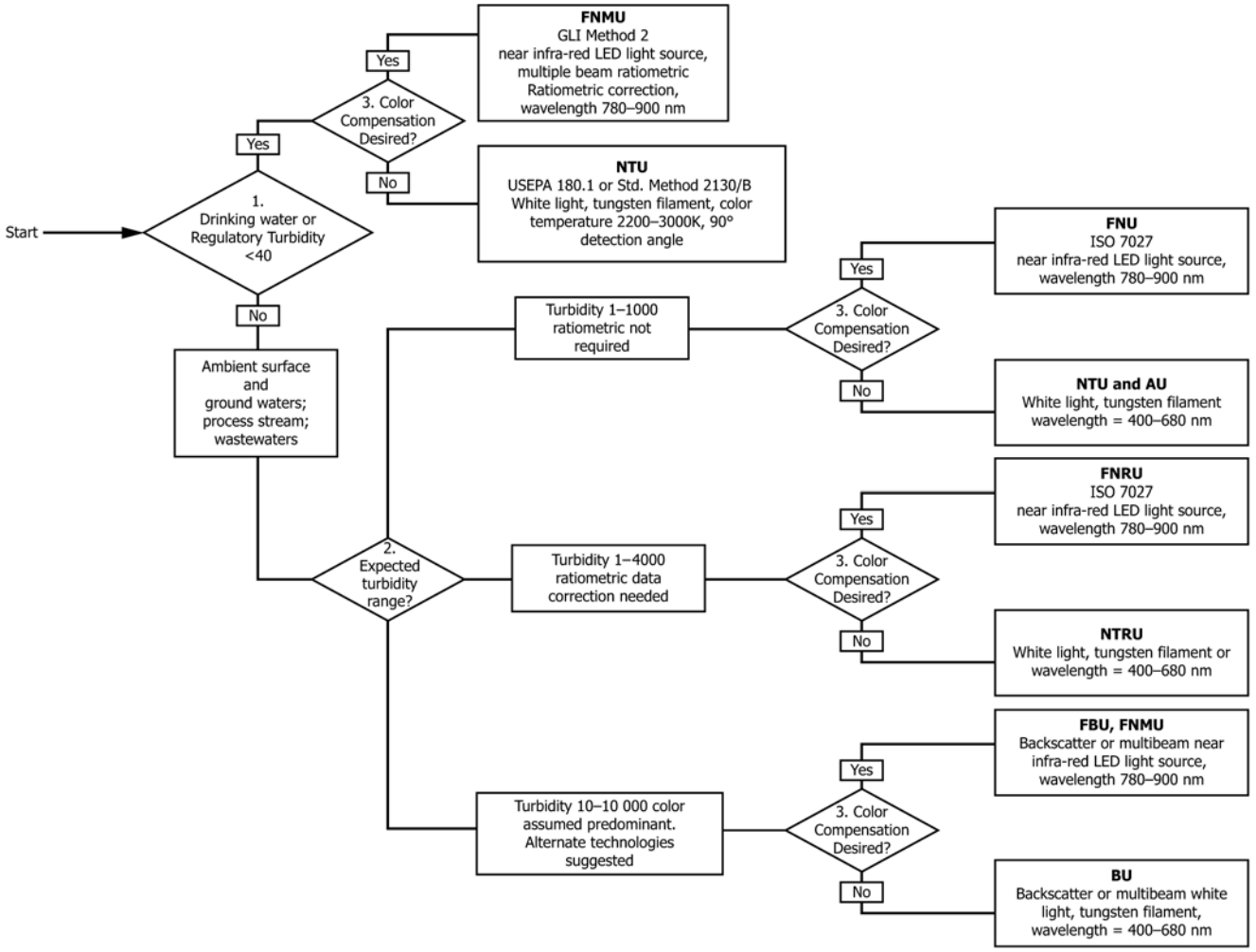

FIG. X2.1 Selection Criteria Flowchart for High-Level Turbidity Measurement

X3. CLEANING, AND MAINTENANCE OF TURBIDITY SAMPLE CELLS AND CAPS

X3.1 Introduction

X3.1.1 Sample cells and caps must be kept scrupulously clean both inside and outside. This level of cleanliness must be established prior to cell matching process and maintained throughout the cell's working lifetime.

X3.2 Cleaning

X3.2.1 Sample cells and caps must be examined prior to cleaning. All scratched, blemished, and scuffed cells should be discarded. All caps with liners that show signs of deterioration also must be discarded. Caps with TFE-fluorocarbon or polytetrafluoroethylene (PTFE) liners are recommended.

X3.2.2 Prepare a 1 % solution of a liquid detergent such as Liqui-Nox.[9] The quantity prepared should be sufficient to fill all cells twice with this solution.

