August 2001

Environmental Technology Verification Report

ABB INSTRUMENTATION SERIES 4670 ON-LINE TURBIDIMETER

Prepared by

Battelle
. . . Putting Technology To Work

Battelle

Under a cooperative agreement with

EPA U.S. Environmental Protection Agency

ETV ETV ETV

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**ON-LINE TURBIDIMETER**	
APPLICATION:	**MEASURING LOW TURBIDITY LEVELS**	
TECHNOLOGY NAME:	**Series 4670**	
COMPANY:	**ABB Instrumentation**	
ADDRESS:	**200 West 22 St. Suite 255** **Lombard, IL 60148-4883**	**PHONE: (800) 323-5838** **FAX: (630) 371-6397**
WEB SITE: **E-MAIL:**	**www.abb.com** **beth.schlitt@us.abb.com**	

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups which consist of buyers, vendor organizations, and permitters; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Advanced Monitoring Systems (AMS) Center, one of six technology centers under ETV, is operated by Battelle in cooperation with EPA's National Exposure Research Laboratory. The AMS Center has recently evaluated the performance of on-line turbidimeters for use in water treatment facilities. This verification statement provides a summary of the test results for the ABB Series 4670 on-line turbidimeter.

VERIFICATION TEST DESCRIPTION

The verification test described in this report was conducted by Battelle between March 2 and April 16, at the City of Columbus Water Division's Dublin Road Water Plant in Columbus, Ohio. The verification test was conducted in two phases. An off-line phase challenged the turbidimeter with a series of prepared standards and other test solutions under controlled conditions, whereas an on-line phase assessed long-term performance under realistic conditions by monitoring a sample stream in a municipal water treatment plant. The on-line phase was intended to evaluate performance in continuous unattended monitoring over a low range of turbidity [i.e., 0.3 to 4 nephelometric turbidity units (NTUs)]. No attempt was made to determine the ultimate detection limits of the turbidimeter tested, which the vendor literature indicates can be as low as 0.01 NTU.

In the off-line phase of testing, the linearity, accuracy, and precision of the ABB Series 4670 turbidimeter were determined by comparing turbidity measurements on formazin solutions to reference measurements of the same solutions. By intentionally varying the water temperature, flow rate, and color of the sample solution, the effect of these parameters on the response of the ABB Series 4670 turbidimeter was determined. In the on-line phase, a sample stream from a municipal water plant was continuously monitored by the ABB Series 4670 turbidimeter for approximately 4 weeks. Results from this phase of testing were used to determine the accuracy in measuring real-world samples and the drift characteristics of the ABB Series 4670. Quality assurance (QA) oversight of verification testing was provided by independent Battelle QA staff, who conducted a technical systems audit, and a data audit on 10 percent of the test data.

The verification test relied upon two reference methods: ISO 7027, "Water Quality—Determination of Turbidity," and EPA Method 180.1, "Determination of Turbidity by Nephelometry." The ABB Series 4670 turbidimeter is designed to conform to ISO 7027 requirements, and thus comparison of ABB Series 4670 turbidimeter results to those from the ISO 7027 reference method was the primary means of verification. EPA Method 180.1 uses a different wavelength of light than the ABB Series 4670 turbidimeter (i.e., visible rather than infrared), and thus is not a directly equivalent method. However, the EPA Method 180.1 method is widely recognized in the United States, by virtue of its status as one of the required methods for drinking water compliance measurements. Consequently, comparisons of the ABB Series 4670 turbidimeter results to Method 180.1 results were also made, and are presented as a secondary illustration of performance.

TECHNOLOGY DESCRIPTION

The ABB Series 4670 turbidimeter comprising a wall-mounted analyzer and a sensor, is manufactured by ABB Instrumentation and conforms to ISO 7027. The on-line analyzer requires continuous sample flow. The flow-through system of nephelometric design uses the 90-degree scattered light principle and operates over the 0- to 30-nephelometric turbidity unit (NTU) range with a minimum range of 0 to 1 NTU. Ultralow back scatter enables true zero setting, ensuring accurate and reliable results below 0.1 NTU. The system's process connections use a 12-mm internal dimension (I.D.) tube inlet and 6-mm I.D. tube outlet.

Automatic cleaning and on-line diagnostics are standard features. The automatic cleaning eliminates optical fouling and maintains performance for up to 6 months without manual intervention. The entire sensing loop is regularly self-monitored to ensure that the light source is operating with specifications. The integral wiper cleaning system is programmable to operational frequencies of every 0.25 hour, 0.5 hour, 0.75 hour, or in multiples of 1 hour up to 24 hours. The wiper module is continuously validated by the processor to assure correct performance of the cleaning function.

The system is calibrated upon start-up using a dry secondary calibration standard, supplied for zero and span verification, or formazine standard solution. The dry standard simplifies routine calibration and eliminates the need to produce formazine standard, which is a major safety factor.

The ABB Series 4670 turbidimeter is designed to be operated at temperatures between 0 and 50ºC, at flow rates between 0.5 and 1.5 liters per minute, and at pressures up to 3 bar. Its response time varies with flow rate, but typically exhibits a 90 percent step change in less than 45 seconds at 1 liter per minute.

VERIFICATION OF PERFORMANCE

The following are summaries of key performance characteristics as verified by comparison to the ISO 7027 reference method. Secondary illustrations of performance relative to the EPA Method 180.1 are also shown in the body of the report and generally showed similar performance to that found in the verification comparisons.

Off-Line Testing

Linearity: The ABB Series 4670 turbidimeter provided linear response over the tested range of approximately 0.05 to 5 NTU. The slope of the response curve from approximately 0.05 to 5 NTU for the ABB Series 4670 turbidimeter relative to the ISO 7027 reference turbidimeter was 0.926 at the beginning of this test, with an intercept of 0.013 NTU and $r^2 > 0.999$.

Accuracy: In measuring standard formazin solutions in the range of 0.3 to 5 NTU, the ABB Series 4670 turbidimeter and the ISO 7027 reference turbidimeter agreed within 7.2% or less, which was comparable to the observed differences in the daily calibration checks of the reference turbidimeter.

Precision: The precision in the measurements of the ABB Series 4670 turbidimeter ranged from approximately 0.2% to 3% RSD at turbidities of 0.5 to 5 NTU. These results were approximately the same as for the reference turbidimeter throughout this range of turbidity.

Water Temperature Effect: Water temperature had a negligible effect on the response of the ABB Series 4670 turbidimeter relative to the ISO 7027 method at low turbidity (0.3 NTU) or at higher turbidity (5 NTU).

Flow Rate: In the narrow range of flow rates tested for the ABB Series 4670 turbidimeter (0.1 to 0.4 gpm), there was no statistically significant effect on the turbidity readings as a function of sample flow rate at 5 NTU. At 0.3 NTU, flow rate showed an effect only at 0.4 gpm. At that flow rate, turbidity readings were about 20% higher than at 0.1 or 0.26 gpm.

Color: Color had no effect on readings at low (~0.1 NTU) or high turbidity (5 NTU).

On-Line Testing

Accuracy: In reading the turbidity of treated, unfiltered water from a municipal drinking water plant with a turbidity range of 0.3 to 4 NTU, the ABB Series 4670 turbidimeter usually showed a negative bias of up to 0.8 NTU relative to the reference turbidimeter, corresponding to a percent bias of up to 30%. On average, a bias of -18.8% relative to the ISO 7027 reference turbidimeter was found. Calibration checks of the ABB Series 4670 turbidimeter using a nominal 0.5 NTU formazin solution showed a bias of +1 to -20% with respect to the ISO 7027 reference turbidimeter, with an average bias of -8.3%, indicating a difference in response between the formazin and plant water streams.

Drift: A change of approximately 9% in the slopes of the ABB Series 4670 turbidimeter response curves between the beginning and end of the verification test was observed; however, this change is within the combined experimental uncertainty of the reference measurements over this time period and does not definitively indicate a calibration drift. A change of 0.002 NTU was observed in the values of the intercepts calculated from the initial and final linearity checks. This degree of change is well within the experimental uncertainty of the reference measurements. Furthermore, no apparent drift was observed in the calibration of the ABB Series 4670 turbidimeter throughout the on-line testing on the plant water stream.

Gabor J. Kovacs Date Vice President Environmental Sector Battelle	Gary J. Foley Date Director National Exposure Research Laboratory Office of Research and Development U.S. Environmental Protection Agency

August 2001

Environmental Technology Verification Report

ETV Advanced Monitoring Systems Center

ABB Instrumentation
Series 4670
On-Line Turbidimeter

By

Kenneth Cowen
Robyn Imm
Thomas Kelly
Karen Riggs

Battelle
Columbus, Ohio 43201

Notice

The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development, has financially supported and collaborated in the extramural program described here. This document has been peer reviewed by the Agency and recommended for public release. Mention of trade names or commercial products does not constitute endorsement or recommendation by the EPA for use.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the nation's air, water, and land resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, the EPA's Office of Research and Development provides data and science support that can be used to solve environmental problems and to build the scientific knowledge base needed to manage our ecological resources wisely, to understand how pollutants affect our health, and to prevent or reduce environmental risks.

The Environmental Technology Verification (ETV) Program has been established by the EPA to verify the performance characteristics of innovative environmental technology across all media and to report this objective information to permitters, buyers, and users of the technology, thus substantially accelerating the entrance of new environmental technologies into the marketplace. Verification organizations oversee and report verification activities based on testing and quality assurance protocols developed with input from major stakeholders and customer groups associated with the technology area. ETV consists of six technology centers. Information about each of these centers can be found on the Internet at http://www.epa.gov/etv.

Effective verifications of monitoring technologies are needed to assess environmental quality and to supply cost and performance data to select the most appropriate technology for that assessment. In 1997, through a competitive cooperative agreement, Battelle was awarded EPA funding and support to plan, coordinate, and conduct such verification tests for "Advanced Monitoring Systems for Air, Water, and Soil" and report the results to the community at large. Information concerning this specific environmental technology area can be found on the Internet at http://www.epa.gov/etv/07/07_main.htm.

Acknowledgments

The authors wish to acknowledge the support of all those who helped plan and conduct the verification test, analyze the data, and prepare this report. In particular we would like to thank the staff at the Dublin Road Water Plant, including Tom Camden and Terry Nichols. We also acknowledge the participation of Ms. Beth Ann Schlitt and Mr. Andrew Durant of ABB Instrumentation in this verification test. We would like to thank the Hach Company for supplying the two reference turbidimeters used in this test.

Contents

Figures

Tables

List of Abbreviations

AC	alternating current
AMS	Advanced Monitoring Systems
CU	color unit
DC	direct current
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
gpm	gallons per minute
NIST	National Institute of Standards and Technology
NPT	normal pipe thread
NTU	nephelometric turbidity unit
OD	outer diameter
QA	quality assurance
QC	quality control
QMP	Quality Management Plan
RSD	relative standard deviation
SD	standard deviation

Chapter 1
Background

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer-reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized testing organizations; with stakeholder groups consisting of regulators, buyers, and vendor organizations; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The EPA's National Exposure Research Laboratory and its verification organization partner, Battelle, operate the Advanced Monitoring Systems (AMS) Center under ETV. This verification report presents the procedures and results of the verification test for the ABB Instrumentation Series 4670 on-line turbidimeter.

Chapter 2
Technology Description

The following description of the ABB Series 4670 turbidimeter is based on information provided by the vendor.

The ABB Series 4670 turbidimeter, comprising a wall-mounted analyzer and a sensor, is manufactured by ABB Instrumentation and conforms to ISO 7027. The on-line analyzer requires continuous sample flow. The flow-through system of nephelometric design uses the 90-degree scattered light principle and operates over the 0- to 30-nephelometric turbidity unit (NTU) range with a minimum range of 0 to 1 NTU. Ultralow back scatter enables true zero setting, ensuring accurate and reliable results below 0.1 NTU. The system's process connections use a 12-millimeter internal dimension tube inlet and 6-millimeter internal dimension tube outlet.

Automatic cleaning and on-line diagnostics are standard features. The automatic cleaning eliminates optical fouling and maintains performance for up to 6 months without manual intervention. The entire sensing loop is regularly self-monitored to ensure that the light source is operating within specifications. The integral wiper cleaning system is programmable to operational frequencies of every 0.25 hour, 0.5 hour, 0.75 hour, or in multiples of 1 hour up to 24 hours. The wiper module is continuously validated by the processor to assure correct performance of the cleaning function.

The system is calibrated upon start-up using a dry secondary calibration standard, supplied for zero and span verification, or formazine standard solution. The dry standard simplifies routine calibration and eliminates the need to produce formazine standard, which is a major safety factor.

Figure 2-1. ABB Series 4670 Turbidimeter

The ABB Series 4670 turbidimeter is designed to be operated at temperatures between 0 and 50ºC, at flow rates between 0.13 and 0.40 gallons per minute (gpm), and at pressures up to 3 bar. Its response time varies with flow rate, but typically exhibits a 90% step change in less than 45 seconds at 1 liter per minute.

Chapter 3
Test Design and Procedures

3.1 Introduction

This verification test was conducted according to procedures specified in the *Generic Test/QA Plan for Verification of On-Line Turbidimeters*.[(1)] Performance characteristics evaluated in the verification test are listed in Table 3-1 along with the dates that data were collected for these evaluations. The test was conducted at a full-scale municipal water treatment facility in Columbus, Ohio. The verification test described in this report was conducted from March 2 through April 16, 2001, as indicated in Table 3-1.

Table 3-1. Performance Characteristics Evaluated and Schedule of Verification Test

Performance Characteristic	Date Data Collected
Off-Line Phase	
Linearity	March 2, 5, 7; April 16
Accuracy	March 2, 5, 7
Precision	March 2, 5, 7
Water temperature effects	March 5, 7
Flow rate sensitivity	March 5-6, 8
Color effects	March 12-13
On-Line Phase	
Accuracy	March 13 to April 13
Calibration checks	March 20, 23, 27, 30 and April 3, 6, 10, and 13

3.2 Test Design Considerations

Since turbidity is a measurement of light scattering, a number of factors can influence the measurement of turbidity in a given sample solution. Instrument design, including light source selection and geometric differences, may result in significant differences between the responses of different turbidimeters. Further differences may result from the variable nature of both the size and composition of particles typically found in water streams, relative to those in standard solutions made with formazin or with polymer beads. These issues were addressed in this verification test in two ways: (1) by using different instrumental designs for the reference turbidimeters and (2) by evaluating a variety of samples.

To avoid potential bias associated with a single method of comparison, the verification test used two reference methods for data comparisons: ISO 7027, "Water Quality—Determination of Turbidity,"[(2)] and EPA Method 180.1, "Determination of Turbidity by Nephelometry."[(3)] Both of these methods measure turbidity using a nephelometric turbidimeter, but they differ in the type of light source and the wavelength used. ISO 7027 calls for an infrared light source, whereas Method 180.1 calls for a visible light source. The ABB Series 4670 turbidimeter is designed to conform to the requirements of ISO 7027, and thus that method is the appropriate reference for verification of the ABB Series 4670 turbidimeter's performance. Verification results presented in this report, and summarized in the Verification Statement, are based on comparisons with the ISO 7027 data. However, secondary comparisons also are shown in this report, based on data from the ABB Series 4670 turbidimeter and Method 180.1. These secondary comparisons are of interest because Method 180.1 is widely recognized in the United States and is designated as the required method for drinking water compliance measurements. These secondary comparisons are shown only to illustrate the performance capabilities of the ABB Series 4670 turbidimeter and should not be taken as having equal weight as the comparisons with ISO 7027.

Additionally, to assess the response of the ABB Series 4670 turbidimeter to both prepared solutions and real-world water samples, verification involved both off-line and on-line phases. The off-line phase challenged the turbidimeter with a series of prepared standards and other test solutions to verify performance under controlled conditions. The on-line phase assessed long-term performance under realistic operating conditions by monitoring a sample stream in a municipal water treatment plant under normal operation. With the cooperation of the City of Columbus' Water Division, both off-line and on-line phases were performed at the division's Dublin Road Water Plant in Columbus, Ohio.

3.3 Experimental Apparatus

On-line turbidimeters measure turbidity continuously on flowing sample streams, as opposed to the static grab samples analyzed by the bench-top reference turbidimeters. Consequently, great care was taken to ensure that the samples collected for reference analysis were representative of the sample flow measured by the ABB Series 4670 turbidimeter. A cylindrical distribution manifold provided identical sample streams to sample ports spaced equally around the circumference of the manifold. Throughout the verification test, a single port was used for the turbidimeter being verified, and two ports provided streams for the grab sample collection. A single port centered in the bottom of the distribution manifold introduced the sample stream to the manifold. All the ports were tapped for ½" male normal pipe thread (NPT) fittings, and hard plastic compression fittings were used to connect the distribution manifold to the tubing (½" OD polyethylene) used in the recirculation system. Providing identical samples to each of the manifold ports minimized biases arising from water quality or turbulence issues.

A schematic representation of the recirculation system is provided in Figure 3-1, where ABB represents the on-line turbidimeter undergoing verification testing. Prepared solutions were supplied to the ABB Series 4670 turbidimeter for the off-line test in a closed-loop recirculation system that used a 40-L reservoir and a centrifugal pump. For the on-line tests, stream water from the plant was sampled from a pressurized source in a once-through configuration (i.e., without the use of the pump or reservoir). In-line particle filters were inserted into the water flow, using appropriate valving, when reduction of turbidity levels was needed.

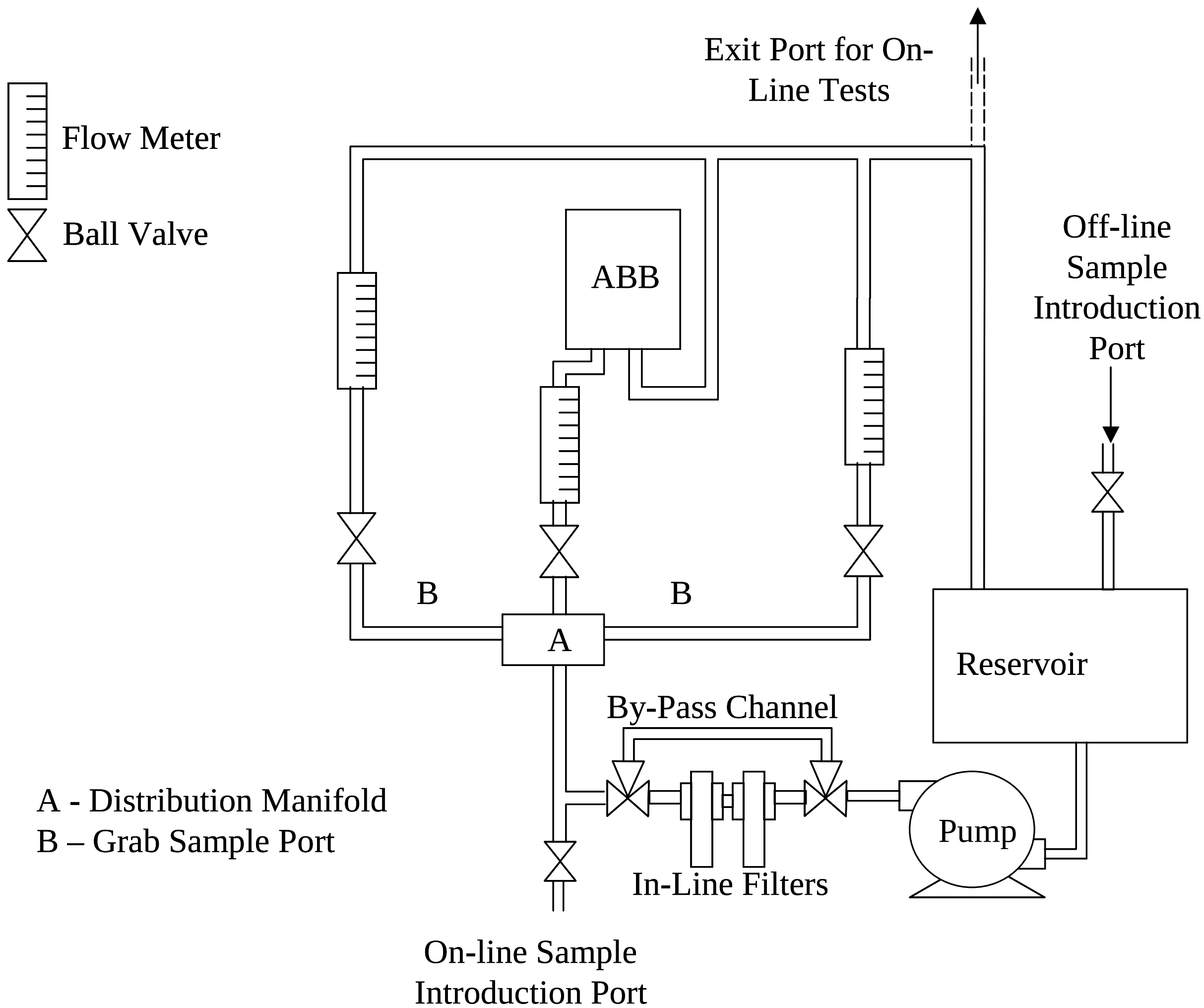

Figure 3-1. Manifold Recirculation System

Before verification testing began, a series of five grab samples was collected from each port on the distribution manifold while recirculating a formazin solution with a nominal turbidity of 0.5 NTU. These samples were analyzed with the reference turbidimeters and compared to ensure uniformity of the turbidity of the solution. Comparison of the sample analyses indicated agreement in turbidity readings within ± 1.2% of the average turbidity among all of the ports.

The ABB Series 4670 turbidimeter verified in this test was installed in the test apparatus at the Dublin Road Water Plant. Much of the recirculation system, including the flow meters and the distribution manifold, was mounted to a ¼"-thick aluminum panel installed in the water plant specifically for this verification test. The Series 4670 turbidimeter tested consisted of a Model 7997-201 sensor (Serial Number P-14734) and a Model 4670 Analyzer. Both the sensor and the analyzer units were installed by a representative of ABB. The mounting bracket housing the sensor unit was bolted to the aluminum panel, and the analyzer unit was mounted to the panel using the mounting holes in the analyzer case.

Prior to introduction to the sensor, the sample stream passed through an in-line flowmeter with a ball valve for flow control. A section of Tygon™ tubing (~2') connected the flowmeter to the sensor unit. The sample stream entered an inlet port near the base of the turbidimeter housing and exited the turbidimeter though a port near the top of the sensor unit. A break in the output stream was introduced to prevent siphoning through the turbidimeter in the case of flow interruption.

The control unit for the ABB Series 4670 turbidimeter was installed above the sensor unit and mounted to the aluminum panel using the available bolt holes in the housing of the control unit. Power was supplied to the controller from a standard wall outlet (120 V AC), and to the sensor unit through a hard-wire connection to the controller. The controller output was converted from a 4-20 mA signal to a DC voltage using a precision resistor and was collected every 10 seconds throughout the test using a Fluke Hydra data logger. The data were transferred in real time to a personal computer at the test site that stored the data. Since the intent of the verification test was to assess performance in routine unattended operation, the ABB Series 4670 turbidimeter was operated in its 0 to 10 NTU range throughout all test activities, and no changes in the output range were made.

3.4 Reference Instruments

Owing to the nature of turbidity measurement and the inherent differences in response arising from different instrumental designs, separate bench-top turbidimeters meeting the design criteria detailed in ISO 7027[(2)] and EPA Method 180.1[(3)] were used as reference instruments in this test. Both methods measure the nephelometric light scattering of a formazin solution, albeit with different prescribed instrumental designs. The primary difference between these two methods is in the choice of light source. Method 180.1 requires the use of a broadband visible incandescent tungsten lamp, while ISO 7027 requires the use of a narrowband IR source. Since the Series 4670 is designed to comply with ISO 7027 requirements, that reference method is the basis for this verification. Comparisons of data with Method 180.1 are also shown because of the widespread recognition and use of that method. However, Method 180.1 comparisons are secondary to the ISO 7027 comparisons used for verification. The bench-top turbidimeters used as the reference methods were the Hach 2100N (Serial Number 00030000601) and the Hach 2100N IS (Serial Number 981100000195), which, according to the manufacturer's literature, comply with the design specifications described in EPA Method 180.1[(3)] and ISO 7027,[(2)] respectively. Throughout the test the reference turbidimeters were operated in the non-ratio mode (i.e., only 90° scatter was measured).

3.5 Off-Line Testing

The off-line phase of the verification test involved off-line sample introduction aimed at assessing the linearity, accuracy, and precision of the on-line turbidimeter relative to the reference methods. Additionally, response to various upset conditions was quantified. As a means of testing these parameters, the off-line test phase included the introduction of standard formazin solutions or other samples and the intentional manipulation of flow and water quality parameters.

Throughout the verification test, continuous turbidity measurements from the ABB Series 4670 turbidimeter were recorded at preset intervals using a data logging system. Grab samples were collected simultaneously with some of these recorded measurements and analyzed using the bench-top reference turbidimeters to provide a basis of comparison for the performance evaluations. The collection of grab samples was timed to coincide within 10 seconds with the recording of real-time turbidity measurements from the ABB Series 4670 turbidimeter, and the grab samples were analyzed within three minutes after collection to minimize possible temperature and settling effects.

Additionally, off-line testing included monitoring the instrumental responses of the ABB turbidimeter to variations in water temperature, flow rate, and color. Each of these parameters was varied within a range consistent with conditions encountered under typical plant operation. The following subsections describe the procedures used for the off-line phase of the verification test.

Table 3-2 provides a summary of the parameters tested in the off-line phase, the test solutions used, and the expected number of readings recorded for each parameter.

3.5.1 Linearity

Linearity was measured in the range from approximately 0.05 to 5 NTU as an initial check in the off-line phase. The recirculation system was filled with tap water, which was then recirculated and filtered in the test apparatus using an in-line filter for several hours. After filtering, the in-line filter was bypassed and the turbidity of the water in the recirculation system was measured by the reference turbidimeters to be approximately 0.05 NTU. A series of five turbidity measurements was taken at that turbidity level, with intervals of at least five minutes between successive measurements. A corresponding set of five measurements also was recorded at approximately 0.3, 0.5, 2, and 5 NTU. To reach each turbidity level, a small amount of 4000 NTU StablCal formazin stock solution was diluted in the recirculation system and allowed to flow through the recirculation system unfiltered for at least 15 minutes before turbidity readings were recorded. At each turbidity level, a series of five turbidity readings was recorded with at least a five-minute interval between successive readings.