X3.2.3 Fill each cell to half of its capacity with the solution, cap each cell, and shake each cell vigorously for at least 1 min. Flush each cell and cap with tap water 5 times.

X3.2.4 Refill each cell to capacity with the solution, cap each cell, and allow to stand for 2 h.

NOTE X3.1—Plastic test tube racks should be used for storage of cells.

X3.2.5 Uncap each cell, empty each, and flush each cell and cap with tap water 5 times making sure to rid each cell and cap of any residual detergent solution.

X3.2.6 Fill each cell with deionized (DI) water that has been filtered through a 0.2 µm filter, and cap. Allow to stand for 1 h.

[9] The sole source of supply of the apparatus known to the committee at this time is SPI Supplies, P.O. Box 656, West Chester, PA 19381-0656. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

X3.2.7 Uncap each cell and empty.

X3.2.8 Prepare a 1:4 hydrochloric acid (HCl) solution.

X3.2.9 Fill each cell to half of its capacity. Replace the cap and invert the cell 5 times (1 s inversion cycle). Uncap the cell, and pour off the HCl solution to the next cell to be rinsed.

X3.2.9.1 Repeat step X3.2.9 for up to 10 cells, after which the HCl solution is discarded. The process is repeated for every 10 cells. Each sample cell should be rinsed at least 3 times with the HCl solution.

NOTE X3.2—Caps with Teflon liners are not damaged by the HCl solution. If less chemical resistant liners are present on caps, this procedure can be completed by using several caps that are dedicated for acid rinsing.

X3.2.10 After acid rinsing each cell 3 times, rinse the cells and caps 5 times with tap water and 5 times with 0.22 µm filtered DI water.

X3.2.11 Fill the cell with DI water, and place into a plastic test tube rack.

X3.2.12 Sample cells now are ready for matching, sample analyses, or both.

X3.3 Maintenance

X3.3.1 Sample cells must be evaluated frequently (weekly evaluations are recommended) to determine if they remain matched. Prior to the evaluation, all cells must be prepared as per X3.2.

X3.3.2 Fill a thoroughly clean container with sufficient 0.22 µm filtered DI water so that each cell can be filled 4 times. Acclimate the water so that it is at 20–25 °C.

X3.3.3 Fill each cell with the water, degas the water by placing the cell into an ultrasonic bath for no more than 2 s. Cap the cell, and wipe the outside of the cell dry with a lint free tissue to eliminate any moisture.

X3.3.4 Place the water filled clean and dry cell in an indexed manner into the instrument and record the stable value.

X3.3.5 Repeat this process for each cell. If any cell is more than 0.010 NTU from any other cell, replace it with a cell that is.

X3.3.6 Continue with the evaluation of the cells until sufficient cells are obtained that meet the 0.010 NTU criteria and fulfill the analytical needs of the user.

X3.3.7 The cells passing the evaluation criteria now can be used for sample analysis.

X3.3.8 After sample determinations cells must be well rinsed with 0.22 µm filtered DI water and stored filled.

X4. CRITICAL VALUES OF F AT 1 % SIGNIFICANCE (99 % CONFIDENCE) LEVEL (ONE-SIDED)