Table 3-2. Summary of Measurements for Off-Line Testing

Parameter Tested	Test Solution	Number of Readings
Linearity	Filtered Water (< 0.1 NTU)	5
Linearity (accuracy, precision)[a]	0.3 NTU Formazin	5
Linearity (accuracy, precision)	0.5 NTU Formazin	5
Linearity (accuracy, precision)	2 NTU Formazin	5
Linearity (accuracy, precision)	5 NTU Formazin	5
Water Temperature Effect	0.3 NTU Formazin	5 each at ~11, 15, 20°C
Water Temperature Effect	5 NTU Formazin	5 each at ~12, 17, 22°C
Flow Rate Effect	0.3 NTU Formazin	5 each at 0.1, 0.26, 0.4 gpm
Flow Rate Effect	5 NTU Formazin	5 each at 0.1, 0.26, 0.4 gpm
Color Effect	~ 0.1 NTU	5 each at 5, 15, 30 CU
Color Effect	5 NTU Formazin	5 each at 5, 15, 30 CU

[a] ( ) indicates additional parameters analyzed using collected data.

These readings were compared to the reference measurements of grab samples collected simultaneously with each reading; that is, the turbidity of the solutions was determined by measurement with the reference turbidimeters, rather than simply by calculations based on the dilution process. After the prescribed measurements were recorded at each turbidity level, additional formazin stock solution was added to the recirculation system to increase the turbidity of the solution to the next value in the series.

Before measurements were recorded, the calibration of the reference turbidimeters was checked using a 0.5 NTU StablCal formazin solution purchased from Hach Company, Loveland, Colorado. Pursuant to the requirements of the test/QA plan,(1) agreement between the reference measurement and the certified turbidity of the standard was required to be within 10% before recording any series of measurements. After each series of measurements, the calibration of the reference turbidimeters was again checked with the same standard, and the same acceptance limits were applied. In addition to the 0.5 NTU calibration checks, before and after the measurements on the filtered water level, a < 0.1 NTU blank standard also was measured to ensure proper calibration of the reference instruments at low levels. The < 0.1 NTU standard also was purchased from Hach Company; agreement between the reference measurement and the turbidity reported on the certificate of analysis was required to be within 0.02 NTU.

3.5.2 Accuracy and Precision

Data obtained from the linearity measurements were used to establish the accuracy and precision of the ABB Series 4670 turbidimeter in measuring formazin solutions. Accuracy was assessed by comparing continuous turbidity measurements with those from the ISO 7027 reference turbidimeter. Precision was assessed from the five replicate results at each turbidity level.

3.5.3 Water Temperature

Variations in the temperature of the water stream were introduced to simulate a range of conditions under which the on-line turbidimeters may typically operate. During off-line testing, the temperature of the recirculating water equilibrated at 20 to 22°C, which was slightly above the ambient temperature in the water plant during testing. To assess the effect of temperature on the turbidimeter performance, the temperature of the recirculating solution was lowered using an immersion type chiller; and replicate turbidity measurements were recorded at 15 to 17°C and again at 10 to 12°C. In these tests, the solution temperature in the reservoir was held within 2.5°C of the nominal 11°C and 16°C targets, while a series of five measurements was recorded at each temperature. To ensure equilibration, the solution was allowed to recirculate for one hour before the turbidity measurements were recorded. For the temperature tests at approximately 11°C and 16°C, the temperature of the sample stream was recorded at the grab sample port within 30 seconds of sample collection, and the temperature of the grab sample was measured within 30 seconds of completion of the reference measurement. To assess temperature effects at different turbidities, this test was conducted with both 0.3 and 5 NTU solutions.

3.5.4 Flow Rate

The flow rate of the sample stream through the ABB Series 4670 turbidimeter was manipulated to assess the response of the turbidimeter to various realistic operational conditions. A manual ball valve and needle valve were included upstream of the Series 4670 turbidimeter and were adjusted to vary the flow rate through the turbidimeter. Owing to the nature of the Series 4670 design, the flow requirements for the sample stream cover a narrow range of approximately 0.1 to 0.4 gpm. During normal testing, the flow rate was held at 0.26 gpm. The flow test was performed at a minimum flow rate of 0.1 gpm and at a maximum flow rate of 0.4 gpm. To assess the effect of flow rates on performance, measurements were made at both the minimum and maximum flow rates at turbidity levels of both 0.3 NTU and 5 NTU.

3.5.5 Color

Changes in water color were introduced by spiking the sample stream with colored solutions prepared from commercial food coloring dye. Stock solution was added to the system reservoir to give sample solutions approximately 5, 15, and 30 color units (CU) successively, and the instrumental response to these color changes was monitored. Five measurements were made for each color level at both low turbidity (~ 0.1 NTU) and higher turbidity (~ 5 NTU).

The color of the recirculated solution was determined by analyzing the grab samples instrumentally using a Perkin-Elmer Spectronic 21 spectrophotometer. The reference turbidimeter was calibrated for color measurements using a series of prepared color standards. Solutions used in the color calibration of the reference turbidimeter were prepared by dilution of a commercial cobalt-platinum color standard[4] (Hach Company, Loveland, Colorado).

At ~ 0.1 NTU, the color of the solution before addition of the dye was approximately 0 CU. However, at the 5 NTU level, light scattering from the presence of formazin introduced an apparent color to the solution of approximately 30 CU. Consequently, for the 5 NTU test, dye solution was added to increase the color by 5, 15, and 30 CU; i.e., to bring the absolute color to approximately 35, 45, and 60 CU, respectively.

3.6 On-Line Testing

The on-line test phase focused on assessing the long-term performance of the ABB turbidimeter under realistic unattended operating conditions and assessing its accuracy in monitoring an actual sample stream. Specifically, this phase of testing addressed the calibration and drift characteristics of the turbidimeter over a four-week period of monitoring a sample stream from the water plant. Routine reference measurements were used for comparison with the on-line readings to assess accuracy, and a reevaluation of the calibration at the end of the test period helped establish drift characteristics. Natural meteorological and demand changes contributed to the variability of water quality in the treatment facility and provided a natural range of turbidity for characterizing performance.

Table 3-3 provides a summary of the parameters tested in the on-line phase, the test solutions used, and the number of readings recorded for each parameter.

Table 3-3. Summary of Measurements for On-Line Testing

Parameter Tested	Test Solution	Number of Readings
Accuracy	Plant Water	5 per weekday for 4 weeks (100 total)
Drift	0.3 NTU Standard	5 for final linearity check
Drift	0.5 NTU Standard	5 each for eight calibration checks (40 total) and 5 for final linearity check
Drift	2 NTU Standard	5 for final linearity check
Drift	5 NTU Standard	5 for final linearity check

3.6.1 Accuracy

In the on-line testing, the accuracy of the ABB Series 4670 turbidimeter relative to the ISO 7027 reference method was assessed on water samples from the plant stream. A sample stream was drawn from a flocculation settling basin at the Dublin Road Water Plant facility, containing unfiltered water that had been treated with lime, caustic, and alum. The sample stream was directed to the ABB Series 4670 turbidimeter through the distribution manifold. At least five grab samples of this stream were collected and analyzed by the reference turbidimeters each weekday (Monday through Friday) for the four weeks of testing. The reference measurements of these samples were compared with the simultaneous results from the ABB Series 4670 turbidimeter. The observed range of turbidity as continuously measured by the ABB Series 4670 turbidimeter in the sample stream was 0.3 to 4 NTU.

3.6.2 Drift

Drift was determined in two ways: (1) through off-line calibration checks conducted regularly throughout the course of the verification test using formazin solutions and (2) through a comparison of multi-point linearity checks performed initially during the off-line phase (described in Section 5.1) and after completing the on-line phase. The turbidimeter was calibrated by the vendor during installation at the water plant. After that calibration, no further manual calibration or adjustment was performed for the duration of the verification test period. The housing of the ABB Series 4670 turbidimeter was opened once during the on-line testing, at which time the sample chamber was cleaned to remove accumulated deposits.

The ABB Series 4670 turbidimeter was taken off line briefly twice each week for routine calibration checks against a nominally 0.5 NTU formazin solution. These intermediate calibration checks were performed twice weekly for four consecutive weeks. Freshly diluted StablCal solutions were used as the standards for these calibration checks.

Upon completion of the four-week period, calibration and linearity were checked again by comparing them with the reference measurements using standard solutions of nominally 0.3, 0.5, 2, and 5 NTU. A linear fit of these data was compared with the initial linearity check performed in the off-line phase to assess the degree of calibration drift.

Chapter 4
Quality Assurance/Quality Control

Quality control (QC) procedures were performed in accordance with the quality management plan (QMP) for the AMS pilot[5] and the test/QA plan[1] for this verification test.

4.1 Data Review and Validation

Test data were reviewed and approved according to the AMS pilot QMP,[5] the test/QA plan,[1] and Battelle's one-over-one policy. The Verification Test Coordinator, or the Verification Test Leader, reviewed the raw data and the data sheets that were generated each day and approved them by adding their signature and the date. Laboratory record notebook entries were also reviewed, signed, and dated.

4.2 Deviations from the Test/QA Plan

No deviations from the test/QA plan occured during the verification test.

4.3 Calibration

4.3.1 Reference Turbidimeters

The reference turbidimeters were calibrated according to the procedures described in their respective instrument manuals. The calibrations were performed on February 21, 2001. Calibration was performed using a blank and 20, 200, 2,000, and 4,000 NTU StablCal calibration standards (Hach Company, Loveland, Colorado). After calibration and before proceeding with the verification test, the calibration of each reference turbidimeter also was checked through a five-point linearity test using solutions with the following turbidities: < 0.1, 0.3, 0.5, 2, and 5 NTU. The < 0.1, 0.3, and 0.5 NTU solutions were purchased and used as is, whereas the 2 and 5 NTU solutions were prepared by diluting a purchased 20 NTU StablCal formazin standard solution. The results of the linearity check are summarized in Table 4-1, indicating that the two reference turbidimeters gave essentially identical results. For each reference turbidimeter, the slope of this linear fit was within the 0.90 and 1.10 limits prescribed in the test/QA plan,[1] and each fit had an $r^2 > 0.98$ as called for in the test/QA plan.[1]

Table 4-1. Results of Linearity Check of Reference Turbidimeters

Parameter	Hach 2100AN IS (ISO 7027)	Hach 2100AN (180.1)
Slope (std. error)	1.064 (0.009)	1.064 (0.010)
Intercept (std. error)	0.053 (0.021)	0.049 (0.023)
r^2	0.998	0.998

The calibration of each reference turbidimeter also was checked both before and after each series of test measurements, using a nominal 0.5 NTU StablCal standard solution. The reference turbidimeters were to be recalibrated if agreement between the turbidity reading and the certified 0.501 NTU turbidity value of this standard solution was not within ± 10% (i.e., 0.451 - 0.551 NTU). If this calibration check criterion was met before but not after a series of test measurements, those measurements were to be repeated after recalibration of the reference turbidimeters. Throughout the course of the verification test, neither reference turbidimeter was ever found to be out of calibration, and consequently no recalibration of the reference turbidimeters was performed.

Before the turbidity of the filtered water was measured in the linearity test, an additional calibration check with < 0.1 NTU standard also was performed on the reference turbidimeters to ensure proper calibration at low levels. The results showed agreement within 0.02 NTU between the turbidity reading of the < 0.1 NTU standard and the value as reported on the certificate of analysis.

4.3.2 Temperature Sensors

Two J-type thermocouples were used throughout the verification test to determine water temperature and the ambient air temperature. The temperatures were recorded every ten seconds during the verification test using the Fluke Hydra data logging system. The Fluke data system was calibrated on December 14, 2000.

4.3.3 Flow Meters

The flow meter used in the verification test to measure the water flow through the ABB Series 4670 turbidimeter was a panel-mounted, direct-reading meter purchased from Cole-Parmer (Catalog Number P-03248-56), capable of measuring up to 1 gpm. The flow meter was factory calibrated and was checked once during the verification test by measuring the time required to fill a container of known volume through the meter at a setting of 0.2 gpm and at a setting of 1.0 gpm. Table 4-2 summarizes the results of the flow meter calibration check.

Table 4-2. Summary of Flow Meter Calibration Check

Flow Meter Setting (gpm)	Volume (gallon)	Time (seconds)	Calculated Rate (gpm)
0.2	0.53	149.8	0.21
1.0	1.05	63.6	1.00

The calibration check was performed on February 26, 2001, and indicated agreement within the 10% criterion established in the test/QA plan.(1)

4.4 Data Collection

Electronic data were collected using a Fluke Hydra data logger and transferred in real time to a PC for storage and real-time graphical display. Data were collected from the ABB Series 4670 turbidimeter every 10 seconds over the course of verification testing. These data were saved in .csv format, along with the time of collection and the water and ambient air temperatures. Data files were stored electronically both on the hard drive of the data collection system and on floppy discs for backup purposes. Data collected manually included turbidity readings of the reference turbidimeters, flow rates, and water and ambient air temperature measurements. An example of the data recording sheet used to record these data is shown in Appendix A.

4.5 Assessments and Audits

4.5.1 Technical Systems Audit

The Battelle Quality Manager conducted a technical systems audit over the period of March 6, 2001 to April 16, 2001 to ensure that the verification test was being performed in accordance with the test/QA plan and the AMS Center QMP. As part of the audit, the reference standards and methods used were reviewed, actual test procedures were compared to those specified in the test/QA plan, and data acquisition and handling procedures were reviewed. Observations and findings from this audit were documented and submitted to the Verification Test Coordinator for response. No corrective action was required. The records concerning the technical systems audit (TSA) are permanently stored with the Battelle Quality Manager.

4.5.2 Performance Evaluation Audit

Performance evaluation audits were conducted to assess the quality of the measurements made in the verification test. These audits addressed only those measurements made by Battelle staff in conducting the verification test, i.e., the reference turbidimeter readings and temperature measurements. The audits were conducted by analyzing the standards or comparing them with references that were independent of those used in the verification test. Each audit was made at least once during the verification test.

The audit of the reference turbidimeters was performed by analyzing a reference solution that was independent of the formazin standards used for calibration of the reference turbidimeters during the verification test. The independent reference solution was an AMCO-AEPA-1 0.5 NTU standard solution obtained from APS Analytical Standards, Redwood City, California. This audit was conducted at least once daily throughout the verification test and served as an independent verification of the calibration of the reference turbidimeters. Agreement between the National Institute of Standards and Technology (NIST) traceable turbidity value of the AMCO-AEPA-1 solution and the turbidity readings from each reference turbidimeter was recorded and tracked graphically using a control chart. Furthermore, similar calibration assessments were performed daily using a purchased 0.5 NTU StablCal formazin standard (Hach Company, Loveland, Colorado), as described in Section 4.3.1. The results of these StablCal daily calibration assessments always showed agreement between the turbidity reading from each reference turbidimeter and the certified turbidity within ± 10%, as required in the test/QA plan.[1] The results of the daily calibration assessments are shown in Figures 4-1a and 4-1b for both the AMCO-AEPA-1 standard and the formazin standard on the 2100N IS (ISO 7027) and 2100N (180.1) reference turbidimeters, respectively. The solid lines in Figures 4-1a and 4-1b show the ± 10% control limits of the calibration checks for the formazin standard.

The average of the daily readings of the AMCO-AEPA-1 (0.500 NTU) standard, as measured by the ISO 7027 reference turbidimeter, was 0.524 NTU, with a standard deviation of 0.006 NTU (~1.1% relative standard deviation). The range of daily readings was 0.512 to 0.535 NTU, or approximately 2.4% to 7.0% high relative to the certified turbidity value. As measured by the EPA Method 180.1 reference turbidimeter, the average of the daily readings was 0.539 NTU, with a standard deviation of 0.008 NTU (~1.5% relative standard deviation). The range of daily readings with the EPA Method 180.1 reference turbidimeter were 0.513 to 0.550 NTU, or approximately 2.6% to 10% greater than the certified turbidity value. Similarly, for the formazin 0.501 NTU standard, readings of the ISO 7027 reference turbidimeter ranged from 0.500 to 0.549 NTU (i.e., 0.2% less than to 9.6% greater than the certified value), with an average reading of 0.527 (± 0.012 NTU, ~2.3% relative standard deviation). With the EPA Method 180.1 reference turbidimeter, daily readings of the formazin standard ranged from 0.506 to 0.550 NTU (i.e., 1.0% to 9.8% greater than the certified value), with an average reading of 0.531 (± 0.011 NTU, ~2.1% relative standard deviation). Although the average deviations from the true turbidity values for these standards were approximately the same, the scatter in the readings was greater in the formazin readings.

The audit of the thermocouple that measured the ambient air temperature during the verification test consisted of a comparison of the temperature readings from the thermocouple with those of an independent temperature sensor. The thermocouple was checked for accuracy by comparison with an American Society for Testing and Materials mercury-in-glass thermometer on April 13, 2001. That comparison was done at ambient temperature, and agreement between the thermocouple used in the verification test and the mercury-in-glass thermometer was well within the two-degree specification established in the test/QA plan.[1]

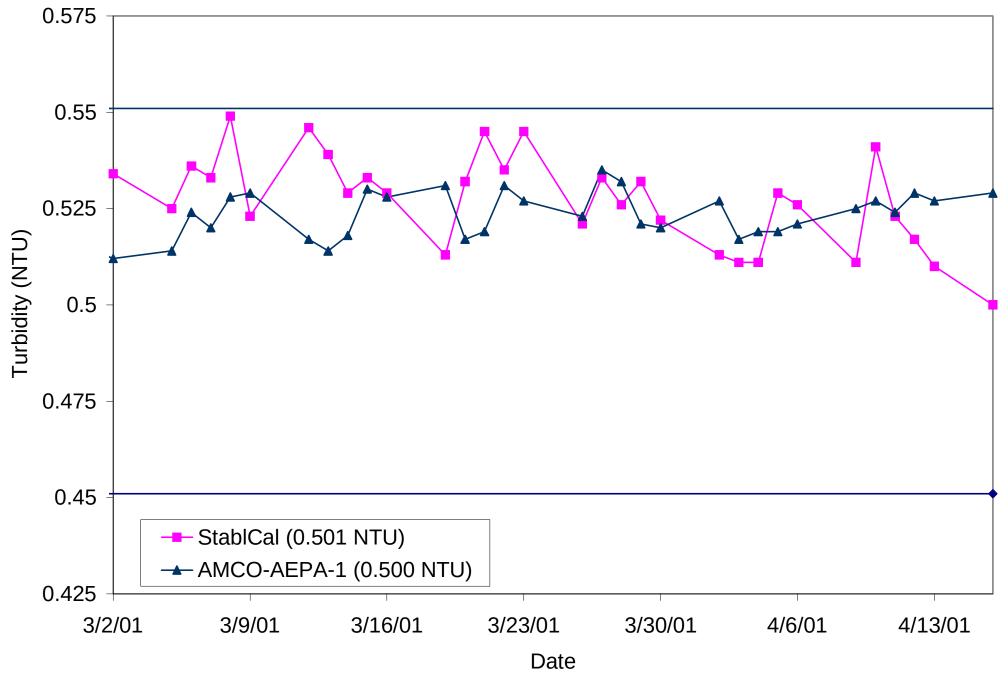

Figure 4-1a. Control Chart for Performance Evaluation Calibration Checks of ISO 7027 Reference Turbidimeter (solid lines show ± 10% control limits of calibration checks for formazin standards)

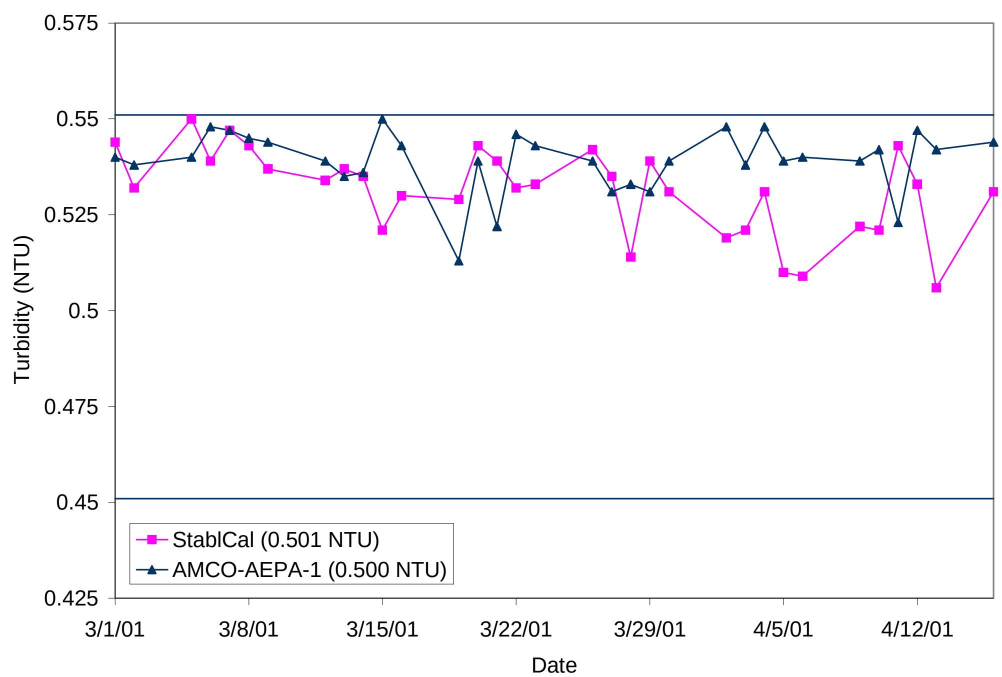

Figure 4-1b. Control Chart for Performance Evaluation Calibration Checks of Method 180.1 Reference Turbidimeter (solid lines show ± 10% control limits of calibration checks for formazin standards)

4.5.3 Audit of Data Quality

Battelle's Quality Manager audited at least 10% of the verification data acquired during the verification test. The Quality Manager traced the data from initial acquisition, through reduction and statistical comparisons, to final reporting. All calculations performed on the data undergoing the audit were checked.

4.6 Audit Reporting

Each assessment and audit was documented in accordance with Sections 3.3.4 and 3.3.5 of the QMP. Once the assessment report was prepared, the Verification Test Coordinator ensured that a response was provided for each adverse finding or potential problem, and implemented any necessary follow-up corrective action. The Battelle Quality Manager ensured that follow-up corrective action was taken. The results of the TSA were sent to EPA.

Chapter 5
Statistical Methods

5.1 Off-Line Testing

The turbidimeter performance characteristics were quantified on the basis of statistical comparisons of the test data. This process began by converting the files that resulted from the data acquisition process into spreadsheet data files suitable for data analysis. The following statistical procedures were used to make the comparisons.

5.1.1 Linearity

Linearity was assessed by linear regression, with the reference turbidity reading (*R*) as an independent variable and the turbidimeter response (*T*) as a dependent variable. The regression model was

$$T = \mu_1 \times R + \beta$$

where μ_1 and β are the slope and intercept of the response curve, respectively. The turbidimeter performance was assessed in terms of the slope, intercept, and the square of the correlation coefficient of the regression analysis. Estimates for the standard errors of the slope and intercept are reported.

5.1.2 Accuracy

The accuracy of the turbidimeter with respect to the reference method was assessed in terms of the average relative bias (B), as follows:

$$B = \left(\frac{(R - T)}{R} \right) \times 100$$

where *R* is the turbidity reading of the reference turbidimeter, and *T* is the corresponding turbidity reading of the ABB Series 4670 turbidimeter.

Accuracy relative to the reference turbidimeter was assessed both for the prepared solutions and the samples from the plant water stream. The accuracy of the ABB Series 4670 turbidimeter was assessed relative to the ISO 7027 reference method for verification purposes and relative to Method 180.1 as an additional illustration of performance.

5.1.3 Precision

Precision was reported in terms of the percent relative standard deviation (RSD) of a group of similar measurements. For a set of turbidity measurements given by T_1, T_2, ..., T_n, the standard deviation (*SD*) of these measurements is

$$SD = \left[\frac{1}{n-1} \sum_{k=1}^{n} (T_k - \overline{T})^2 \right]^{1/2}$$

where $\overline{T}$ is the average of the turbidity readings. The RSD is calculated as follows:

$$RSD = \frac{SD}{\overline{T}} \times 100$$

and is a measure of the dispersion of the measurements relative to the average value of the measurements. This approach was applied to the groups of replicate measurements on each test solution. In some cases, the turbidity of the prepared solution changed approximately linearly with time due to loss of particles in the recirculation system. In those cases, a linear regression of the data was performed to assess the slope of the turbidity change as a function of time. This slope was used to adjust the individual turbidity readings to approximate the initial concentration. The precision was then calculated on the adjusted values as described above.

5.1.4 Water Temperature Effects

The effect of water temperature on the response of the ABB Series 4670 at 0.3 NTU and 5 NTU was assessed by linear regression. The turbidity readings relative to the ISO 7027 reference turbidimeter were analyzed as a function of water temperature to identify trends in the relative turbidity at each of the two levels of turbidity. The calculations were performed using separate linear regression analyses for the data at each turbidity level. A similar calculation was done for illustrative purposes using the Method 180.1 reference data.

5.1.5 Flow Rate Sensitivity

Analysis of flow rate influence on turbidity readings was similar to that for water temperature effects. The turbidimeter response relative to the ISO 7027 reference turbidimeter was analyzed as a function of flow rate to assess trends in the response of the turbidimeter with changes in sample flow rate. The analyses were performed separately for the 0.3 NTU and 5 NTU data. A similar calculation was done for illustrative purposes using the Method 180.1 reference data.

5.1.6 Color Effects

The influence of color on turbidity was assessed through a linear regression analysis of the turbidity measured for each color relative to the ISO 7027 reference turbidimeter. Separate analyses were performed for the measurements recorded at 0.1 NTU and those recorded at 5 NTU. A similar calculation was done for illustrative purposes using the Method 180.1 reference data.

5.2 On-Line Testing

5.2.1 Accuracy

As described in Section 5.1.2, accuracy in the on-line measurements was determined as a bias relative to the ISO 7027 reference turbidimeter. Daily reference measurements of the sample stream from the water plant were used to assess accuracy. A similar calculation was done for illustrative purposes using the Method 180.1 reference data.