Degrees of Freedom for Denominator (dfS_0)	Degrees of Freedom for Numerator (dfS_1)										
	1	2	3	4	5	6	7	8	9	10	12
1	4052.	4999.	5403.	5625.	5764.	5859.	5928.	5981.	6022.	6056.	6106.
2	98.50	99.00	99.17	99.25	99.30	99.33	99.36	99.37	99.39	99.40	99.42
3	34.12	30.82	29.46	28.71	28.24	27.91	27.67	27.49	27.34	27.23	27.05
4	21.20	18.00	16.69	15.98	15.52	15.21	14.98	14.80	14.65	14.54	14.37
5	16.26	13.27	12.06	11.39	10.97	10.67	10.46	10.29	10.16	10.05	9.89
6	13.74	10.92	9.78	9.15	8.75	8.47	8.26	8.10	7.98	7.87	7.72
7	12.25	9.55	8.45	7.85	7.46	7.19	6.99	6.84	6.72	6.62	6.47
8	11.26	8.65	7.59	7.01	6.63	6.37	6.18	6.03	5.91	5.81	5.67
9	10.56	8.02	6.99	6.42	6.06	5.80	5.61	5.47	5.35	5.26	5.11
10	10.04	7.56	6.55	5.99	5.64	5.39	5.20	5.06	4.94	4.85	4.71
11	9.65	7.21	6.22	5.67	5.32	5.07	4.89	4.74	4.63	4.54	4.40
12	9.33	6.93	5.95	5.41	5.06	4.82	4.64	4.50	4.39	4.30	4.16
13	9.07	6.70	5.74	5.20	4.86	4.62	4.44	4.30	4.19	4.10	3.96
14	8.86	6.51	5.56	5.04	4.69	4.46	4.28	4.14	4.03	3.94	3.80
15	8.68	6.36	5.42	4.89	4.56	4.32	4.14	4.00	3.89	3.80	3.67
16	8.53	6.23	5.29	4.77	4.44	4.20	4.03	3.89	3.78	3.69	3.55
17	8.40	6.11	5.18	4.67	4.34	4.10	3.93	3.79	3.68	3.59	3.46
18	8.28	6.01	5.09	4.58	4.25	4.01	3.84	3.71	3.60	3.51	3.37
19	8.18	5.93	5.01	4.50	4.17	3.94	3.77	3.63	3.52	3.43	3.30
20	8.10	5.85	4.94	4.43	4.10	3.87	3.70	3.56	3.46	3.37	3.23
21	8.02	5.78	4.87	4.37	4.04	3.81	3.64	3.51	3.40	3.31	3.17
22	7.95	5.72	4.82	4.31	3.99	3.76	3.59	3.45	3.35	3.26	3.12
23	7.88	5.66	4.76	4.26	3.94	3.71	3.54	3.41	3.30	3.21	3.07
24	7.82	5.61	4.72	4.22	3.90	3.67	3.50	3.36	3.26	3.17	3.03
25	7.77	5.57	4.68	4.18	3.85	3.63	3.46	3.32	3.22	3.13	2.99
26	7.72	5.53	4.64	4.14	3.82	3.59	3.42	3.29	3.18	3.09	2.96
27	7.68	5.49	4.60	4.11	3.78	3.56	3.39	3.26	3.15	3.06	2.93
28	7.64	5.45	4.57	4.07	3.75	3.53	3.36	3.23	3.12	3.03	2.90
29	7.60	5.42	4.54	4.04	3.73	3.50	3.33	3.20	3.09	3.00	2.87
30	7.56	5.39	4.51	4.02	3.70	3.47	3.30	3.17	3.07	2.98	2.84
40	7.31	5.18	4.31	3.83	3.51	3.29	3.12	2.99	2.89	2.80	2.66
60	7.08	4.98	4.13	3.65	3.34	3.12	2.95	2.82	2.72	2.63	2.50
120	6.85	4.79	3.95	3.48	3.17	2.96	2.79	2.66	2.56	2.47	2.34
∞	6.63	4.61	3.78	3.32	3.02	2.80	2.64	2.51	2.41	2.32	2.18

FIG. X4.1 Critical Values of F at 1 % Significance (99 % Confidence) Level (One-Sided)

X5. DEFINITIONS RELATING TO THE OPTICAL DESIGN OF TURBIDIMETER INSTRUMENTATION

X5.1 Introduction

X5.1.1 This appendix is provided for the user of this test method in the case that additional information related to scientific definitions that relate to turbidity measurements. These definitions can be applied to the designs listed in this test method.

X5.2 Definitions

X5.2.1 *absorption*—the conversion of light or NIR to heat as it passes through water or wastewater. Unlike scattering, absorption does not alter the direction of radiation transfer. In a turbidity sample, radiation is absorbed by water, dissolved radiation-absorbing materials, the sample matrix, and by suspended particles. The absorption coefficient, a in m^{-1}, is the quantitative measure of this IOP. Turbidimeters respond to light absorption by a sample but they do not quantitatively measure the coefficient a.

X5.2.2 *attenuation*—the combined effects of absorption and scattering in water and wastewater that reduce (attenuate or extinguish) the intensity of light or NIR as it passes through a turbidity sample. A light beam that enters a sample with an initial intensity of 100 units and leaves the sample with an intensity of 30 units, for example, is attenuated by 70 units, or 70 %. Attenuation equals $1.0 - T$ when the quantities are expressed as ratios. The attenuation coefficient, c in m^{-1}, is the quantitative measure of this inherent optical property. Turbidimeters respond to attenuation by samples but they do not quantitatively measure c. The attenuation coefficient equals the sum of a and b ($a + b = c$).

X5.2.3 *automatic power control (APC)*—the regulation of light or NIR power at the entrance window to a turbidity sample such that the irradiance in W m^{-2} remains constant with time and temperature. Automatic power control is achieved with the output from a light/NIR monitoring detector and an electronic feedback circuit.

X5.2.4 *broadband "white-light" sources*—for the purposes of this test method, a broadband, "white-light" light source is one that is visible (380–770 nm) and has a full bandwidth at half maximum intensity (FWHM) greater than 80 nm. Tungsten filament lamps and white LEDs with or without color-correction filters are used to create broadband sources in turbidimeters.