5.2.2 Drift

Drift was assessed in two ways. The drift in the calibration of the ABB Series 4670 turbidimeter was assessed by a comparison of the regression analyses of the multi-point linearity tests performed at the beginning and end of the verification test. This comparison was used to establish any long-term drift in instrumental calibration during the verification test. Also, the reference and on-line turbidity results from the twice-weekly calibration checks were used to assess drift associated with the operation of the instrument (e.g., fouling of the optics, etc.). Trends in the intermediate calibration data toward a positive bias were used to identify when the turbidimeter needed cleaning.

Chapter 6
Test Results

The results of the verification test are presented in this section, based upon the statistical methods of comparison shown in Chapter 5. For all performance characteristics verified, two sets of results are shown. The primary verification results are based on comparisons with the ISO 7027 reference method; a secondary illustration of performance is based on comparisons with the 180.1 reference method.

6.1 Off-Line Testing

Off-line testing was performed to assess the performance of the ABB Series 4670 turbidimeter when measuring known solutions under controlled conditions. The first of the off-line tests was performed to establish the linearity of the turbidimeter response in the range from < 0.1 to 5 NTU. Data from the linearity test also were used to assess the accuracy and precision of the Series 4670 in this turbidity range. After the linearity test, the effects of sample temperature, sample flow rate, and sample color were evaluated. The results of these tests are described in this section.

6.1.1 Linearity

The verification data from the initial linearity test are shown in Figure 6-1a, relative to the ISO 7027 reference turbidimeter. A series of at least five data points was recorded at each of the five nominal turbidity levels (approximately 0.05, 0.3, 0.5, 2, and 5 NTU). The data from the linearity test were fit using a linear regression as described in Section 5.1.1, and the results of these fits are shown in Table 6-1. The secondary comparison with the Method 180.1 data is shown in Figure 6-1b, with the regression results shown in Table 6-1.

The verification results of the linear regression indicate that the ABB Series 4670 turbidimeter responded linearly to turbidity throughout the range of about 0.05 to 5 NTU. The slope of the response curve was 7.4% lower than unity with respect to the ISO 7027 reference method. The five-point calibration check of the ISO 7027 reference turbidimeter showed a slope of 1.06, indicating that the reference turbidimeter was reading approximately 6% high relative to the formazin standards. Based on this uncertainty of the reference measurements, the 95% confidence interval of the slope relative to the reference method includes unity. A near zero intercept was determined for the linearity plot; the 95% confidence interval for the intercept includes zero.

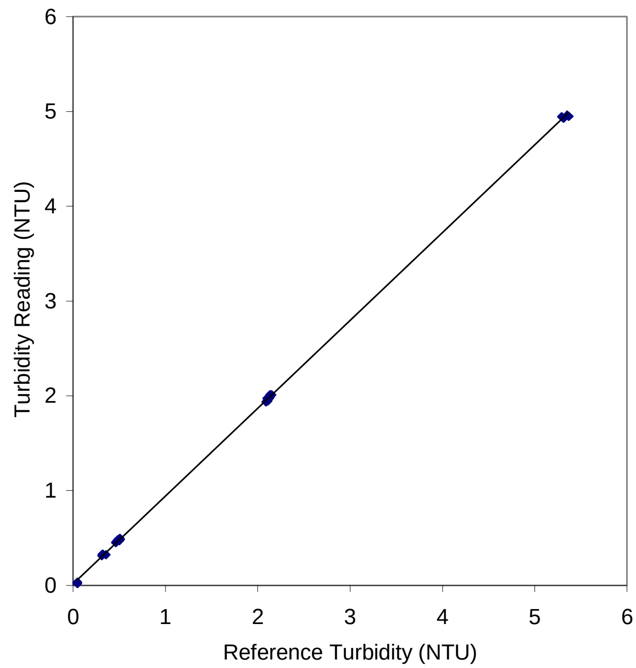

Figure 6-1a. Linearity Plot for ABB Series 4670 Turbidimeter vs. ISO 7027 Reference Turbidimeter

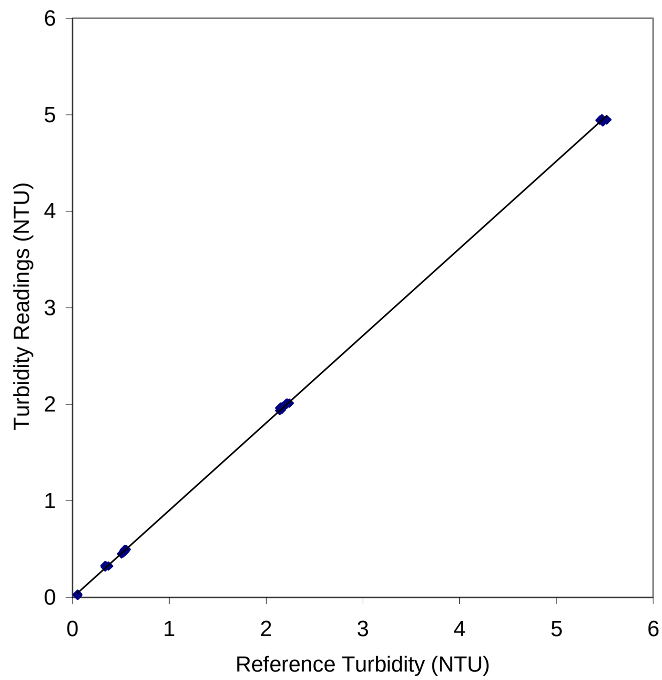

Figure 6-1b. Linearity Plot for ABB Series 4670 Turbidimeter vs. Method 180.1 Reference Turbidimeter

Table 6-1. Statistical Results of Initial Linearity Test on the ABB 4670 Turbidimeter

Linear Regression Parameter	Verification Results[a]	Secondary Comparison[b]
Slope (std. error)	0.926 (0.002)	0.904 (0.002)
Intercept (std. error)	0.013 (0.044)	-0.003 (0.004)
r^2 (std. error)	0.9999	0.9999

[a] Comparison with ISO 7027 reference method (2100A IS reference turbidimeter).
[b] Comparison with EPA Method 180.1 (2100A reference turbidimeter).

The secondary comparison in Table 6-1 shows that the ABB Series 4670 turbidimeter also exhibited good linearity relative to Method 180.1.

6.1.2 Accuracy

Data obtained from the initial linearity test were used to assess accuracy for the off-line tests. The results of the accuracy verification are given in Table 6-2 and are presented as the average difference between the ABB Series 4670 turbidimeter and the reference turbidimeter, as well as the relative bias of the ABB Series 4670 turbidimeter with respect to the reference measurements. Negative values indicate a negative bias in the ABB Series 4670 turbidimeter readings when compared with the reference turbidimeter, and positive numbers indicate a positive bias in the ABB Series 4670 readings.

The verification results in Table 6-2 show a negative bias of 0.2 to about 7% over all turbidity levels from 0.3 to 5 NTU, resulting from average measured differences of 0.001 to 0.385 NTU. A trend of the average bias with NTU level is evident, with larger relative bias at higher NTU values. The observed bias is comparable to the degree of fluctuations in the daily calibration checks of the reference turbidimeter.

The secondary comparison in Table 6-2 shows similar performance relative to Method 180.1, with average negative bias results of 6.1 to 10.5%.

6.1.3 Precision

Data from the linearity test were used to calculate precision at 0.3, 0.5, 2, and 5 NTU. The results of these calculations are shown in Table 6-3. For comparison, the calculated precision values for the two reference turbidimeters are also included in that table. At both 0.5 NTU and 2 NTU, a second set of five readings was recorded as a check of the first set of readings at those levels. The values presented in this table are based on five readings at each level and include the second set of measurements at the 0.5 and 2 NTU levels.

Table 6-2. Bias of ABB Series 4670 Turbidimeter Relative to Reference Measurements on Prepared Test Solutions

Nominal Turbidity of Test Solution (NTU)	Verification Results[a] Average Difference (NTU)	Verification Results[a] Relative Bias (%)	Secondary Comparison[b] Average Difference (NTU)	Secondary Comparison[b] Relative Bias (%)
0.3	-0.001	-0.2	-0.022	-6.1
0.5	-0.02	-3.9	-0.057	-10.5
2	-0.150	-7.1	-0.194	-9.0
5	-0.385	-7.2	-0.535	-9.8

[a] Comparison with ISO 7027 reference method (2100N IS reference turbidimeter).
[b] Comparison with EPA Method 180.1 (2100N reference turbidimeter).

Table 6-3. Precision of ABB Series 4670 Turbidimeter and Reference Turbidimeters

Nominal Turbidity	ABB Series 4670		ISO 7027 (2100N IS)		Method 180.1 (2100N)	
	SD (NTU)	RSD (%)	SD (NTU)	RSD (%)	SD (NTU)	RSD (%)
0.3 NTU	0.005	1.6	0.017	5.4	0.015	4.4
0.5 NTU	0.011	2.2	0.004	0.9	0.008	1.4
0.5 NTU	0.013	2.8	0.011	2.2	0.010	2.0
2 NTU	0.017	0.9	0.015	0.7	0.013	0.6
2 NTU	0.004	0.2	0.007	0.3	0.012	0.6
5 NTU	0.012	0.2	0.037	0.7	0.029	0.5

The results of these calculations indicate that the ABB Series 4670 turbidimeter has approximately the same precision as the reference turbidimeter through the range of turbidity measured in this verification test. From 0.3 to 5 NTU, the Series 4670 exhibited precision of 0.2 to 2.8% as RSD.

6.1.4 Water Temperature Effects

The verification data obtained for the temperature test are shown in Figure 6-2a. Since the turbidity of the test solution may have changed over the course of testing, the absolute turbidity readings alone cannot be used as an indication of temperature effects. Therefore, the readings recorded for the ABB Series 4670 turbidimeter were normalized to the corresponding reference readings to get a relative measure of turbidity. These relative values (i.e., ratios of Series 4670 to ISO 7027 data) are shown in Figure 6-2a and were analyzed by linear regression to assess the effect of water temperature on turbidity reading. The results of the regression analysis are given in Table 6-4.

Table 6-4. Statistical Results of Temperature Test on the ABB Series 4670 Turbidimeter

Linear Regression Parameter	Verification Results[a]		Secondary Comparison[b]	
	0.3 NTU	5 NTU	0.3 NTU	5 NTU
Slope (std. error)	-0.002 (0.001)	0.002 (0.0004)	-0.006 (0.002)	0.0000 (0.0003)
Intercept (std. error)	0.961 (0.019)	0.900 (0.008)	0.983 (0.024)	0.905 (0.006)
r^2	0.226	0.531	0.581	0.001

[a] Comparison with ISO 7027 reference method (2100AN IS reference turbidimeter).
[b] Comparison with EPA Method 180.1 (2100AN reference turbidimeter).

These verification results indicate that, relative to the ISO 7027 reference turbidimeter, the ABB Series 4670 shows no statistically significant relation between the turbidity readings and the water temperature at 0.3 NTU, since the 95% confidence interval includes zero slope in both cases, i.e., water temperature has no effect on Series 4670 readings within the tested temperature range. At 5 NTU, temperature has a small, but statistically significant effect on the turbidity reading. The effect results in an increase in relative turbidity of 0.2% per degree. This effect is likely to be negligible in a practical sense.

The secondary results in Figure 6-2b and Table 6-4 suggest a slight negative dependence of turbidity reading on temperature at 0.3 NTU, but no dependence at 5 NTU. However, the difference in measurement method between the Series 4670 and Method 180.1 may account for the results at 0.3 NTU, rather than any actual temperature dependence of the Series 4670. This test covered only a small range of temperatures and may not accurately represent the performance of the turbidimeter in monitoring cold water (i.e., < 10°C).

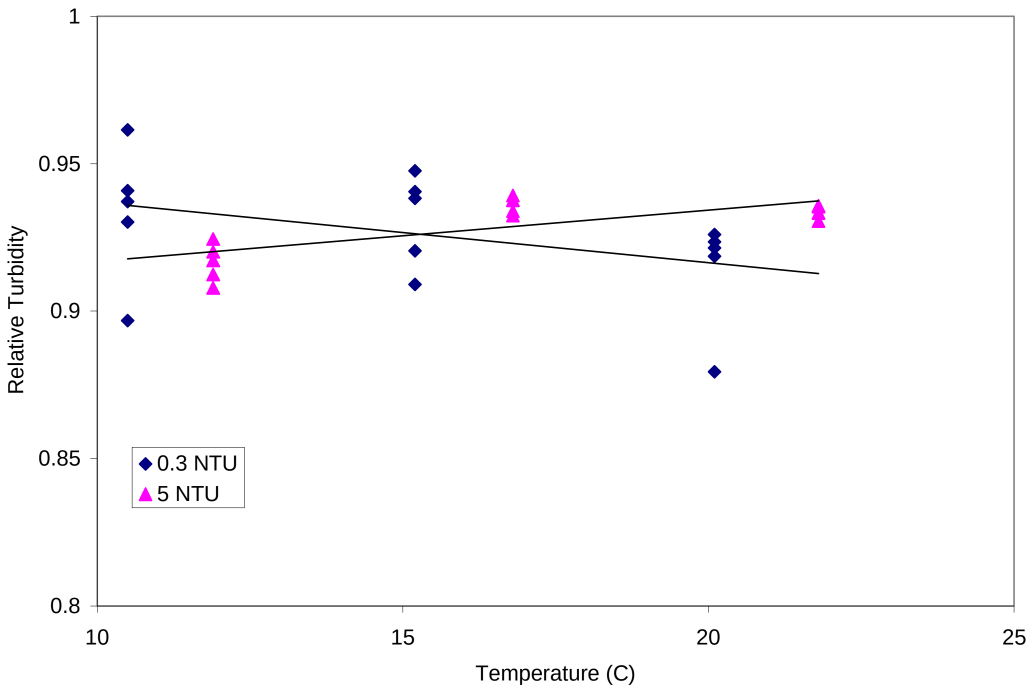

Figure 6-2a. Effect of Temperature on ABB Series 4670 Turbidimeter vs. ISO 7027 Reference Turbidimeter at Both 0.3 and 5 NTU

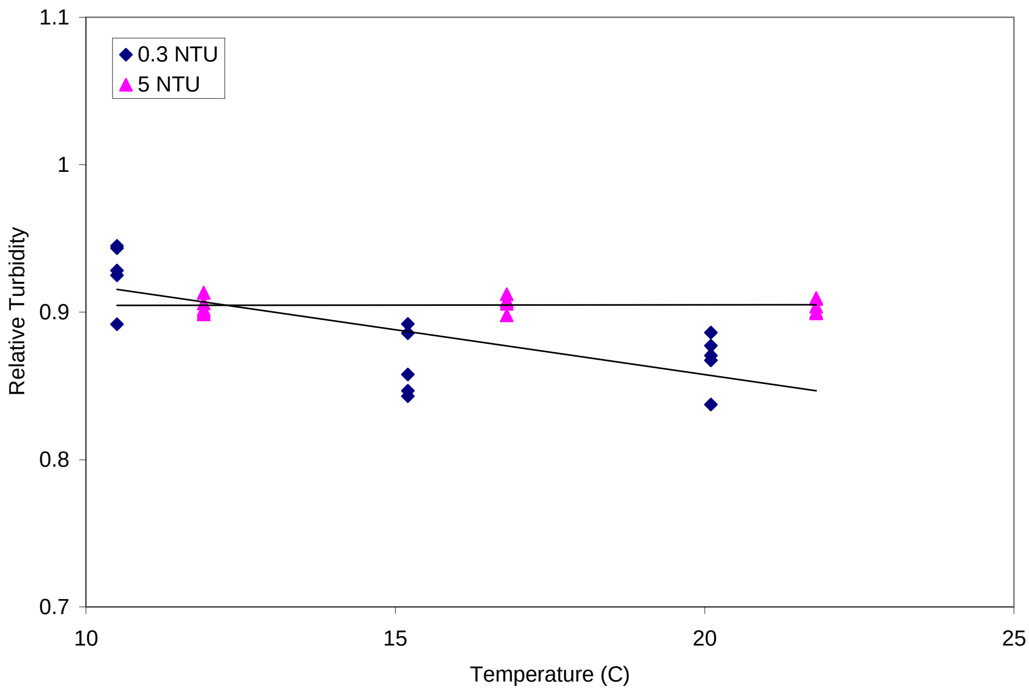

Figure 6-2b. Effect of Temperature on ABB Series 4670 Turbidimeter vs. Method 180.1 Reference Turbidimeter at Both 0.3 and 5 NTU

6.1.5 Flow Rate

The results of the flow rate test are summarized in Figures 6-3a and b. The data are again presented and analyzed as relative turbidity readings, rather than absolute turbidity readings to account for any loss of formazin during the testing. The results of the statistical analysis of the flow data are presented in Table 6-5.

These results show a statistically significant effect of sample flow rate on the response of the ABB Series 4670 turbidimeter at 0.3 NTU over the range of 0.1 to 0.4 gpm, based on the 95% confidence intervals of the regression slope. From Figures 6-3a and 6-3b, there appears to be no effect in the range from 0.1 to 0.26 gpm, but a substantial effect above 0.26 gpm. In the range from 0.1 to 0.26 gpm, linear regression analysis shows no statistically significant effect at the 95% confidence level (i.e., slope values not statistically different from zero). Since only three flow rate values were used in this test, it is not possible to conclude whether the Series 4670 response is sensitive to flow rate at all flows between 0.26 and 0.40 gpm, or whether the observed effect occurs only at the upper extreme of the instrument's flow range (i.e., at 0.40 gpm).

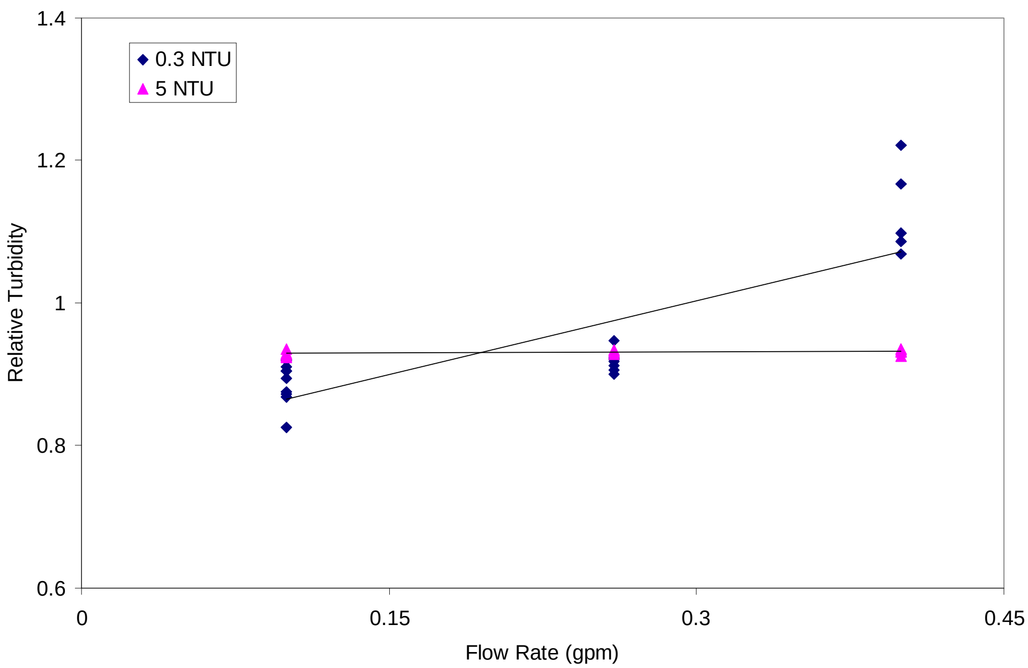

Figure 6-3a. Effect of Sample Flow Rate on Response of ABB Series 4670 Turbidimeter vs. ISO 7027 Reference Turbidimeter at Both 0.3 and 5 NTU.

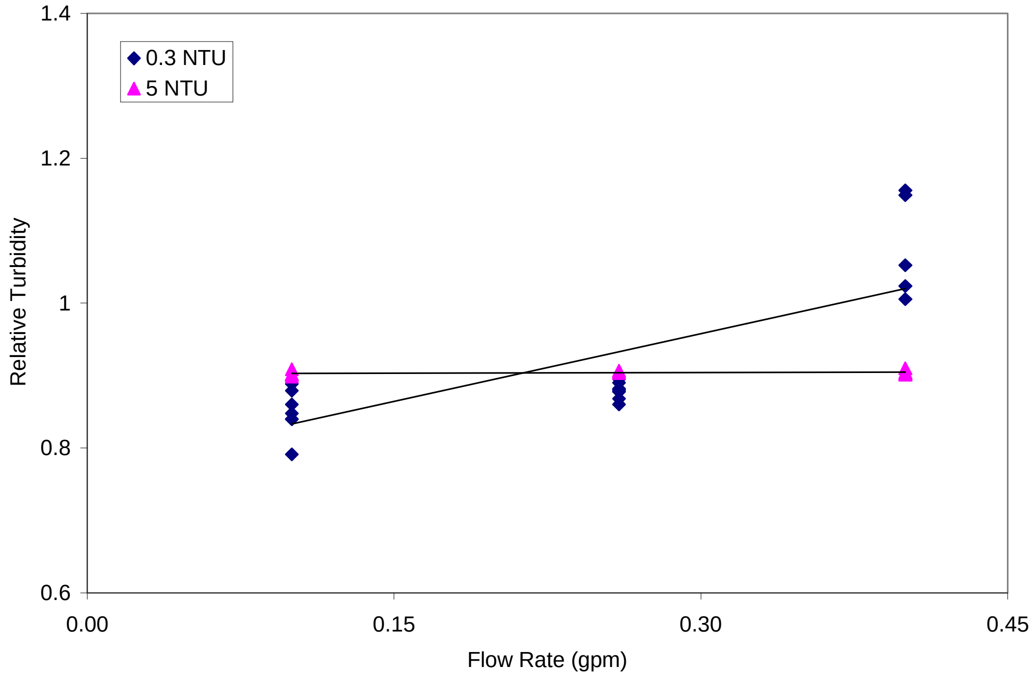

Figure 6-3b. Effect of Sample Flow Rate on Response of ABB Series 4670 Turbidimeter vs. EPA 180.1 Reference Turbidimeter at Both 0.3 and 5 NTU.

Table 6-5. Statistical Results of Flow Rate Test on the ABB Series 4670 Turbidimeter

	Verification Results[a]		**Secondary Comparison[b]**	
Parameter	**0.3 NTU**	**5 NTU**	**0.3 NTU**	**5 NTU**
Slope (std. error)	0.688 (0.102)	0.006 (0.007)	0.622 (0.106)	0.013 (0.008)
Intercept (std. error)	0.796 (0.026)	0.902 (0.002)	0.771 (0.026)	0.928 (0.002)
r^2 (std. error)	0.663	0.057	0.601	0.155

[a] Comparison with ISO 7027 reference method (2100AN IS reference turbidimeter).
[b] Comparison with EPA Method 180.1 (2100AN reference turbidimeter).

The results show no statistically significant effect at the 5 NTU level, since, at the 95% confidence level, the slope values are not significantly different from zero.

It should be noted that the specifications of the ABB Series 4670 turbidimeter require a small range of operational flow rates. It is reasonable that, within the specified range, minimal flow rate effects are present.

6.1.6 Color Effects

The verification data obtained from the color tests are shown in Figures 6-4a and b. In this figure, the data at each color level are plotted as relative values with respect to the reference turbidimeter readings, and the statistical analysis of these data involved a linear regression analysis of the relative data as a function of solution color. At 5 NTU, the background color reading of approximately 30 CU was subtracted, and only the effect of color added during the test is shown. The results of the statistical calculations are summarized in Table 6-6.

The verification results in Table 6-6 show that there was no significant effect on the response of the ABB Series 4670 turbidimeter at either 0.1 NTU or at 5 NTU, based on the 95% confidence interval of the regression slope. Very similar results also are shown in the secondary comparison in Table 6-6.

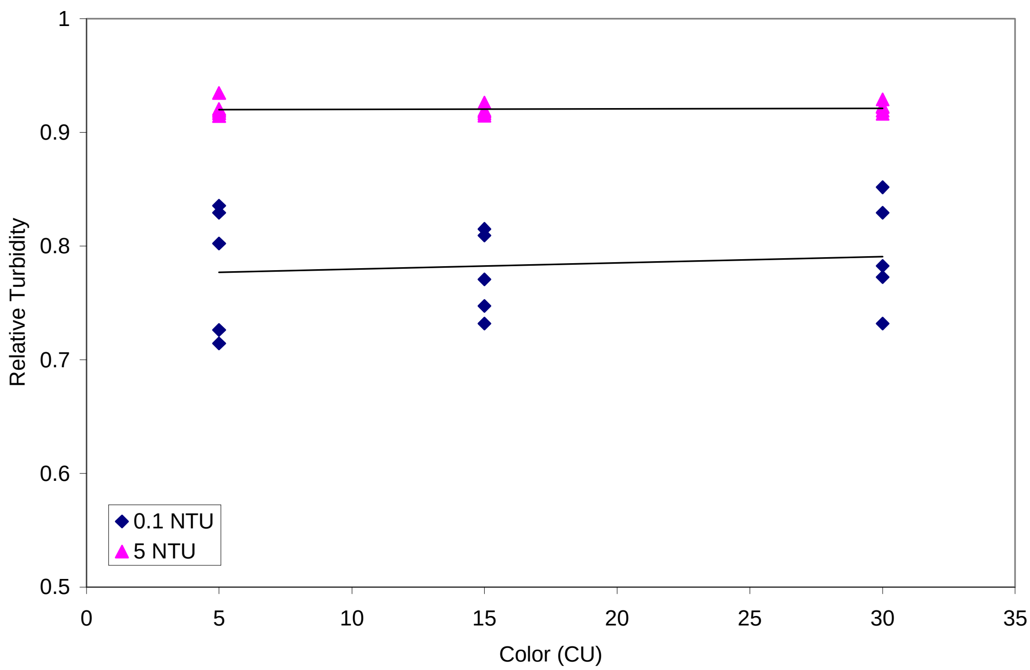

Figure 6-4a. Effect of Color on Relative Turbidity with the ABB Series 4670 Turbidimeter vs. the ISO 7027 Turbidimeter at Both 0.1 and 5 NTU