X5.2.5 *detector angle*—the angle between the axis of the detector acceptance cone and the axis of the source light or NIR beam. The detector angle equals 180°-θ.

X5.2.6 *dilution water*—distilled waster with a turbidity less than 0.25 NTU, measured by Test Method D6855 (low range, static mode) used for the preparation of calibration standards for this test method.

X5.2.7 *inherent optical properties (IOPs)*—the physical properties, including absorption, scattering, and attenuation, that influence the transfer of light and NIR through water and wastewater and that are unaffected by ambient illumination or radiation. Turbidimeters respond to the IOPs of a sample but they do not quantitatively measure them.

X5.2.8 *interferences*—sample properties and a wide variety of factors including, but not limited to: *(1)* sample-handling artifacts, *(2)* particle settling, *(3)* bubble formation and dissolution, *(4)* chemical precipitation and dissolution, *(5)* biological production and decomposition of particles, and *(6)* changes in the transparency and reflectivity of optical components caused by chemical, biological, and sediment buildup on such components or in the sample volume. Interferences cause turbidity readings to be higher or lower than they would be in the absence of these factors. Positive interference causes turbidity measurements to increase while negative interferences lower turbidity values.

X5.2.9 *intermediate-band radiation sources*—for the purposes of this test method, an intermediate-band light or NIR source is one that has a full bandwidth at half maximum intensity (FWHM) of 5 to 80 nm. LEDs, IREDs, and broadband, "white-light" sources with band-pass optical filters are used to create intermediate-band sources in turbidimeters.

X5.2.10 *monitor photo/NIR detector*—a solid-state device used to detect the radiance from a turbidimeter light source.

X5.2.11 *narrow-band, "monochromatic" radiation sources*—for the purposes of this test method, a narrow-band or "monochromatic" light or NIR source is one that has a full bandwidth at half maximum intensity (FWHM) of less than 5 nm. Lasers and broadband, "white light" sources with appropriate interference filters are used to create narrow-band sources in turbidimeters.

X5.2.12 *operating spectrum*—the spectrum resulting from the wavelength by wavelength product of source intensities and filter and detector response. The shape of the operating spectrum represents the relative contributions of measurement wavelengths. In this test method, turbidimeters with narrow-band, "monochromatic," sources have an operating wavelength. All others have an operating spectrum.

X5.2.13 *photo/NIR detector*—a solid-state device used to detect the relative intensity of radiance from a turbidity sample.

X5.2.14 *particle size distribution (PSD)*—after suspended-sediment concentration (SSC), PSDs have the largest single influence on turbidity values in surface-water measurements.

X5.2.15 *scattering angle (θ)*—the angle between a source light or NIR beam and the scattered beam. Forward-scattered radiation fills the hemisphere surrounding a source beam and oriented away from the source ($0 < \theta < 90°$) and backscattered radiation fills the opposite hemisphere ($90° = \theta < 180°$).

X5.2.16 *scatter (also referred to as scattering)*—the interaction of a light or NIR beam with suspended particles and inhomogenieties of the matrix refractive index that alter the direction of radiation transport without changing the wavelength. The scattering coefficient, b in m^{-1}, is the quantitative measure of this IOP. The volume scattering function, VSF,

expresses the angular distribution and relative intensity of light scattered from a sample. It depends, among other things, on the size of the scattering particles relative to the operating wavelength or spectrum (see definition of the size parameter). Turbidimeters respond to the intensity and direction of light scattering by samples but they not quantitatively measure the coefficient *b* or the VSF.

X5.2.17 *size parameter (x)*—the product of particle radius and $2\pi n$, where n = the refractive index of the particle-suspending medium, divided by operating wavelength. For this test method, $2\pi n$ is a constant about equal to 8.2. Other factors being equal, the shape of the volume scattering function depends on the value of x.

X5.2.18 *transmission (T)*—the ratio, T, of light or NIR intensity at a measurement location to its initial intensity. When expressed in ratios, $T = 1.0 - A$, where A is the proportion of light or NIR intensity that is attenuated by scattering and absorption. Turbidimeters do not quantitatively measure T. (Transmittance: $T = P/P_0$, where P_0 is the radiant power of light striking the sample on one side of the cell (or chamber) and P is the radiant power of light emerging from the other side of the sample.) This is the universal definition that is used.

X5.2.19 *turbidimeter design*—an arrangement of optical (lenses, windows, filters, field stops, etc.), opto-electronic (light/NIR sources and detectors, etc.), mechanical components, and electrical circuits for determining the turbidity of a water or wastewater sample in a numerical value relative to a calibration standard. This test method presents the specifications for ten turbidimeter designs.

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