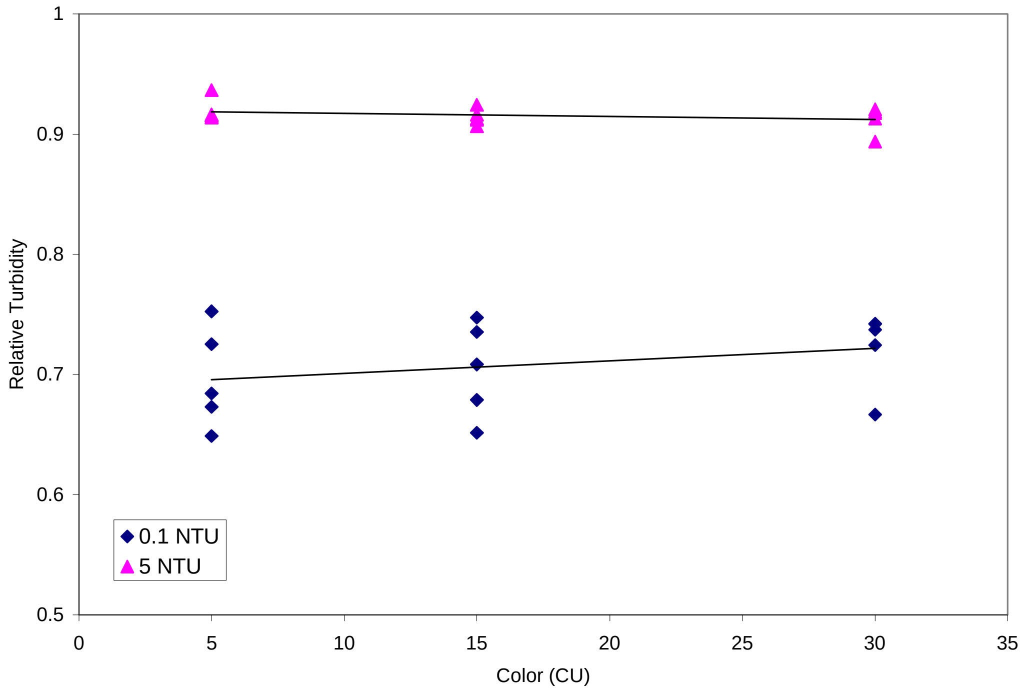

Figure 6-4b. Effect of Color on Relative Turbidity with the ABB Series 4670 Turbidimeter vs. Method 180.1 Reference Turbidimeter at Both 0.1 and 5 NTU

Table 6-6. Statistical Results of the Color Test on the ABB Series 4670 Turbidimeter

Reference Parameter	Verification Results[a] 0.1 NTU	5 NTU	Secondary Comparison[b] 0.1 NTU	5 NTU
Slope (std. error)	0.0004 (0.0012)	0.0000 (0.0001)	0.0009 (0.0009)	-0.0003 (0.0002)
Intercept (std. error)	0.777 (0.024)	0.921 (0.003)	0.693 (0.018)	0.920 (0.004)
r^2	0.007	0.003	0.067	0.103

[a] Comparison with ISO 7027 reference method (2100AN IS reference turbidimeter).
[b] Comparison with EPA Method 180.1 (2100AN reference turbidimeter).

6.2 On-Line Testing

Figure 6-5 shows the results from the four weeks of on-line testing. In this figure, data from the ABB Series 4670 turbidimeter and the reference turbidimeters are shown. For convenience, only one data point is shown every fifteen minutes for the ABB Series 4670 turbidimeter, although data were recorded at intervals of 10 seconds throughout the on-line testing. Breaks in the data from the ABB Series 4670 turbidimeter indicate periods during which the turbidimeter was taken off line for calibration checks or for cleaning.

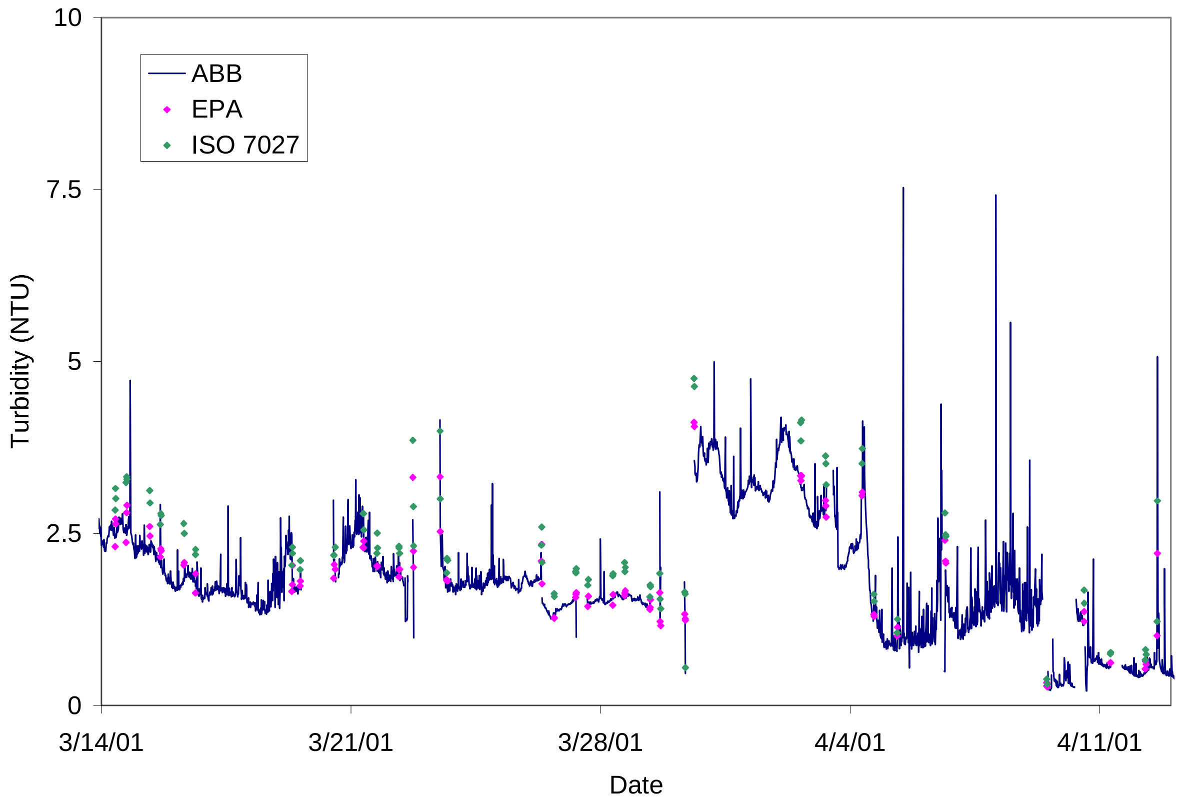

Figure 6-5. Summary of Stream Turbidity Data from On-Line Testing of ABB Series 4670 Turbidimeter

In general, Figure 6-5 illustrates close correlation and sometimes close quantitative agreement between the Series 4670 turbidimeter and the reference measurements. Also, the varying turbidity levels shown by the Series 4670 turbidimeter indicate a temporal pattern similar to that of the reference data. For a few days near the end of the on-line testing, the signal from the Series 4670 turbidimeter showed considerable noise, which was probably the result of bubbles in the sample line (both bubbles and large particles were observed). The noise seemed to be reduced after increased back-pressure was applied to all the sample ports.

6.2.1 Accuracy

A summary of the results from the four weeks of on-line accuracy testing are given in Table 6-7. The results shown in the table are given as the average of the daily readings taken on water stream samples for the ABB Series 4670 turbidimeter and the reference turbidimeter. In general, these values are the average of at least five readings per day. Additionally, the average daily bias in the ABB Series 4670 turbidimeter readings relative to the reference turbidimeter is reported.

The verification results show that the Series 4670 generally read lower than the ISO 7027 reference turbidimeter within a reference turbidity range of 0.3 to 4 NTU. Negative biases of 7 to 29% characterize this data range, with an average bias of -18.8%. At 4 NTU, this average bias would correspond to a difference of approximately 0.8 NTU relative to the reference turbidimeter. The ABB Series 4670 turbidimeter and reference data exhibited a linear regression (based on all of the individual sample readings) of the form:

$$\text{Series 4670} = 0.876\ (\text{ISO 7027}) - 0.041\ \text{NTU},$$

with $r^2 = 0.899$.

The secondary comparison in Table 6-7 shows better accuracy of the Series 4670 relative to Method 180.1 (i.e., biases ranging from -19 to 8%, with an average bias of -4.0%), and the same degree of correlation ($r^2 = 0.905$). In this case, the data exhibited a linear regression (based on all of the individual sample readings) of the form:

$$\text{Series 4670} = 1.049\ (\text{Method 180.1}) - 0.065\ \text{NTU}.$$

It should be noted that the agreement between the ABB Series 4670 turbidimeter and the ISO 7027 reference method was about the same as that between the two reference methods. As Table 6-7 shows, the ABB turbidimeter often gave readings close to those from Method 180.1, and the -18% average bias of the Method 180.1 results relative to ISO 7027 is about equal to the average bias of the ABB results relative to ISO 7027.

6.2.2 Drift

6.2.2.1 Calibration Checks

The results from the twice weekly calibration checks at 0.5 NTU with formazin standards are shown in Figure 6-6 and summarized in Table 6-8.

The verification results in Table 6-8 show that the ABB Series 4670 turbidimeter read from 1% higher than, to 20% lower than, the ISO 7027 reference turbidimeter on the twice-weekly calibration solutions, with an average bias of -8.3% (and an average uncertainty of ± 4.0%).

During the initial linearity check (Section 6.1.2), data from the ABB Series 4670 turbidimeter showed an average bias of -7.4% relative to the ISO 7027 reference turbidimeter. No significant

Table 6-7. On-Line Daily Accuracy Check Results from Water Stream Samples

Date	ABB Series 4670 NTU	Verification Results[a] NTU (Relative Bias %)	Secondary Comparison[b] NTU (Relative Bias %)
03/14/2001	2.508	3.182 (-21.2)	2.678 (-6.3)
03/15/2001	2.205	2.902 (-24.0)	2.398 (-8.0)
03/16/2001	1.807	2.398 (-24.7)	1.932 (-6.5)
03/19/2001	1.828	2.130 (-14.2)	1.837 (0.5)
03/20/2001	2.051	2.208 (-7.1)	1.956 (4.8)
03/21/2001	2.338	2.517 (-7.1)	2.154 (8.5)
03/22/2001	2.153	2.578 (-16.5)	2.105 (2.3)
03/23/2001	2.416	2.745 (-12.0)	2.332 (3.6)
03/26/2001	1.617	1.968 (-17.8)	1.670 (-3.2)
03/27/2001	1.516	1.872 (-19.0)	1.572 (-3.5)
03/28/2001	1.564	1.944 (-19.5)	1.593 (-1.8)
03/29/2001	1.323	1.655 (-20.1)	1.368 (-3.3)
03/30/2001	2.571	3.149 (- 18.4)	2.676 (-3.9)
04/02/2001	3.199	3.960 (-19.2)	3.298 (-3.0)
04/03/2001	2.904	3.476 (-16.5)	2.884 (0.7)
04/04/2001	2.304	2.591 (-11.1)	2.191 (5.2)
04/05/2001	1.024	1.138 (-10.0)	1.063 (-3.7)
04/06/2001	1.839	2.558 (-28.1)	2.168 (-15.2)
04/09/2001	0.240	0.342 (-29.8)	0.298 (-19.5)
04/10/2001	1.196	1.600 (-25.3)	1.306 (-8.4)
04/11/2001	0.542	0.760 (-28.7)	0.623 (-13.0)
04/12/2001	1.060	1.359 (-22.0)	1.145 (-7.4)
04/13/2001	1.948	2.488 (-21.7)	2.190 (-11.0)

[a] Comparison with ISO 7027 reference method (2100AN IS reference turbidimeter).
[b] Comparison with EPA Method 180.1 (2100AN reference turbidimeter).

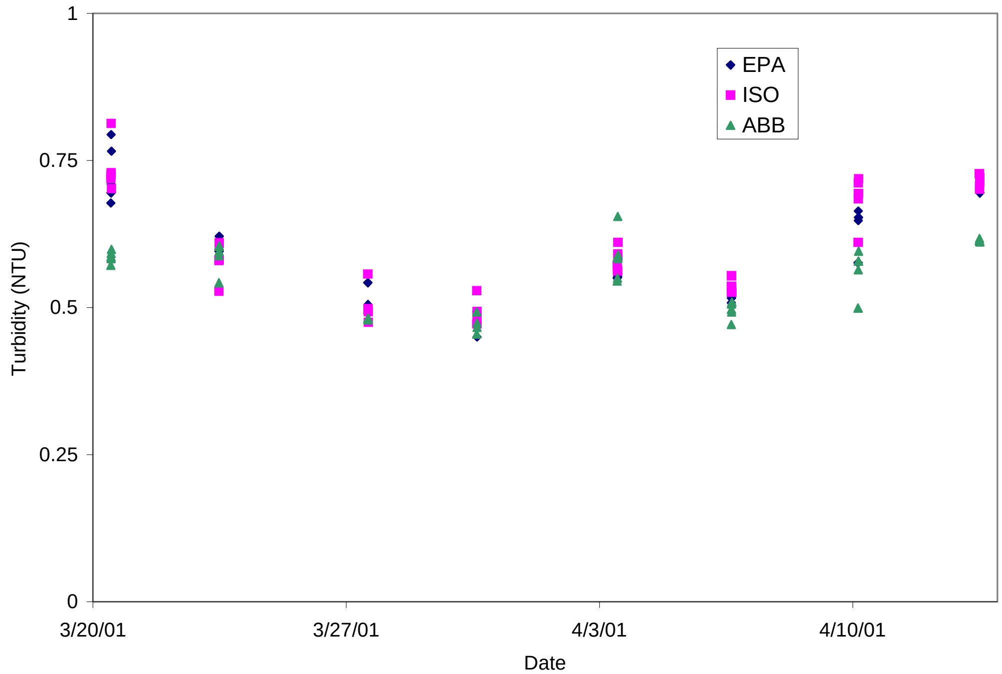

Figure 6-6. Twice-Weekly Calibration Checks During On-Line Testing of the ABB Series 4670 Turbidimeter

Table 6-8. Results of Calibration Checks Performed During On-Line Testing

Date	ABB Series 4670 NTU	Verification Results[a] NTU (Relative Bias %)	Secondary Comparison[b] NTU (Relative Bias %)
03/20/01	0.586	0.738 (-20.5)	0.728 (-19.5)
03/23/01	0.587	0.582 (0.9)	0.594 (-1.2)
03/27/01	0.481	0.504 (-4.6)	0.510 (-5.8)
03/30/01	0.472	0.494 (-4.5)	0.471 (0.2)
04/03/01	0.593	0.583 (1.5)	0.567 (4.6)
04/06/01	0.495	0.535 (-7.5)	0.524 (-5.5)
04/10/01	0.563	0.684 (-17.7)	0.645 (-12.7)
04/13/01	0.614	0.714 (-14.1)	0.708 (-13.4)

[a] Comparison with ISO 7027 reference method (2100AN IS reference turbidimeter).
[b] Comparison with EPA Method 180.1 (2100AN reference turbidimeter).

drift can be inferred from the results of the initial linearity check and the on-line calibration checks because the uncertainties in these measurements overlap substantially.

The secondary comparison data in Table 6-9 show slightly better agreement of the ABB Series 4670 turbidimeter with the EPA Method 180.1 results than with the ISO 7027 results (i.e., -6.6% average bias compared to -8.2% relative to ISO 7027).

6.2.2.2 Final Linearity Check

Data from the final linearity check are shown in Figure 6-7a. These data were recorded after completion of the four weeks of on-line testing and after the ABB Series 4670 turbidimeter had been cleaned. As with the data from the initial linearity test, these data were analyzed by linear regression. The results are summarized in Table 6-9. In Table 6-10, the results of the final linearity test are compared with those from the initial linearity check conducted at the start of the verification as part of the off-line phase.

The verification results of the regression analysis (Table 6-9) show a high degree of linearity, with a slight negative bias in the slope with respect to the reference turbidimeter and a small positive intercept.

The verification results in Table 6-10 show a change of 9.1% in the slope of the Series 4670 response relative to the ISO 7027 reference method between the initial and final linearity tests. Based on the results of the daily calibration checks, the average difference between the reference turbidimeter readings and the stated turbidity value of the formazin standard used for the checks was 5.5%, with a standard deviation of 2.4%. With these uncertainties, at the 95% confidence level, no drift can be inferred from the difference between the initial and final slopes. A very slight change in intercept (0.002 NTU) also was observed. Again, these changes are within the total estimated uncertainty of the reference method, and thus do not definitively indicate significant drift in the Series 4670 calibration.

The secondary comparison shown in Figure 6-7b, Table 6-9, and Table 6-10 leads to a similar conclusion, as a difference of only 7.1% in slope was observed relative to Method 180.1.

6.3 Other Performance Parameters

6.3.1 Cost

As tested, the cost of the ABB Series 4670 was approximately $2,000.

6.3.2 Maintenance/Operational Factors

After installation, the ABB Series 4670 turbidimeter required no operator input and provided data continuously throughout the verification test.

The only maintenance of the ABB Series 4670 turbidimeter involved cleaning the sample chamber. The chamber was cleaned once during the on-line testing to remove residues and material deposits that had accumulated. Since the optics in the ABB Series 4670 turbidimeter were cleaned at preset intervals of two hours using a wiper, fouling of the optics was not apparent.

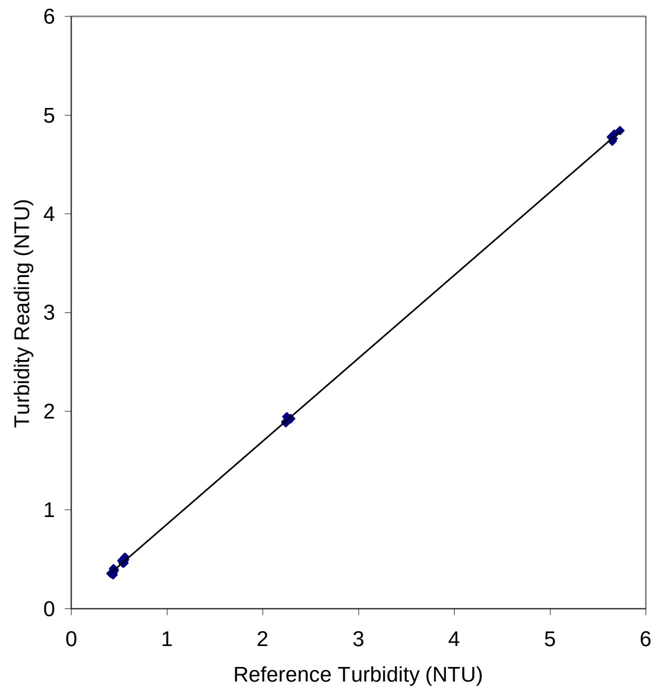

Figure 6-7a. Final Linearity Plot for ABB Series 4670 vs. ISO 7027 Reference Turbidimeter

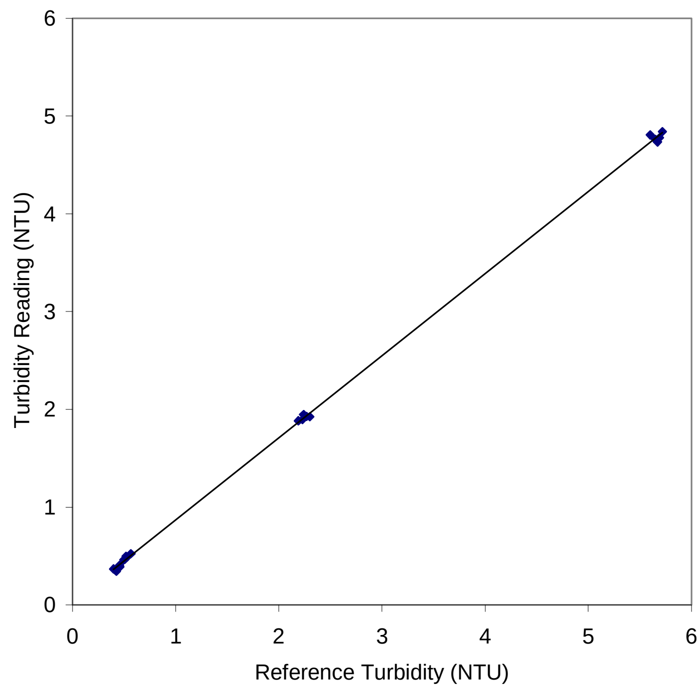

Figure 6-7b. Final Linearity Plot for ABB Series 4670 vs. Method 180.1 Reference Turbidimeter

Table 6-9. Statistical Results of Final Linearity Test

Linear Regression	Reference Turbidimeter Verification Results[a]	Reference Turbidimeter Secondary Comparison[b]
Slope (std error)	0.841 (0.002)	0.838 (0.003)
Intercept, NTU (std error)	0.015 (0.007)	0.030 (0.008)
r^2 (std. error)	0.9999	0.9998

[a] Comparison with ISO 7027 reference method (2100AN IS reference turbidimeter).
[b] Comparison with EPA Method 180.1 (2100AN reference turbidimeter).

Table 6-10. Comparison of Results from Linearity Tests at Beginning and End of Verification

	Verification Results[a]		Secondary Comparison[b]	
	Slope	Intercept (NTU)	Slope	Intercept (NTU)
Initial Linearity Test	0.926	0.013	0.904	0.028
Final Linearity Test	0.841	0.015	0.838	0.030
Difference	-0.085	0.002	-0.066	0.002
% Difference	9.1	-	7.1	-

[a] Comparison with ISO 7027 reference method (2100AN IS reference turbidimeter).
[b] Comparison with EPA Method 180.1 (2100AN reference turbidimeter).

Chapter 7
Performance Summary

The ABB Series 4670 turbidimeter is an on-line turbidimeter designed to provide continuous, real-time measurement of the turbidity of aqueous solutions. The ABB Series 4670 turbidimeter provided linear response over the tested range of approximately 0.05 to 5 NTU. The slope of the response curve from <0.1 to 5 NTU for the ABB Series 4670 turbidimeter relative to the ISO 7027 reference turbidimeter was 0.926 at the beginning of this test, with an intercept of 0.013 NTU and $r^2 > 0.999$.

In measuring standard formazin solutions in the range of 0.3 to 5 NTU, the ABB Series 4670 turbidimeter and the ISO 7027 reference turbidimeter agreed within 7.2% or less, which was comparable to the fluctuations in the daily calibration checks of the reference turbidimeter. The precision in the measurements of the ABB Series 4670 turbidimeter ranged from approximately 0.2% to 3% RSD at turbidities of 0.5 to 5 NTU. These results were approximately the same as for the reference turbidimeters throughout this range of turbidity.

Water temperature had no effect on the response of the ABB Series 4670 turbidimeter relative to the ISO 7027 method at low turbidity (0.3 NTU) or at higher turbidity (5 NTU). Likewise, there was no effect of color on readings at low (0.1 NTU) or high turbidity (5 NTU). In the narrow range of flow rates tested for the ABB Series 4670 turbidimeter (0.1 to 0.4 gpm), there was no statistically significant effect on the turbidity readings as a function of sample flow rate at 5 NTU. At 0.3 NTU, flow rate showed an effect only at 0.4 gpm. At that flow rate, turbidity readings were about 20% higher than at 0.1 or 0.26 gpm.

In reading the turbidity of treated, unfiltered water from a municipal drinking water plant with a turbidity range of 0.3 to 4 NTU, the ABB Series 4670 turbidimeter usually showed a negative bias of up to 0.8 NTU relative to the reference turbidimeter, corresponding to a percent bias of up to approximately 30%. Occasional readings with positive biases (up to ~0.7 NTU) were observed, but were probably the result of bubbles or large particles in the sample stream. On average, a bias of -18.8% relative to the reference ISO 7027 turbidimeter was found. Calibration checks of the ABB Series 4670 turbidimeter using a nominal 0.5 NTU formazin solution showed a bias of +1 to -20% with respect to the ISO 7027 reference turbidimeter, with an average bias of -8.3%, indicating a difference in response between the formazin and plant water streams.

A change of approximately 9% in the slopes of the ABB Series 4670 turbidimeter response curves between the beginning and end of the verification test was observed; however, this change is within the combined experimental uncertainty of the reference measurements over this time period and does not definitively indicate a calibration drift. A change of 0.002 NTU was observed in the values of the intercepts calculated from the initial and final linearity checks. This degree of change is well within the experimental uncertainty of the reference measurements. Furthermore, no apparent drift was observed in the calibration of the ABB Series 4670 turbidimeter throughout the on-line testing on the plant water stream.

Chapter 8
References

1. *Generic Test/QA Plan for Verification of On-Line Turbidimeters,* Battelle, Columbus, Ohio, December 16, 1999.

2. "Water Quality—Determination of Turbidity," *International Standard ISO 7027,* Second Edition, International Organization for Standardization, Geneva, 1990.

3. "Determination of Turbidity by Nephelometry," *Methods for the Determination of Inorganic Substances in Environmental Samples*, Method 180.1, EPA/600/R-93/100, U. S. Environmental Protection Agency, Cincinnati, Ohio, August 1993.

4. "Color in Water by Visual Comparison to Standards," *Standard Methods for the Examination of Water and Wastewater*, 18th Edition, Method 2120-B, American Public Health Association, 1992.

5. *Quality Management Plan (QMP) for the ETV Advanced Monitoring Systems Pilot*, U.S. EPA Environmental Technology Verification Program, Battelle, Columbus, Ohio, Version 2.0, October 2000.

Appendix A
Example Data Recording Sheet

Verification of On-Line Turbidimeters - Round 2 (G003383-33TURBR2)

Test:	**Operator:**	**Date:**
Solution:	**Reviewer:**	**Date:**

SYSTEM CONFIGURATION

Port	Turbidimeter	Flow (GPM)
1		
2		
3		
4		
5		
6		

Water Temp.	
Ambient Temp.	

Comments:

CALIBRATION CHECK

Reference Turbidimeter	< 0.1 NTU	0.5 NTU	Time	Accept
(Ref. Turb.# 1)				
(Ref. Turb. # 2)				

TEST RESULTS

Sample	Time of Collection	Turbidity (Ref. Turb. # 1)	Time of Analysis	Turbidity (Ref. Turb. # 2)	Time of Analysis	Accept
1						
2						
3						
4						
5						
6						

CALIBRATION CHECK

Reference Turbidimeter	< 0.1 NTU	0.5 NTU	Time	Accept
(Ref. Turb.# 1)				
(Ref. Turb. # 2)				

Comments: