Lawrence Berkeley National Laboratory LBID-2561
EETD – Applications Team

Side-by-side Fume Hood Testing: Human-as-Mannequin Report

Comparison of a Conventional and a Berkeley Fume Hood

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Conducted at Lawrence Berkeley National Laboratory

1 Executive Summary

Lawrence Berkeley National Laboratory (LBNL) has developed and patented a high-performance fume hood, The Berkeley hood. The Berkeley hood's main design feature uses a gentle flow of air, introduced at the sash perimeter, to direct fumes inside the hood away from the face of the hood, and therefore away from the user. This push-pull approach not only provides for improved containment and greater operator safety, but also allows for much lower exhaust volume – 50% lower in the tests reported herein – dramatically reducing the amount of conditioned air that must be continually supplied and exhausted to a laboratory.

To confirm that the Berkeley hood is not only more efficient but also safer to operate under actual conditions, LBNL researchers worked with California's Occupational Safety and Health Administration (Cal/OSHA) staff to devise an innovative test that measures hood containment performance via exposure to a "tracer gas" in a user's breathing zone while performing work within the hood. This report explains the results of this dynamic, Human-As-Mannequin (HAM) test series.

The HAM test compares two otherwise identical hoods – one conventional and one Berkeley hood – by measuring the actual escape of the tracer gas from each, while an operator performs an identical set of choreographed movements with the same objects within each hood. Test results indicate that the Berkeley hood provides substantially better containment of potentially harmful fumes, and therefore greater operator safety, than a conventional fume hood. It outperformed the conventional hood in all tests, and on average provided two and a half to three times better containment.

2 Overview

2.1 Fume Hood Testing

The purpose of an enclosing or containment laboratory-type hood is to contain toxic materials generated within the hood in order to keep exposure to laboratory hood operators below the relevant health hazard exposure guidelines (e.g. OSHA PEL's or ACGIH TLV's). Consequently, testing fume hood containment performance is a very important safety issue. It has long been recognized that many factors affect the hood's ability to contain including inward airflow (a.k.a. face velocity), hood design, room airflow patterns, and user activities. Prior to the 1980's, visual smoke observations and face velocity were used as the major indicators of hood performance. Recent studies have indicated that measuring face velocity alone may not be predictive of adequate hood performance.[1]

[1] From correspondence by ANSI/AIHA Z9.5 Standards committee, June 2003.

2.1.1 ASHRAE 110-1995 Method

The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) is a leading technical standards organization in the ventilation industry. ASHRAE's 110-1995 *Method of Testing Performance of Laboratory Fume Hoods* is the most widely used test method for evaluating a hood's containment performance. This method recommends three types of tests: face velocity testing, flow visualization, and a tracer gas test. However, the Method does not stipulate performance values that need to be attained by a fume hood.

2.1.2 ANSI/AIHA Performance Standard

The ASHRAE 110-1995 standard specifies the tracer gas test method, not the performance standard. The American National Standards Institute (ANSI) has adopted the ASHRAE Method as an ANSI specification, and assigned it ANSI/ASHRAE 110-1995. In recommending the ASHRAE 110 static tracer gas containment test, ANSI, and American Industrial Hygiene Association (AIHA), have established performance standards in ANSI/AIHA Z9.5-2003 *Standard for Laboratory Ventilation* for as manufactured (AM) as installed (AI), and as used (AU) fume hoods, as defined in the ASHRAE 110 method.

2.1.3 Containment Performance

ANSI Z9.5-2003 requires that some form of containment test using a challenge agent such as a tracer gas that can quantitatively measure hood "leakage" be used to determine if a hood's containment performance is acceptable. In this case, "performance" refers to the level of confinement of possible hazards and protection of the employees for the work which is performed inside a laboratory-type hood. ANSI/AIHA provides the following regarding containment performance thresholds for static tracer gas testing:

> "The hood "user" or "owner" needs to define what containment is acceptable. At the current time ANSI Z9.5 recommends that ASHRAE 110-1995 be used as this containment test. For a 4 lpm challenge the recommended maximum acceptable "leakage" is 0.05 ppm at the breathing zone for hoods tested under controlled conditions and/or 0.1 ppm for hoods as installed in the laboratory."[2]

2.2 Static Containment Testing

ASHRAE's containment testing method uses a mannequin to simulate the presence of an operator at the fume hood. A detection instrument is located in the "breathing zone" of the mannequin. A test agent (tracer gas; usually sulfur-hexafluoride, SF6) is introduced inside the hood and the amount that escapes the face is measured. Operator safety is improved when the ANSI/ASHRAE tracer gas test is performed, since actual contaminant escape is measured. This is a direct, performance-based test of operator hazard, not an inferred test based on face velocity. While actual contaminant escape is measured, this test is not performed using a human operator conducting experiments inside the hood.

2.3 Human-As-Mannequin (HAM) Dynamic Containment Testing

So-called "Human-as-Mannequin (HAM) Dynamic Tests" are intended to be practical, dynamic challenges by simulating actual operator hand and arm movements through manipulation of objects within a fume hood that may cause loss of containment. These

[2] From correspondence by ANSI/AIHA Z9.5 Standards committee, June 2003.

tests , or challenges, account for the combined ability of the hood to contain, capture internally, and remove contaminants. Tracer gas concentrations are measured at a technician's breathing zone and averaged over the test period, details provided below.

2.3.1 Non-Standard Containment Challenges

HAM testing is not presented in the ASHRAE 110-1995 Method or the ANSI Z9.5-2003 Ventilation Standard. There are no industry standards for Human-as-Mannequin (HAM) dynamic challenges, and no recommended threshold values for pass and fail. Therefore, thresholds may be established by testing hoods in a facility.

2.3.2 Sample Test Protocol

A sample HAM test protocol is provided below. It was compiled from information and points-of-view from numerous sources including: Tom Smith at Exposure Control Technologies, Inc.; Dale Hitchings at SafeLab Corporation; Mike Ratcliff at RWDI, Debbie Decker, et al, at University of California Industrial Hygienists; Geoffrey Bell at the LBNL Applications Team.

2.4 Side-by-side hood evaluations

2.4.1 An Innovative Laboratory-type hood

Researchers at Lawrence Berkeley National Laboratory (LBNL) are developing an innovative containment technology that reduces required airflow through laboratory fume hoods. This technology provides containment at 50 to 70 percent lower airflow than a typical fume hood, based on total exhaust volume. It does not rely on face velocity, in the traditional sense, to maintain fume containment within a hood.

The LBNL containment technology uses a "push-pull" displacement airflow approach to contain fumes and move air through a hood. Displacement air "push" is introduced with supply vents near the hood's sash opening. Displacement air "pull" is provided by simultaneously exhausting air from the hood. Thus, an "air divider" is created, between an operator and a hood's contents, that separates and distributes airflow at the sash opening. This air divider technology is simple and provides increased operator protection.

2.4.2 Comparative Approach

In an effort to demonstrate equivalent or superior performance of a Berkeley fume hood compared to a conventional fume hood (see next section), the California Energy Commission (CEC) sponsored a series of so-called "side-by-side" comparative performance evaluations. An example of each hood type was installed and tested in the same room. The basic hoods were produced by the same manufacturer (Jamestown Metal Products) and are of the same nominal size. Initial testing was conducted using the ASHRAE 110-1995 protocol and the results are summarized below. (A companion report, LBID-2560, provides results for the side-by-side static tracer gas containment tests.) This report provides the results for the innovative human-as-mannequin (HAM) side-by-side test Series.

2.4.3 Establishing Performance Baseline

ANSI provides recommended containment performance thresholds for fume hoods being tested per the ASHRAE 110-1995 Method (see above). However, no established standards organization has either developed a HAM protocol or established threshold containment values for these kinds of test procedures. Therefore, if an organization is interested in conducting HAM tests, they can be performed in a comparative manner, i.e., side-by-side. Each hood should have passed a Static Tracer Gas Containment Test specified in ANSI Z9.5-2003. Note that for the entire **Choreographed Sequence** (see definition below) both hoods were operated with their sashes fully open (a specific request made by California's Occupational Safety and Health Administration, CAL/OSHA). Considering that a HAM test is designed to represent actual hood operation, the hood should be operated during the HAM testing with its sash in its "design position" per the manufacturer's recommendations.

2.5 Summary of Results

2.5.1 Successful Comparative Performance – Static Tests

Table 1 presents comparative results from the ASHRAE 110-1995 Method, including static tracer gas containment performance, per ANSI/AIHA thresholds. Note that both the conventional and Berkeley hood "pass", per ANSI Z9.5-2003. See report LBID-2560 for test details.

Table 1: ASHRAE 110 Test results for Side-by-side Conventional and Berkeley hoods

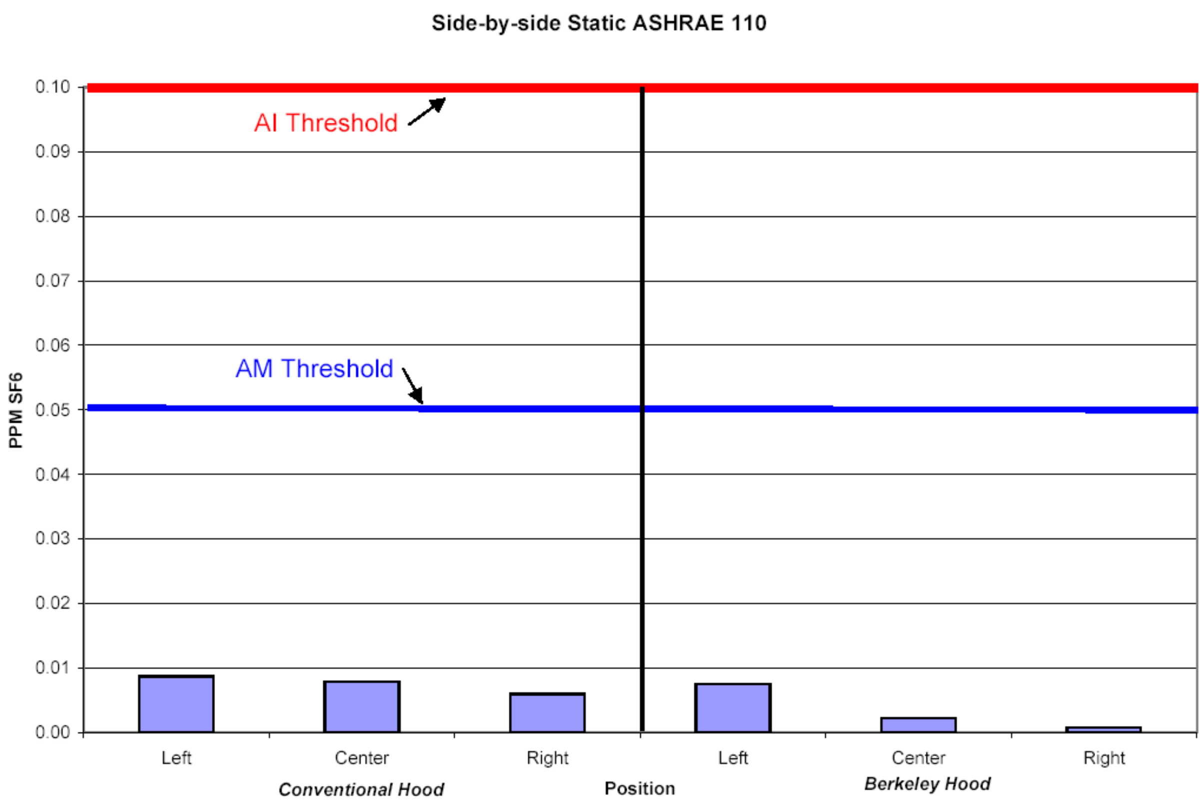
Run	*Test Procedure*	*Detection Medium*	*Test Conditions*	*Conventional Hood Containment AI (as installed)*	*Conventional Hood Containment AM (as mf'g)*	*Berkeley Hood Containment AI (as installed)*	*Berkeley Hood Containment AM (as mf'g)*
1	Local Flow Visualization	Small volume Smoke tube	Visual observation	Good	Good	Good	Good
2	Large-volume Flow Visualization	Large volume Smoke	Visual observation	Good	Good	Good	Good
3	Face Velocity	N/A	Velocity meter	Pass	Pass	N/A	N/A
4	Static Mannequin	Tracer gas	Ejector Center position; Sash full open	Pass [a]	Pass [a]	Pass [a]	Pass [a]
5	Static Mannequin	Tracer gas	Ejector Left position; Sash full open	Pass [a]	Pass [a]	Pass [a]	Pass [a]
6	Static Mannequin	Tracer gas	Ejector Right position Sash full open	Pass [a]	Pass [a]	Pass [a]	Pass [a]
7	Sash Movement Effect (SME)	Tracer gas	Ejector Center position Sash operated	Pass [b]	Pass [b]	Pass [b]	Pass [b]
8	Sash Movement Effect (SME)	Tracer gas	Ejector Left position Sash operated	Pass [b]	Pass [b]	Pass [b]	Pass [b]
9	Sash Movement Effect (SME)	Tracer gas	Ejector Right position Sash operated	Pass [b]	Pass [b]	Pass [b]	Pass [b]
10	Periphery Traverse	Tracer gas	Ejector Center position; Sash full open; no mannequin	Pass [b]	Pass [b]	Pass [b]	Pass [b]

a. Tracer gas Pass/Fail criterion per ANSI Z9.5 2003.
b. No specified Tracer gas Pass/Fail criterion per ANSI Z9.5 2003; however, compared to static tracer gas tests performance thresholds, including a mannequin, averaged values during these tests, a pass rating was achieved.

2.5.2 Containment Performance Comparison – Static Tests

Chart 1 presents comparative results for the ASHRAE 110 static tracer gas containment tests averaged over a 5-minute interval. Note that both the conventional hood and the Berkeley hood performed very well by providing containment far below the ANSI Z9.5 2003 threshold for an as-installed (AI) hood of < 0.10 PPM. Importantly, the ANSI containment threshold for the more stringent as-manufactured limit of <0.05 PPM was also achieved by both hoods.

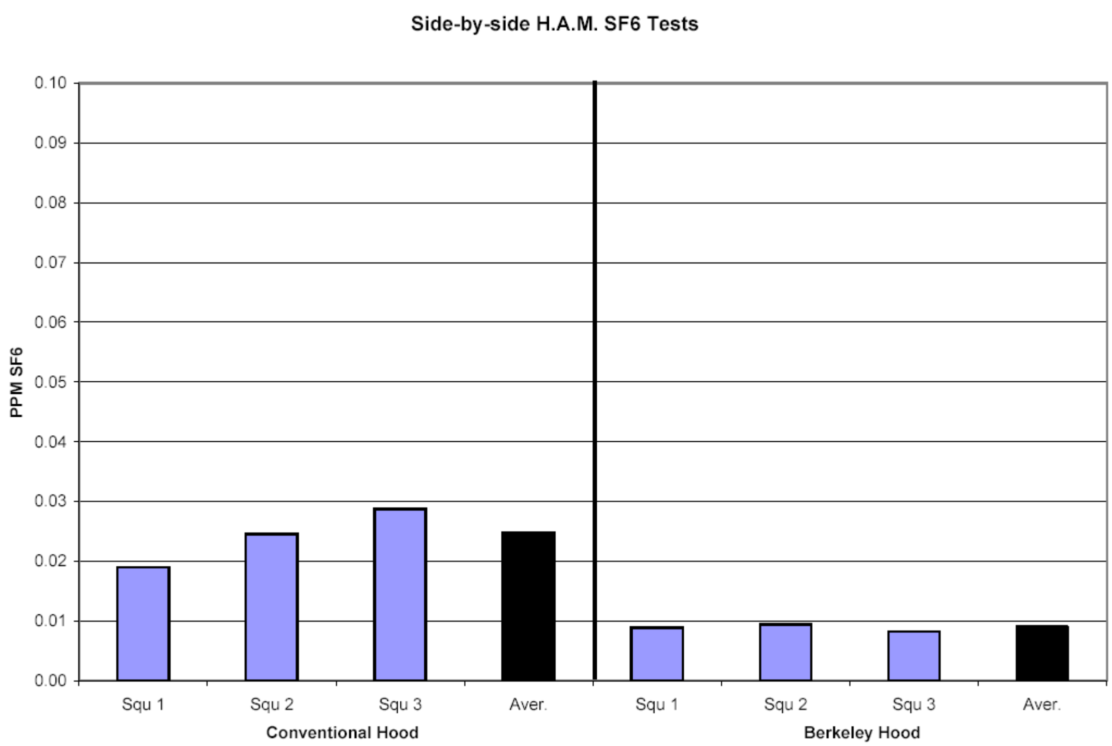
Chart 1: Comparative containment for Side-by-side Conventional and Berkeley hoods



2.5.3 Superior Containment Performance – Dynamic Tests

Chart 2 presents the comparative results for the HAM dynamic tracer gas test Series. “Tests Runs” were performed with the tracer gas ejector and the operator in each position; left, center, and right, as specified in ASHRAE 110-1995. The average tracer gas control level, as detected in the Human-as-Mannequin breathing zone, was recorded for each position Test Run. Each hood’s “Sequence Average” was determined from the average values for the three position Test Runs (excluding the time between the three tests) to yield one number for comparison purposes. The Sequence Average testing was repeated three times (Squ1, Squ2, Squ3). These three Sequence values were averaged to provide a “Series Average” (Aver.). These values are provided in Chart 2, below.

Chart 2: Comparative containment for HAM test series

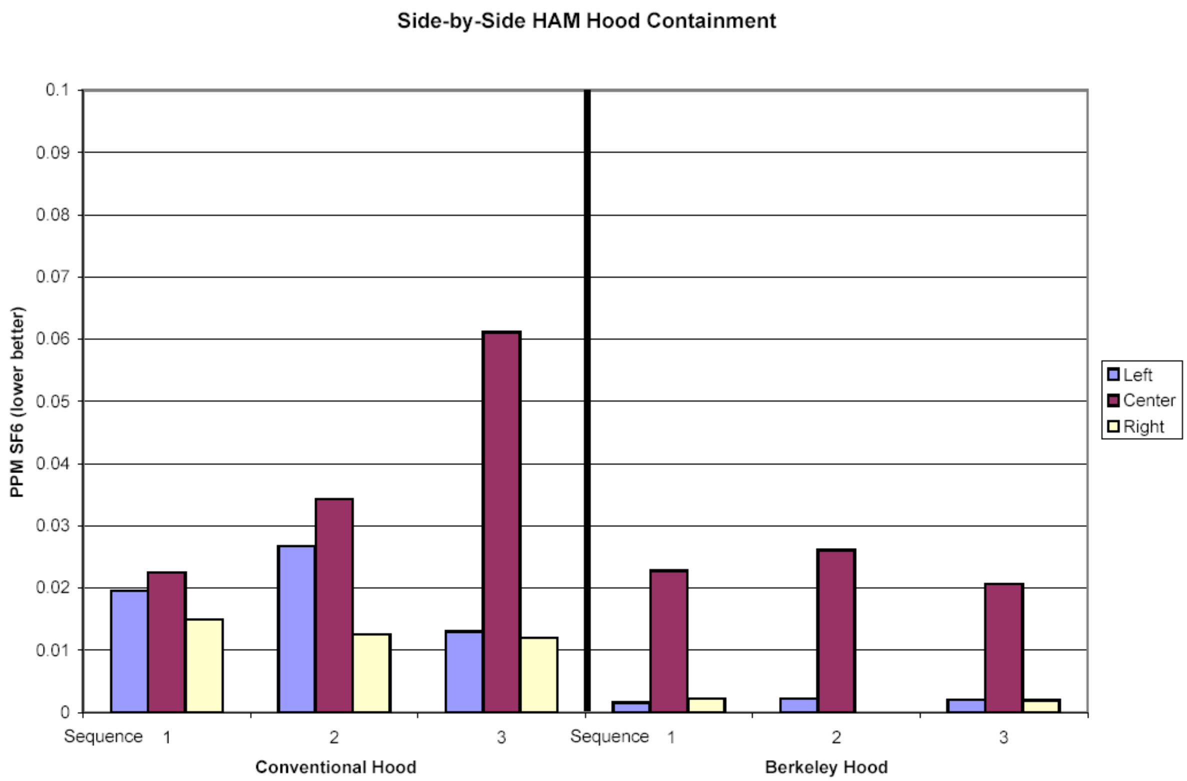


Containment variability was expected given the dynamic nature of the HAM test. Therefore, the three Sequences, each consisting of a left, right, and center test, were performed to define a Series. The Series Total Value is the sum of the three Sequence Averages. This value, without units, represents the degree of leakage over nine Test Runs. The results are as follows:

- Conventional Hood = 0.072
- Berkeley Hood = 0.027

Chart 3 presents the comparative results of the HAM test Series showing the details of each position test in each Sequence (nine tests total for each hood). The Center position test is clearly more challenging than the left and right position tests for both the conventional and Berkeley hood. Therefore, the left and right position tests may be considered optional in future HAM testing. Although lower in both positions, the Berkeley hood had much lower leakage from the left and right tests compared to the conventional hood. This is likely due to the Berkeley hood's "air divider" design of directed airflow (purposefully designed to reduce quiet spots and lazy air movement).

Chart 3: Side-by-Side HAM Hood Containment Performance



The Berkeley hood clearly provides superior containment. HAM testing significantly challenges a hood. However, during these dynamic test conditions, both the conventional and Berkeley hood provided containment better than an ASHRAE 110-1995 static tracer gas test's as-installed (AI) threshold of 0.1 PPM, per ANSI Z9.5-2003. Note that in only one test position did the average leakage rate exceed the more rigorous as-manufactured (AM) threshold of 0.05 PPM by the conventional hood.

Quantitative data, in Table 2, provide details of the Berkeley hood's containment performance, as compared to the baseline conventional hood performance.

Table 2: HAM Test results for Side-by-side Conventional and Berkeley hoods

HAM Tests Results					
		Conventional Hood		**Berkeley Hood**	
		SF6	Duration		Duration
		PPM Average	Time (mm:ss)	PPM Average	Time (mm:ss)
Sequence-1	Center	0.022	0:02:27	0.023	0:02:22
	Left	0.020	0:02:09	0.002	0:02:15
	Right	0.015	0:02:07	0.002	0:02:11
Sequence-2	Center	0.034	0:02:38	0.026	0:02:24
	Left	0.027	0:02:05	0.002	0:02:10
	Right	0.013	0:02:11	0.000	0:02:13
Sequence-3	Center	0.061	0:02:13	0.021	0:02:25
	Left	0.013	0:02:11	0.002	0:02:14
	Right	0.012	0:02:12	0.002	0:02:15
Average	**Series**	**0.024**	0:02:15	**0.009**	0:02:17
	Sequence-1	0.019	0:02:14	0.009	0:02:16
	Sequence-2	0.025	0:02:18	0.009	0:02:16
	Sequence-3	0.029	0:02:12	0.008	0:02:18
Position Aver.	Center	0.039	0:02:26	0.023	0:02:24
Position Aver.	Left	0.020	0:02:08	0.002	0:02:13
Position Aver.	Right	0.013	0:02:10	0.001	0:02:13
Total Time	Sequence-1		0:06:43		0:06:48
	Sequence-2		0:06:54		0:06:47
	Sequence-3		0:06:36		0:06:54
	Series		0:20:13		0:20:29

2.5.4 Statistical Review

The Berkeley hood was determined to be performing significantly better than the conventional hood in the set of tests. The following was provided by the statistician:

Statistical analyses were performed on the data from a conventional and Berkeley fume hood to examine the following two questions: 1) For a given hood, are the center and side areas the same? and 2) Is the Berkeley hood as good or better than the conventional hood? A standard 2-way analysis of variance (ANOVA) showed a 20 ppb decrease in contamination from left or right operation versus center operation for both fume hoods, and a 13 ppb decrease in contamination for the Berkeley hood versus the conventional fume hood. Interaction between location and fume hood type was not statistically significant. Because the data did not appear to be distributed in a Gaussian manner, non-parametric ANOVAs using the one-way exact Kruskal-Wallis test were used to validate the statistical significance. These ANOVAs rejected the null hypothesis that the Berkeley hood is worse or no better than the conventional hood at the 2.5% significance level, and rejected the null hypothesis that the three locations were the same at the 0.8% level.

Conclusions: The Berkeley hood provides better containment of potentially harmful fumes, and therefore greater operator safety, than a conventional fume hood.

3 Test Procedure

3.1 Human-as-Mannequin Test Description

3.1.1 Dynamic Tracer Gas Method

HAM tests were performed using the ASHRAE 110-1995 Method's tracer gas ejector. Each Ejector Position per ASHRAE 110-1995 Tracer Gas Test Procedure (see ASHRAE 110-1995, Section 7) was configured and tested. Tracer gas flow was initiate at the beginning of each Dynamic Test and shut off at the end of each Dynamic Test. Each **Choreographed Sequence** was time-data logged, noting start and finish times and tracer gas control levels, as a function of time. The **Choreographed Sequences** can be performed and documented by an independent testing firm or conducted with the "authority having jurisdiction" in attendance.

3.1.2 Technician

The tracer gas detector probe inlet, connected to an electron capture device, was located on the front of the technician near the technician's breathing zone at approximately 26 inches above the work surface. This was achieved by attaching the end of the tubing to the mouthpiece of a "hands free" telephone headset. The maximum length of tubing from the probe's inlet to the detector should not exceed six (6) feet long. At the beginning of each phase, the technician stood directly in front of the ejector and positioned their breathing zone at approximately three (3) inches away from the plane of the sash. In addition, the technician should be:

- Be familiar with performing the ASHRAE 110-1995 Tracer Gas Test Procedure, Section 7, inclusive.
- Be familiar with **Test Plan Glossary** (below) before performing **Sequence**. **GLOSSARY** terms are shown in ***Bold Italic*** font throughout the text of this document.
- Be practiced in performing each movement listed in the **Glossary** at least two times
- Be practiced in performing the entire **Choreographed Sequence** (without tracer gas flowing) at least two times.
- Be prompted or use other devices such as a metronome to assure a consistent pace.
- Be the same person performing the **Choreographed Sequence** on each hood.
- Be wearing a lab coat.

3.1.3 Test Duration

The duration of each **Dynamic Test**; **Center**, **Left**, **Right**, (three for each hood, there are a total of six **Dynamic Tests** per complete side-by-side **Sequence**) should be equivalent by plus or minus (±) 20 seconds of the averaged duration.

3.2 Acceptability Level

The LBNL Human-as-Mannequin sample protocol is a "one-off" effort to first, challenge a fume hood's ability to contain during actual operator manipulation of objects both within the hood and removal from the hood; second, develop a choreographed sequence that can be duplicated and verified due to its highly structured steps, phases, tests, and sequences; and finally, demonstrate the comparative performance of the Berkeley hood's air divider containment technology. Other fume hood engineers and researchers are experimenting with HAM testing. However, due to the number of highly variable parameters that can be included and excluded from any protocol, a consensus of "acceptable" spillage may never be resolved. The true merit in this type of testing is comparative simulation of hood usage.

3.2.1 Control Level Results

The time-averaged tracer gas control level in the Human-as-Mannequin breathing zone was calculated for the entire **Sequence** (one Dynamic Test totaling Eighteen Phases) for each hood (excluding the time between the three Tests) and reported. This **Sequence Control Level** provides a performance indicator for comparison purposes between hoods.

3.2.2 Additional Control Verification

For each hood, the Human-as-Mannequin **Sequence** was repeated three times developing a **Series**. For each hood, the three time-averaged tracer gas **Sequence Control Levels** were combined and averaged. This provides a **Series Average Value,** an overall performance indicator for comparison purposes between hoods.

3.3 Instrumentation

3.3.1 Total Exhaust Flow Measurement

Total exhaust flow was verified by measuring pressure readings from a pitot tube located in a straight run of each hood's exhaust stack. The volumetric flow was verified with a calibrated flow meter with an accuracy of better than ±3 percent for each hood's pitot tube and a calibration curve was generated using a least squares second-order method. Each hood's calibration curve was plotted and attached to the hood for easy reference during hood setup.

3.3.2 Face Velocity Meter

Face velocities were tested with a TSI velocity meter, model 8360. Readings were averaged with a minimum of three points. Known volumetric flow, from pitot tube readings, correlated well with face velocity readings measured in each hood. However, face velocity readings indicated some level of turbulence not quantified in this study. This is a typical situation for most conventional hoods and is being addressed by many hood manufacturers with advanced design methods and construction enhancements. In the case of the Berkeley hood, the air divider technique addresses this situation by gently pushing air into the hood with low turbulence intensity.

3.3.3 Tracer Gas Ejector

A standard ASHRAE 110 ejector, manufactured by Air Flow Tech Products, Inc., was used during the test runs. A BIOS Dry-Cal DC-1 Flow calibrator was used to verify SF_6 volumetric flow at 4 LPM. A pressure gauge attached to the ejector was monitored during the flow calibration sequence at 23.5 psig and maintained throughout the test runs.

3.3.4 Tracer Gas Detector

The test instrument used to detect SF_6 was a ITI-Qualitek Leakmeter 120. A six-foot long inlet tube to the Leakmeter was located at breathing zone of the human held in place at the end of a telephone headset. Calibration was verified frequently with known concentrations of SF_6 in "cal bags" and corrected for the length of the six-foot long inlet tube. Analog output readings (voltage) from the ITI-Qualitek Leakmeter were recorded with an A-to-D converter (a voltage-ohm-meter, VOM) and stored on a personal computer. Later these data were graphed with Microsoft Excel™ for presentation.

3.4 Deviations from ASHRAE 110 Test Procedure

Human-as-Mannequin protocol developed by LBNL in consultation with CAL/OSHA and industry experts. No known sanctioned standard exists.

4 Side-by-side Setup

4.1 Conventional hood configuration

The conventional hood used for these tests is produced by Jamestown Metal Products. It is a nominal six-foot wide hood. The hood was installed with a dedicated exhaust fan and operates in a conventional manner.

The depth of the nominal six-foot-wide hood is 32.5 inches from the sash to the rear baffle. The fully open sash dimensions are 61.75 inches wide by 26.5 inches high, for a total open area of 11.36 square feet. Testing was conducted with total exhaust flow of 1136 CFM. This corresponds to a 100 FPM face velocity.

4.2 Berkeley hood configuration

The nominal six-foot-wide version of the Berkeley hood is 30.5 inches from the sash to the rear baffle. The fully open sash dimensions are 61.75 inches wide by 30 inches high, for a total open area of 12.865 square feet. Testing was conducted with total exhaust flow of 643 CFM. This corresponds to 50 percent flow in a standard hood operating at a 100 FPM face velocity, respectively.

4.2.1 Push/Pull System

This six-foot version of the Berkeley hood uses four fans to push room air into the hood's cabinet. The "top" plenum fan pushes air from behind the top of the sash towards the rear baffle. The "front" plenum fan blows air from the top of the face area down (and across the front of the sash when it is closed). The "lower" plenum fans push air from behind the lower airfoil towards the rear of the cabinet. All three plena have individual rheostats to manually adjust fan(s) speed. These fans produce a vectored airflow (push) that provides containment at lower than normal exhaust airflow (pull). The push air is introduced at or inside the sash (face) that creates an "air divider." Consequently, face velocity measurements are irrelevant.

4.2.2 Supply Airflow Rate

Each supply grill/screen was measured with a hot wire anemometer with the results provided in Table 3. The velocity of the Front and Top plena was recorded in a vertical orientation at intervals of every two inches. The velocity of the Bottom plenum was recorded in a horizontal orientation every inch. Conversion from velocity to volumetric flows from the supply outlets is approximate.

Table 3: Configuration of Six-foot Berkeley hood at LBNL.

Supply	Approx. Outlet Area Sq. ft.	Average Velocity FPM	Estimated Volume CFM
Front	1.6	57.8	92.5
Top	2.64	35.6	94.0
Bottom	0.65	71.0	45.9
Total	5.89		232

5 Test Run Narrative

5.1 Dynamic Tracer Gas runs

Dynamic Tracer gas **Test** runs were performed with the ejector in the hood center, left, and right positions. The SF_6 gas detector, an Ion Tracker Instruments (ITI) Leakmeter 120, was checked with calibrated bags of SF_6 tracer gas just prior to each test, thus ensuring accurate results.

5.2 HAM Choreographed Sequence

This **Choreographed Sequence** includes three **Dynamic Tests**: **Center**, **Left**, and **Right**. Each **Dynamic Test** includes six (6) phases: **Center Dynamic Test**, **Phase One** through **Six**; **Left Dynamic Test**, **Phase Seven** through **Twelve**; **Right Dynamic Test**, **Phase Thirteen** through **Eighteen**. Therefore, the **Choreographed Sequence** for each hood has eighteen phases. As noted above, terms shown in ***Bold Italic*** font throughout the **Sequence** text are fully defined in the **Test Plan Glossary** (below).

5.2.1 Phase One: Center Dynamic Test

1. Locate ***Ejector - Center*** in hood and Place ***Objects – Center*** according to **Table Phase One**, below.

Table Phase One

12 inches behind sash					
6 inches behind sash	1	2	**E**	3	4

2. Begin **Test** by starting tracer gas flow and waiting for 15 seconds.

5.2.2 Phase Two

3. ***Insert Hands and Arms*** for 15 seconds.
4. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.

5.2.3 Phase Three

5. ***Insert Hands and Arms*** into the hood.
6. Starting from the left and working to the right, Grasp each object, ***Move Objects*** individually to a position that is twelve (12) inches from the plane of the sash (rearward), using each hand as appropriate.

Table Phase Three

12 inches behind sash	1	2		3	4
6 inches behind sash			**E**		

7. ***Remove Hands and Arms***; lower to side for a minimum of five seconds

5.2.4 Phase Four

8. ***Insert Hands and Arms*** into the hood.
9. Starting from the left and working to the right, Grasp each object, ***Exchange Objects*** and ***Move Objects*** individually to a position that is six (6) inches from the plane of the sash (forward) .

Table Phase Four

12 inches behind sash					
6 inches behind sash	4	3	**E**	2	1

10. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.

5.2.5 Phase Five

11. ***Insert Hands and Arms*** into the hood.
12. Grasp object #1 on the right side of the ejector and ***Transfer Liquids*** from object #1 to object #2 (refer to **Table Phase Four**).
13. ***Remove Hands and Arms*** ; lower to side for a minimum of five seconds.

5.2.6 Phase Six

14. ***Insert Hands and Arms*** into the hood.
15. Grasp object number three (3) on the left side of the ejector and ***Remove Hands and Arms***. Note: left hand is holding object number three (3).
16. Lower right hand to side and ***Rotate Body*** to left.
17. ***Insert Hands and Arms*** into the hood.
18. Replace object number three (3).
19. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.
20. End **Test** by waiting for 15 seconds and ending tracer gas flow.

5.2.7 Phase Seven: Left Dynamic Test

21. Locate ***Ejector - Left*** in hood and Place ***Objects – Left*** according to **Table Phase Seven**, below.

Table Phase Seven

12 inches behind sash					
6 inches behind sash	2	**E**	3	4	1

22. Begin **Test** by starting tracer gas flow and waiting for 15 seconds.

5.2.8 Phase Eight

23. ***Insert Hands and Arms*** for 15 seconds.
24. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.

5.2.9 Phase Nine

25. ***Insert Hands and Arms*** into the hood.
26. Starting from the right and working to the left, Grasp each object, ***Move Objects*** individually to a position that is twelve (12) inches from the plane of the sash (rearward), using each hand as appropriate.

Table Phase Nine

12 inches behind sash	2		3	4	1
6 inches behind sash		**E**			

27. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.

5.2.10 Phase Ten

28. ***Insert Hands and Arms*** into the hood.
29. Starting from the right and working to the left, Grasp each object, ***Exchange Objects*** and ***Move Objects*** individually to a position that is six (6) inches from the plane of the sash (forward) .

Table Phase Ten

12 inches behind sash					
6 inches behind sash	3	**E**	2	1	4

30. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.

5.2.11 Phase Eleven

31. ***Insert Hands and Arms*** into the hood.
32. Grasp object #1 on the right side of the ejector and ***Transfer Liquids*** from object #1 to object #2 (refer to **Table Phase Ten**).
33. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.

5.2.12 Phase Twelve

34. ***Insert Hands and Arms*** into the hood.

35. Grasp object number Three (3) on the left side of the ejector with left hand and ***Remove Hands and Arms***. Note: left hand is holding object number Three (3).
36. Lower right hand to side and ***Rotate Body*** to left.
37. ***Insert Hands and Arms*** into the hood.
38. Replace object number Three (3).
39. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.
40. End **Test** by waiting for 15 seconds and ending tracer gas flow.

5.2.13 Phase Thirteen: Right Dynamic Test

41. Locate ***Ejector - Right*** in hood and Place ***Objects – Right*** according to **Table Phase Thirteen**, below:

Table Phase Thirteen

12 inches behind sash					
6 inches behind sash	1	4	3	**E**	2

42. Begin **Test** by starting tracer gas flow and waiting for 15 seconds.

5.2.14 Phase Fourteen

43. ***Insert Hands and Arms*** for 15 seconds.
44. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.

5.2.15 Phase Fifteen

45. ***Insert Hands and Arms*** into the hood.
46. Starting from the left and working to the right, Grasp each object, ***Move Objects*** individually to a position that is twelve (12) inches from the plane of the sash (rearward), using each hand as appropriate.

Table Phase Fifteen

12 inches behind sash	1	4	3		2
6 inches behind sash				**E**	

47. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.

5.2.16 Phase Sixteen

48. ***Insert Hands and Arms*** into the hood.
49. Starting from the left and working to the right, Grasp each object, ***Exchange Objects*** and ***Move Objects*** individually to a position that is six (6) inches from the plane of the sash (forward) .

Table Phase Sixteen

12 inches behind sash					
6 inches behind sash	4	1	2	**E**	3

50. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.

5.2.17 Phase Seventeen

51. ***Insert Hands and Arms*** into the hood.

52. Grasp object #1 on the left side of the ejector and ***Transfer Liquids*** from object #1 to object #2 (refer to **Table Phase Sixteen**).
53. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.

5.2.18 Phase Eighteen

54. ***Insert Hands and Arms*** into the hood.
55. Grasp object number Three (3) on the right side of the ejector with right hand and ***Remove Hands and Arms***. Note: right hand is holding object number Three (3).
56. Lower left hand to side and ***Rotate Body*** to right.
57. ***Insert Hands and Arms*** into the hood.
58. Replace object number Three (3).
59. ***Remove Hands and Arms***; lower to side for a minimum of five seconds.
60. End **Test** by waiting for 15 seconds and ending tracer gas flow.

6 Appendix A: Test Plan Glossary

6.1.1 Ejector – Center

Use the ASHRAE 110-1995 requirements for center placement of the ejector (Section 7.3) and SF_6 flow rate (Section 4.1). Accordingly, the SF_6 ejector should be placed in the center of each fume hood, and six (6) inches into the hood's interior as measured from the plane of the sash for the **Choreographed Sequence; Center Dynamic Test, Phase One** through **Phase Six,** (see above).

6.1.2 Ejector – Left

Use the ASHRAE 110-1995 requirements for left placement of the ejector (Section 7.3) and SF_6 flow rate (Section 4.1). Accordingly, the SF_6 ejector should be placed twelve inches (12 in.) from the left sidewall of each fume hood, and six (6) inches into the hood's interior as measured from the plane of the sash for the **Choreographed Sequence; Left Dynamic Test, Phase Seven** through **Phase Twelve,** (see above).

6.1.3 Ejector – Right

Use the ASHRAE 110-1995 requirements for right placement of the ejector (Section 7.3) and SF_6 flow rate (Section 4.1). Accordingly, the SF_6 ejector should be placed twelve inches (12 in.) from the right sidewall of each fume hood, and six (6) inches into the hood's interior as measured from the plane of the sash for the **Choreographed Sequence; Right Dynamic Test, Phase Thirteen** through **Phase Eighteen,** (see above).

6.1.4 Objects – Center

Provide four objects for the **Center Dynamic Test** in the following order starting from left to the right:

1. a 500 ml beaker, filled halfway with water.
2. a 250 ml graduated cylinder filled halfway with water.
3. a capped, 500 ml (or one pint) bottle.
4. a box, 4 inch cube.

Place these object in the following manner by referring to **Table Phase One**, included below:

- Provide a reference line (#1) on each hood's work surface that is six (6) inches into the hood's interior, as measured from the plane of the sash (with tape or a temporary marker on the hood's work surface).
- Mark a point twelve (12) inches to the left of the ejector's base (see **E** in **Table Phase One**, below) on reference line #1.
- Place the center of object number One (1) on this point behind reference line #1, which is six (6) inches into the hood's interior.
- Mark a point six (6) inches to the left of the ejector's base (see **E** in **Table Phase One**, below) on reference line #1.
- Place the center of object number Two (2) on this point behind reference line #1, which is six (6) inches into the hood's interior.
- Place the remaining two objects; Three (3) and Four (4), in the same geometric arrangement, to the right of the ejector (**E**), i.e., six (6) inches and twelve (12) inches to the right of the ejector's base, respectively and behind reference line #1, which is six (6) inches into the hood's interior, as measured from the plane of the sash.

Table Phase One

12 inches behind sash					
6 inches behind sash	1	2	**E**	3	4

- Provide another reference line (#2) on each hood's work surface that is twelve (12) inches into the hood's interior, as measured from the plane of the sash (with tape or a temporary marker on the hood's work surface). Mark points for intervening positions of each object behind reference line #2 with a line that is perpendicular to each object's point marked behind reference line #1.

Fig. 1 – HAM Test Series – Conventional hood – Center ejector; object's starting position.

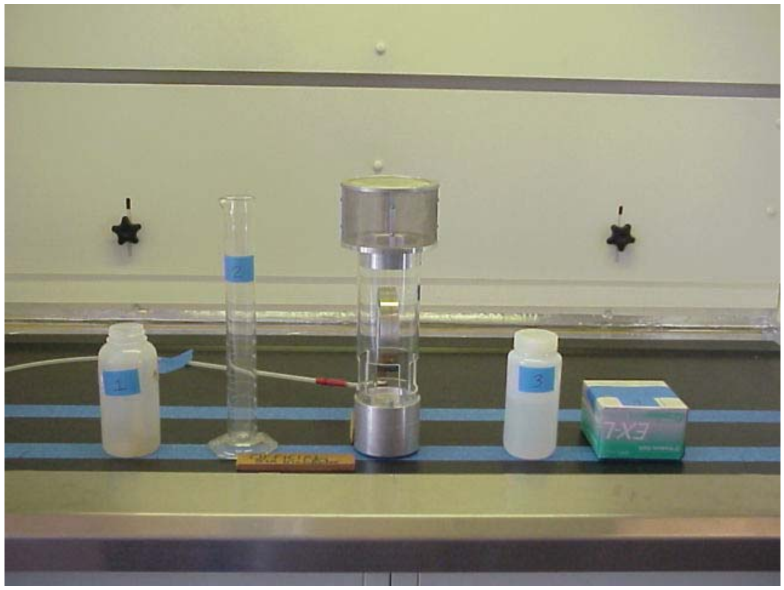


Fig. 2 – HAM Test Series – Conventional hood – Center ejector; close-up.

6.1.5 Objects – Left

Provide four objects for the **Left Dynamic Test**:
1. a 500 ml beaker, filled halfway with water.
2. a 250 ml graduated cylinder filled halfway with water.
3. a capped, 500 ml (or one pint) bottle.
4. a box, 4 inch cube.

Place these object in the following manner by referring to **Table Phase Seven**, included below:
- Provide a reference line (#1) on each hood's work surface that is six (6) inches into the hood's interior, as measured from the plane of the sash (with tape or a temporary marker on the hood's work surface).
- Mark a point six (6) inches to the left of the ejector's base (see **E** in **Table Phase One**, below) on reference line #1.
- Place the center of object number Two (2) on this point behind reference line #1, which is six (6) inches into the hood's interior.
- Mark a point six (6) inches to the right of the ejector's base (see **E** in **Table Phase One**, below) on reference line #1.
- Place the center of object number Three (3) on this point behind reference line #1, which is six (6) inches into the hood's interior.
- Place the remaining two objects; Four (4) and One (1), in the same geometric arrangement, to the right of the ejector's base (**E**), i.e., twelve (12) inches and eighteen (18) inches to the right, respectively and behind reference line #1, which is six (6) inches into the hood's interior, as measured from the plane of the sash.

Table Phase Seven

12 inches behind sash					
6 inches behind sash	2	**E**	3	4	1

- Provide another reference line (#2) on each hood's work surface that is twelve (12) inches into the hood's interior, as measured from the plane of the sash (with tape or a temporary marker on the hood's work surface). Mark points for intervening positions of each object behind reference line #2 with a line that is perpendicular to each object's point marked behind reference line #1.

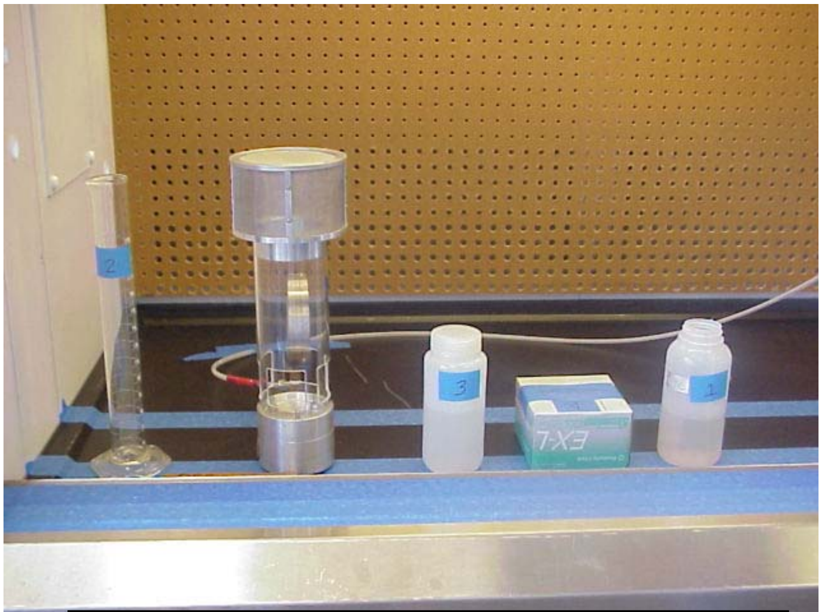


Fig. 3 – HAM Test Series – Berkeley hood – Left ejector; object's starting position.

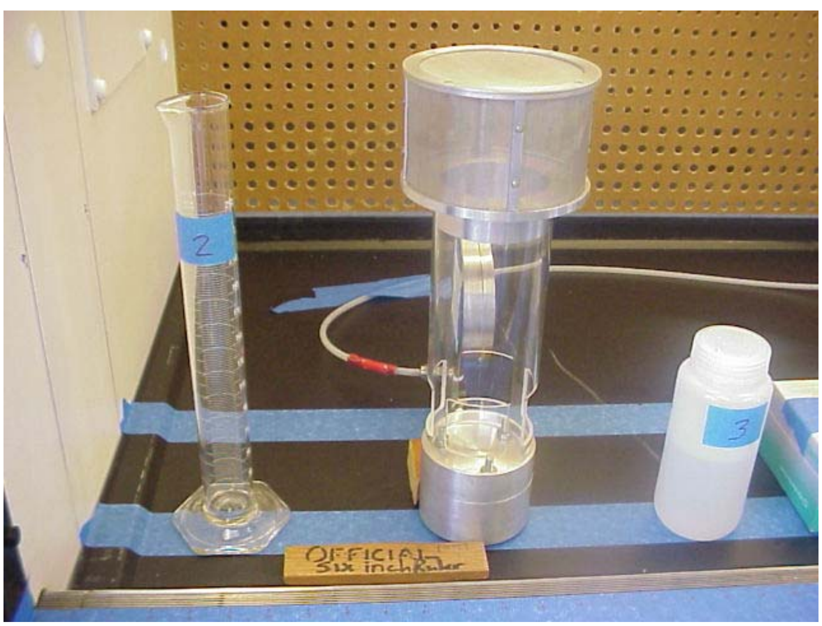


Fig. 4 – HAM Test Series – Berkeley hood – Left ejector; close-up.

6.1.6 Objects – Right

Provide four objects for the **Right Dynamic Test**:

1. a 500 ml beaker, filled halfway with water.
2. a 250 ml graduated cylinder filled halfway with water.
3. a capped, 500 ml (or one pint) bottle.
4. a box, 4 inch cube.

Place these objects in the following manner by referring to **Table Phase Thirteen**, included below:

- Provide a reference line (#1) on each hood's work surface that is six (6) inches into the hood's interior, as measured from the plane of the sash (with tape or a temporary marker on the hood's work surface).
- Mark a point six (6) inches to the right of the ejector's base (see **E** in **Table Phase One**, below) on reference line #1.
- Place the center of object number Two (2) on this point behind reference line #1, which is six (6) inches into the hood's interior.
- Mark a point six (6) inches to the left of the ejector's base (see **E** in **Table Phase One**, below) on reference line #1.
- Place the center of object number Three (3) on this point behind reference line #1, which is six (6) inches into the hood's interior.
- Place the remaining two objects; Four (4) and One (1), in the same geometric arrangement, to the left of the ejector's base (**E**), i.e., twelve (12) inches and eighteen (18) inches to the left, respectively and behind reference line #1, which is six (6) inches into the hood's interior, as measured from the plane of the sash.

Table Phase Thirteen

12 inches behind sash					
6 inches behind sash	1	4	3	**E**	2

- Provide another reference line (#2) on each hood's work surface that is twelve (12) inches into the hood's interior, as measured from the plane of the sash (with tape or a temporary marker on the hood's work surface). Mark points for intervening positions of each object behind reference line #2 with a line that is perpendicular to each object's point marked behind reference line #1.

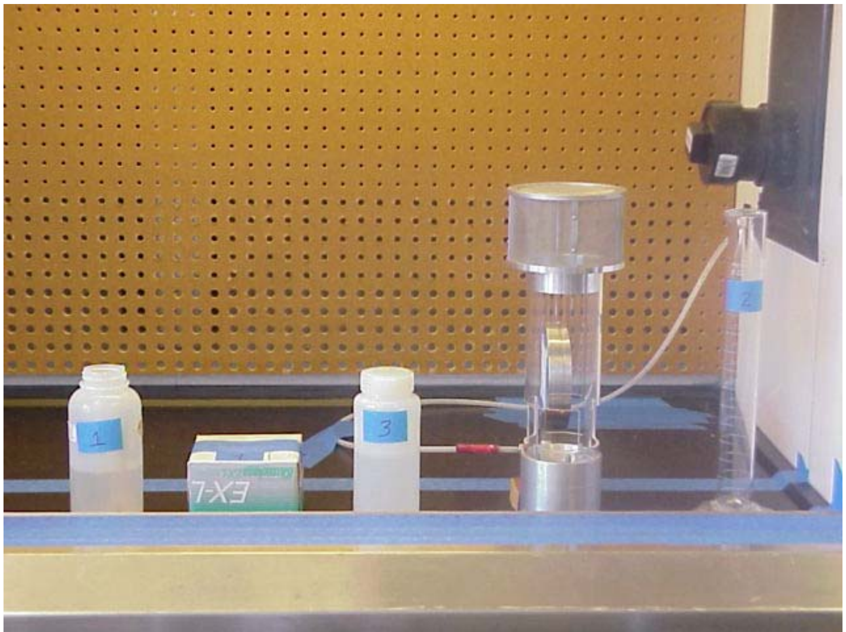


Fig. 5 – HAM Test Series – Berkeley hood – Right ejector; object's starting position.

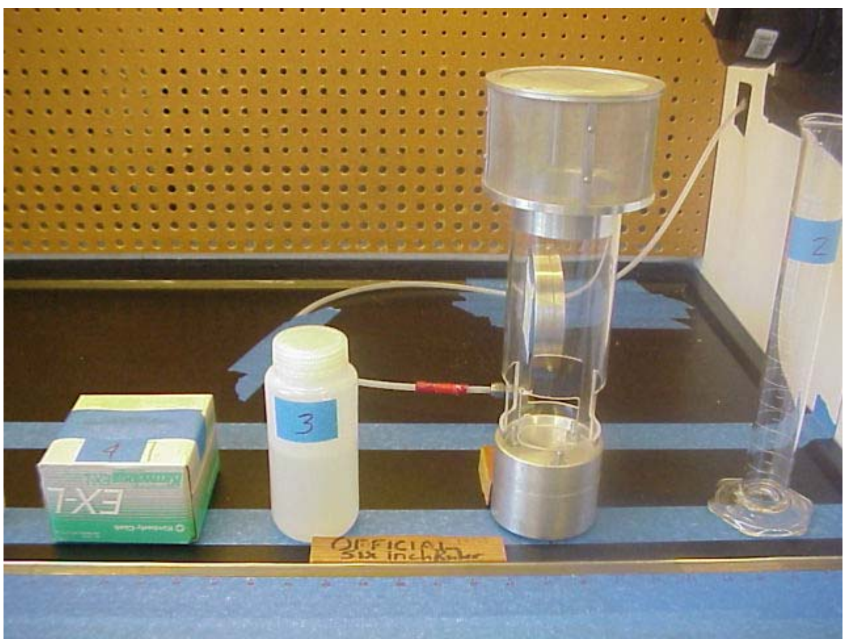


Fig. 6 – HAM Test Series – Berkeley hood – Right ejector; close-up.

6.1.7 Inserting Hands and Arms

Begin with hands three (3) inches away from the sash plane. Both hands and (fore) arms should be inserted into the hood's interior simultaneously (even in phases requiring one hand in use) with palms of hands oriented vertically and fingers relaxed (slightly open, not cupped) and forearms oriented "normal" (perpendicular in all directions) to the plane of the sash. The rate of hand/arm insertion should be approximately one (1) foot per second (1.0 fps).

6.1.8 Removing Hands and Arms

Hands and (fore) arms should be removed from the hood's interior together with palms of hands oriented vertically and fingers relaxed (slightly open, not cupped) and forearms oriented "normal" (perpendicular in all directions) to the plane of the sash. As appropriate, end with hands three (3) inches away from the sash plane. As appropriate, hands and arms should then be lowered to the technician's side for a minimum of five seconds. The rate of hand/arm removal and lowering should be approximately one (1) foot per second (1.0 fps).

Fig. 7 – HAM Test Series – Conventional hood – Left ejector; moving objects rearward.

6.1.9 Moving Objects

When required, the objects should be moved from their resting position to their new position in a line perpendicular to the plane of the hood's sash. The rate of movement should be approximately one (1) foot per second (1.0 fps).

6.1.10 Exchanging Objects

As appropriate, objects should be exchanged behind the ejector maintaining a minimum distance parallel to the plane of the sash of twelve (12) inches until they can be ***Moved***, see above ***Moving Objects*** for additional information. They should be exchanged (handed-off) individually, in turn, starting from their resting position (rearward) to their new position (forward); see appropriate Tables (e.g., **Table Phase Four**). The rate of movement should be approximately one foot per second (1.0 fps). The necessary handoff should be one to two seconds.

Fig. 8 – HAM Test Series – Conventional hood – Left ejector; exchanging objects.

6.1.11 Transferring Liquids

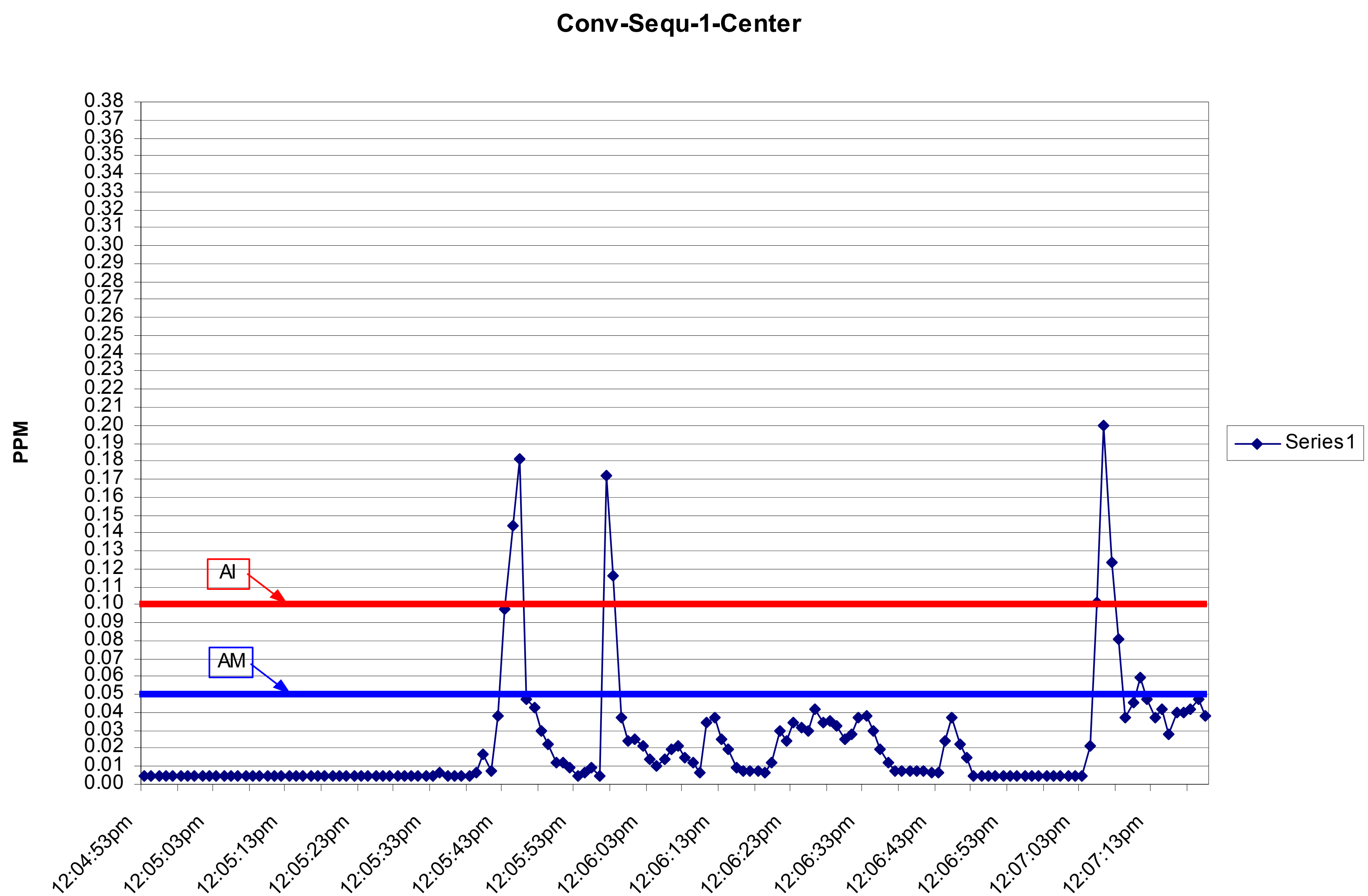
When required, water in the 500 ml beaker should be transferred to the 250 ml graduated cylinder until the cylinder is filled to the 250 ml mark. Return 500 ml beaker to starting position.

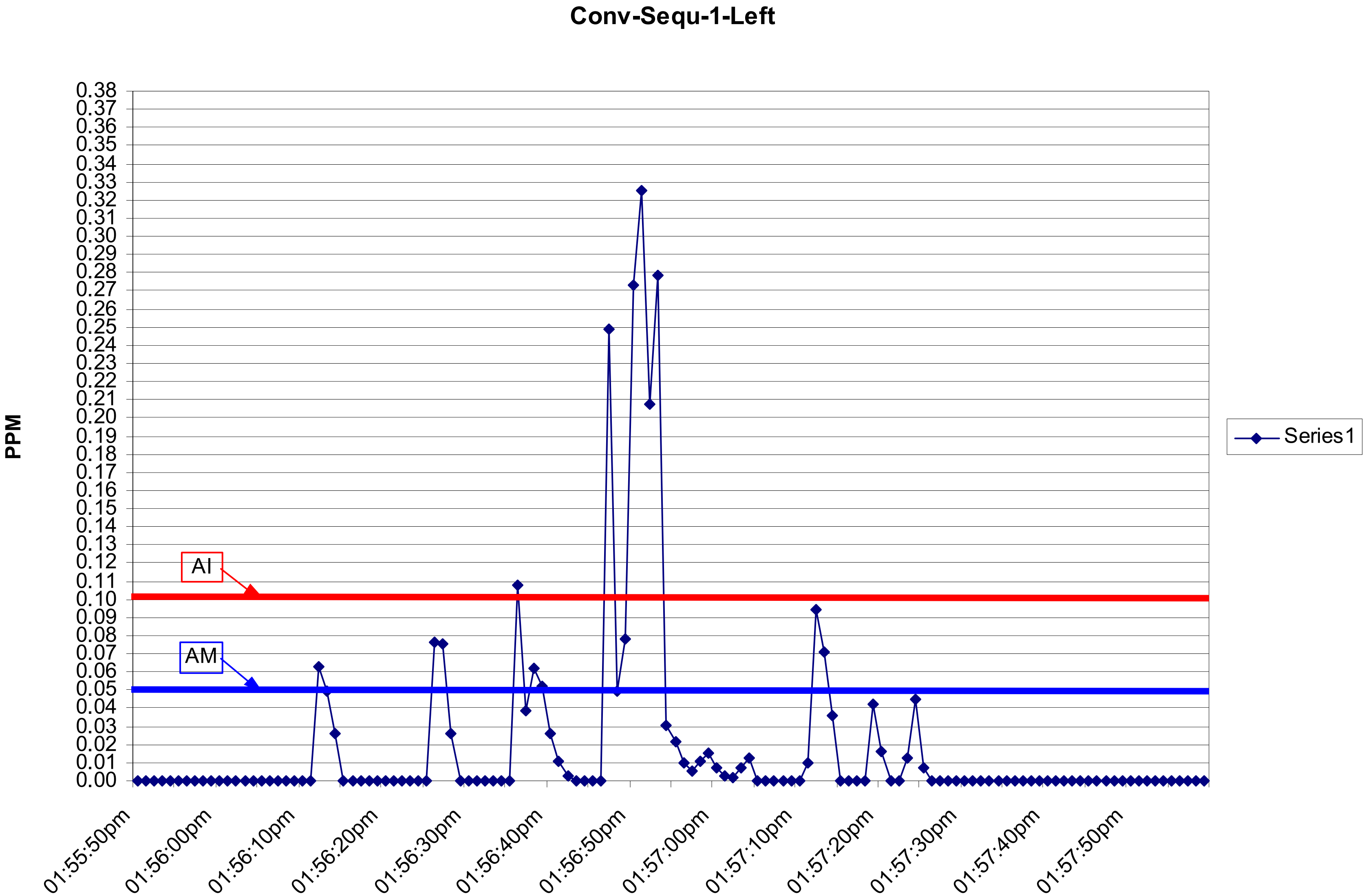
6.1.12 Rotating Body

When required after ***Removing Hands and Arms***, the technician should rotate their body's torso 90 degrees, as noted in **Sequence**, pause for five seconds; return torso to position at start of ***Rotating Body***; pause for five seconds before continuing the test **Sequence**.

Fig. 9 – HAM Test Series – Conventional hood – Left ejector; replacing object after rotating.

7 Appendix B: Containment Test Run Plots

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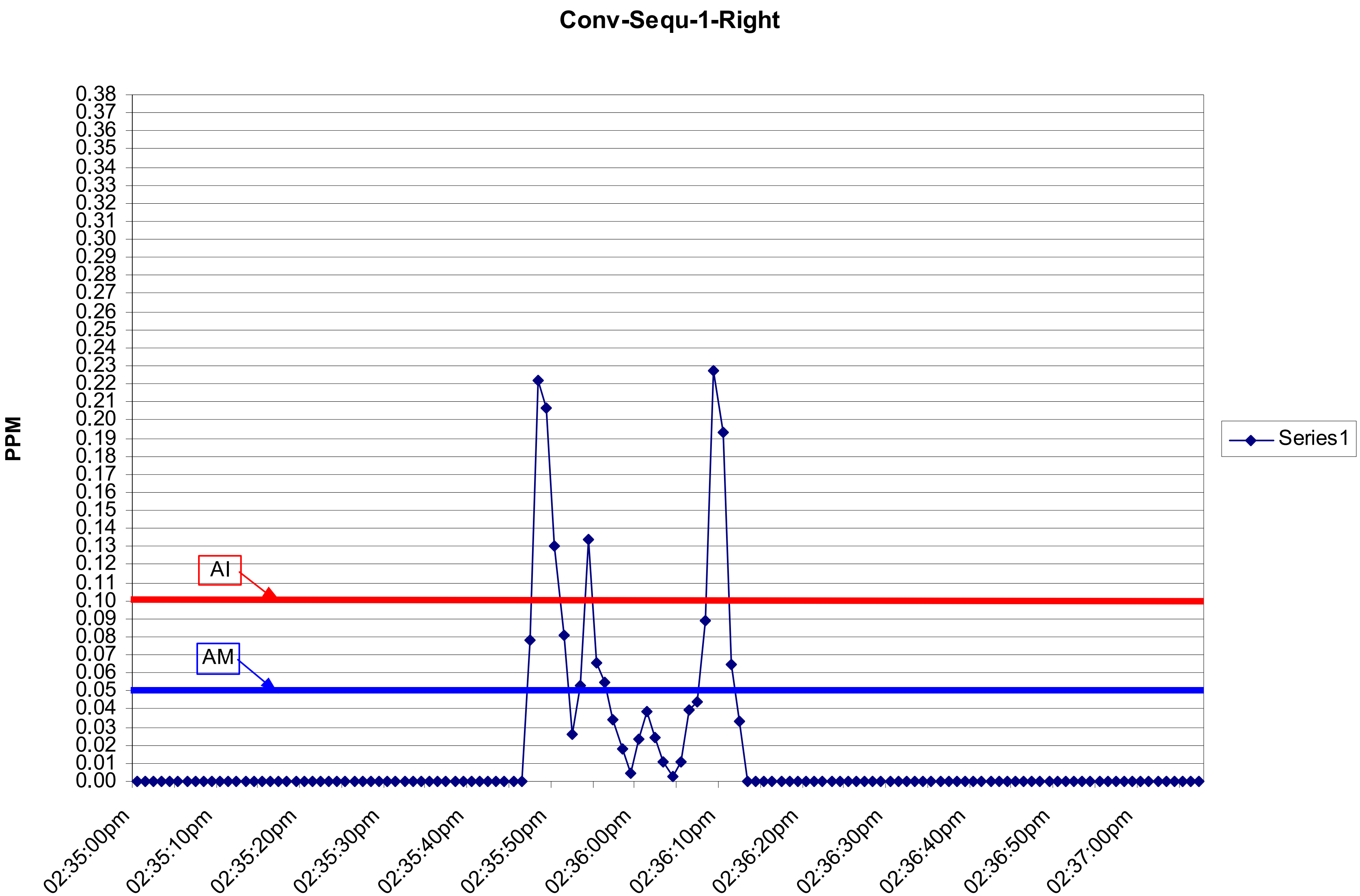
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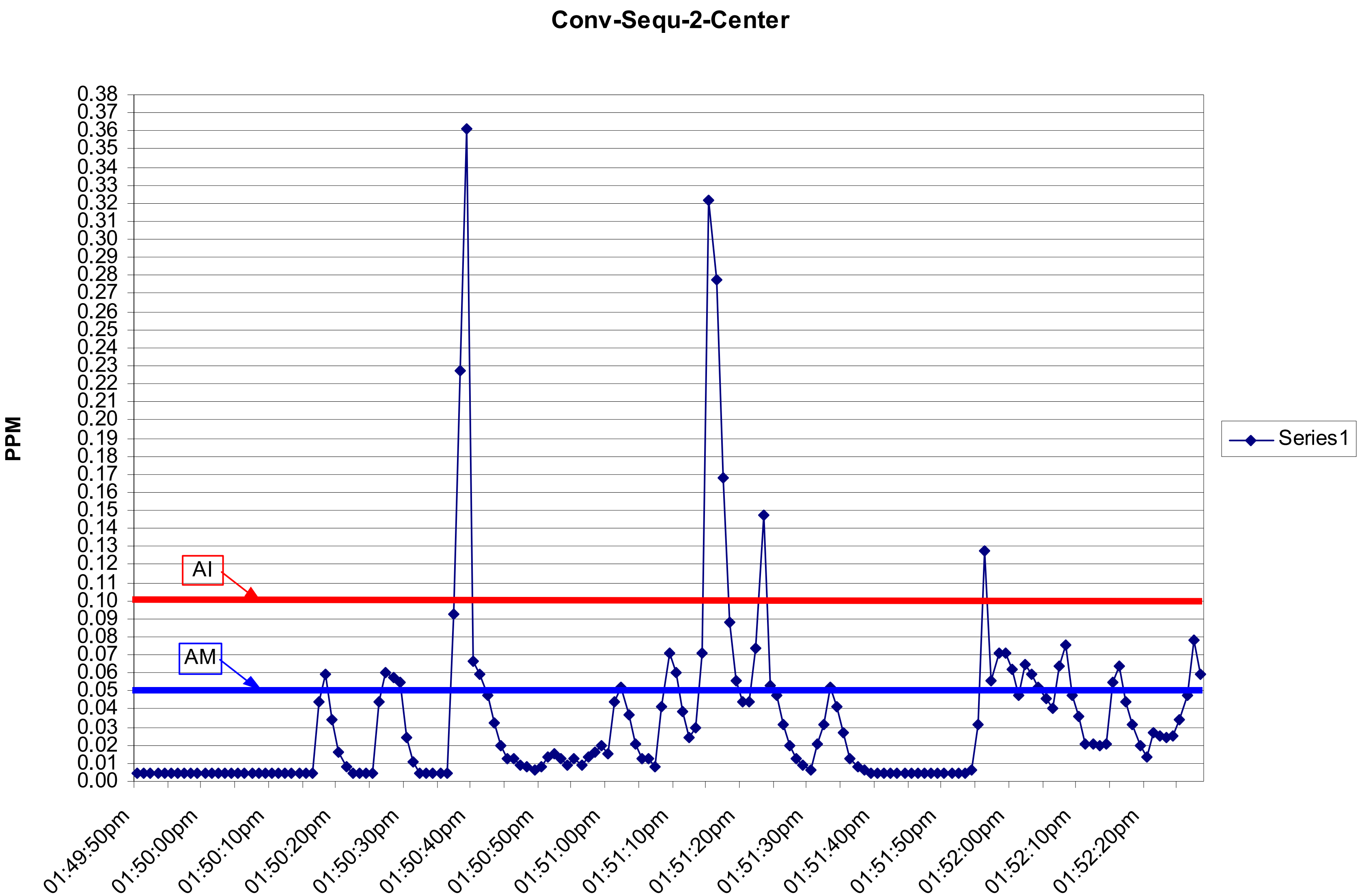
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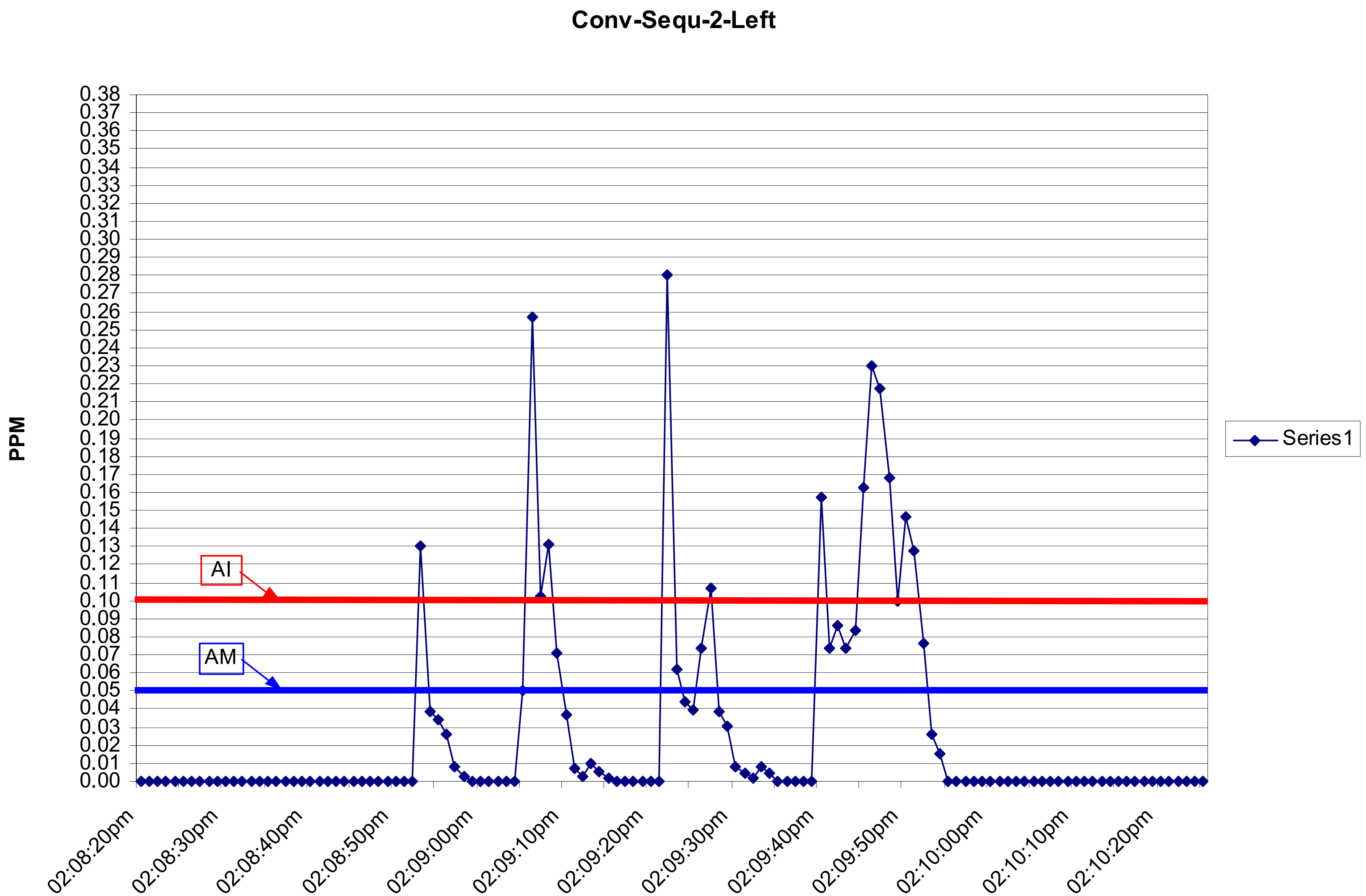
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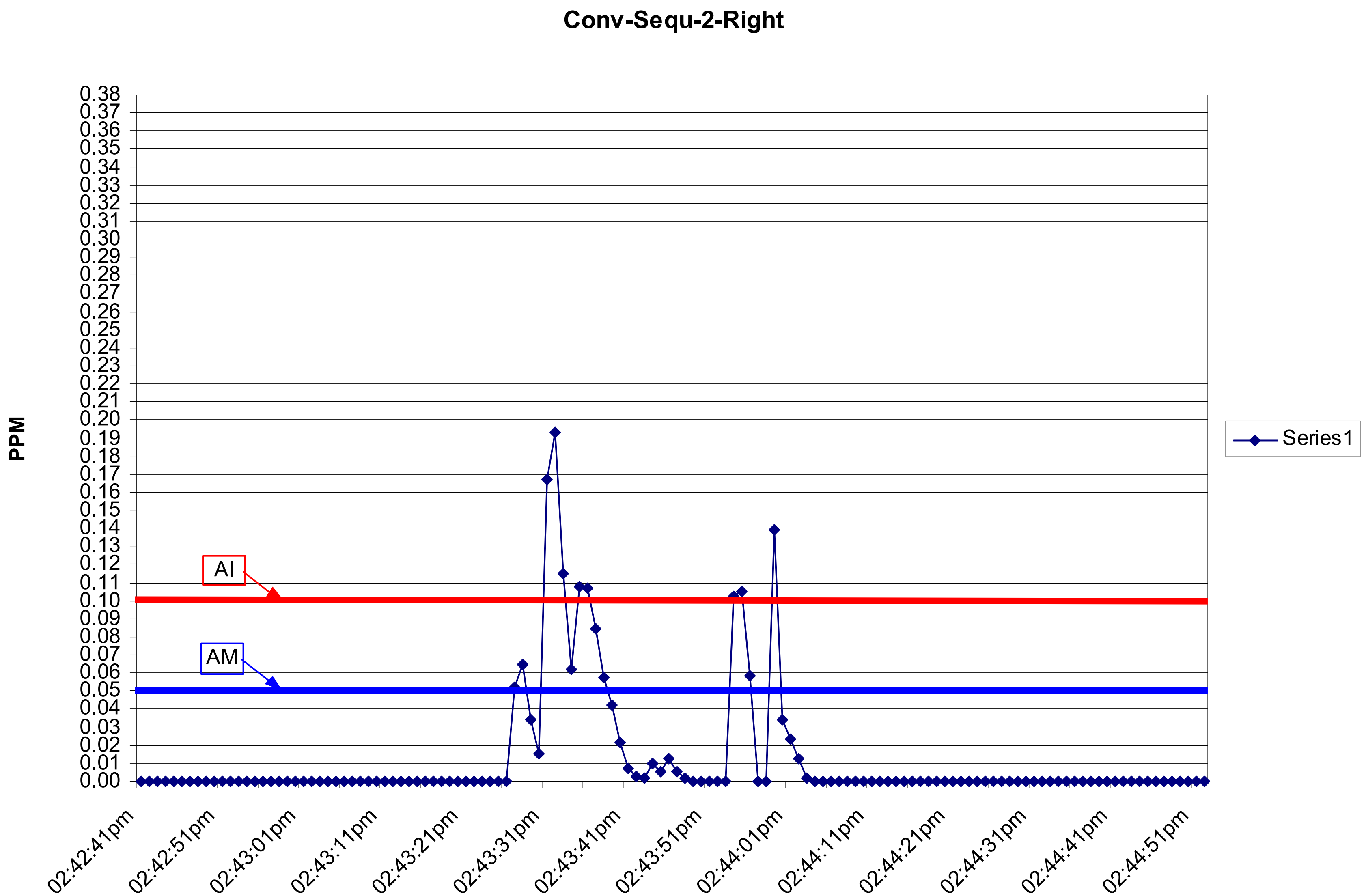
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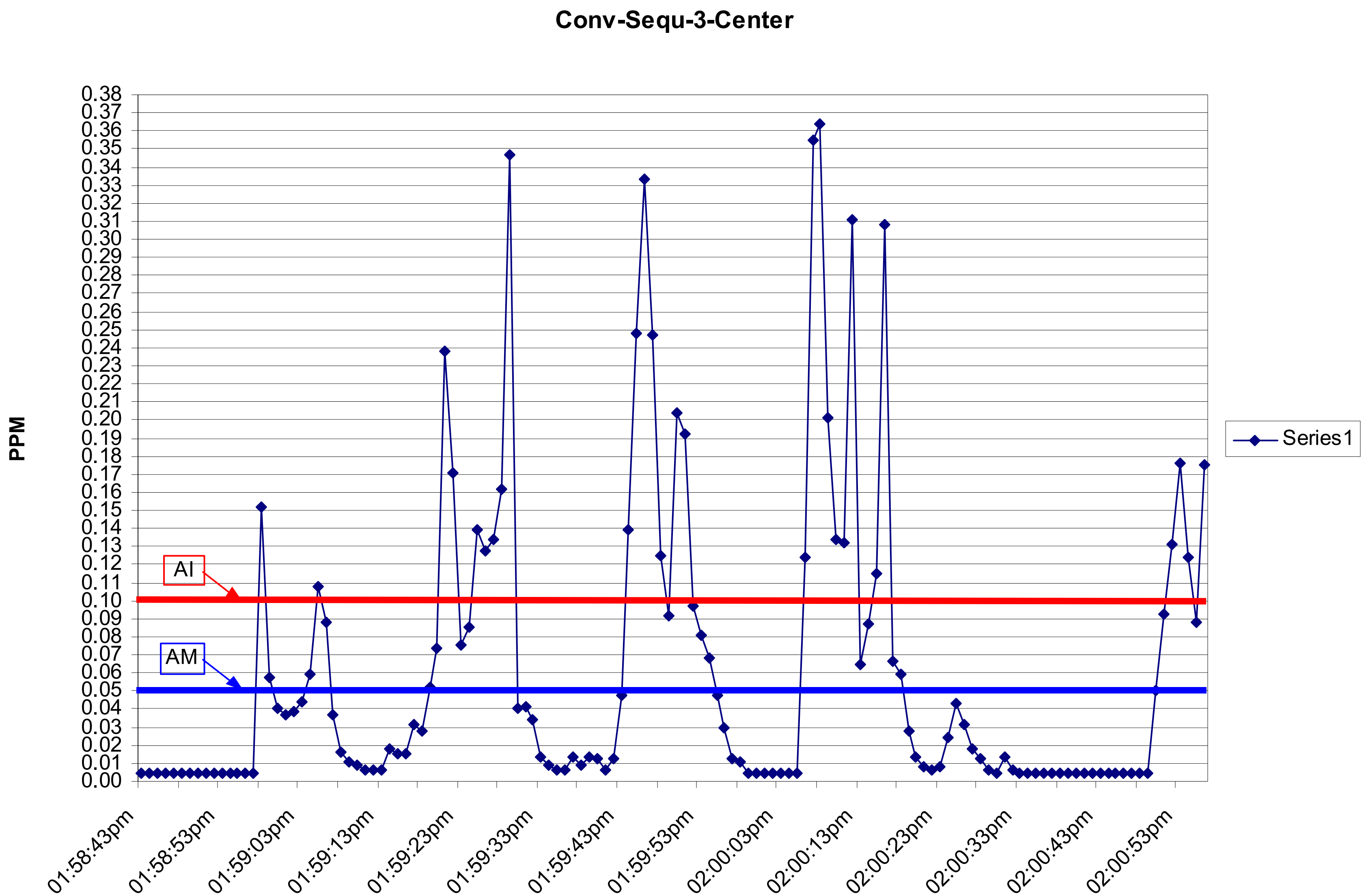
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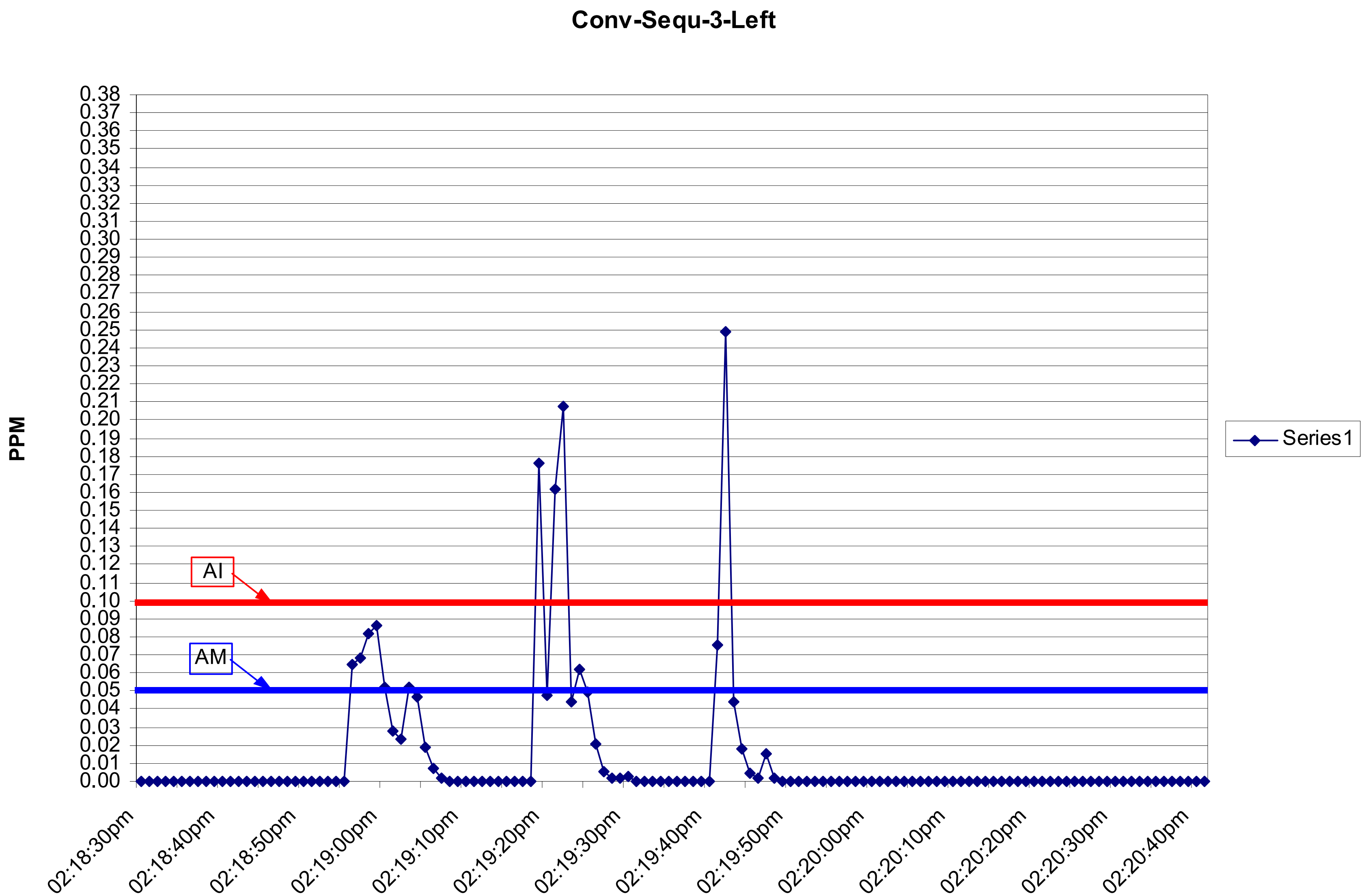
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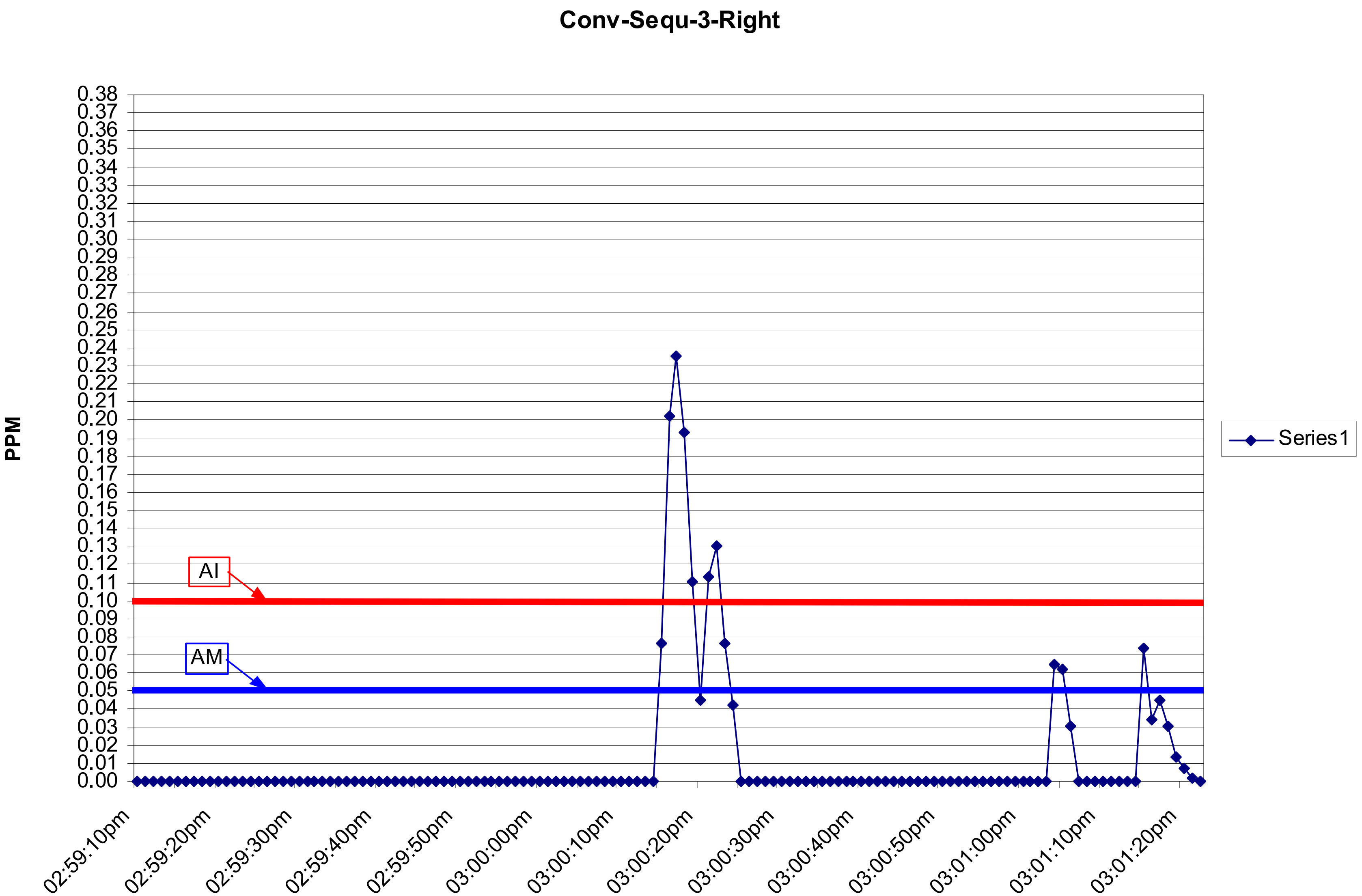
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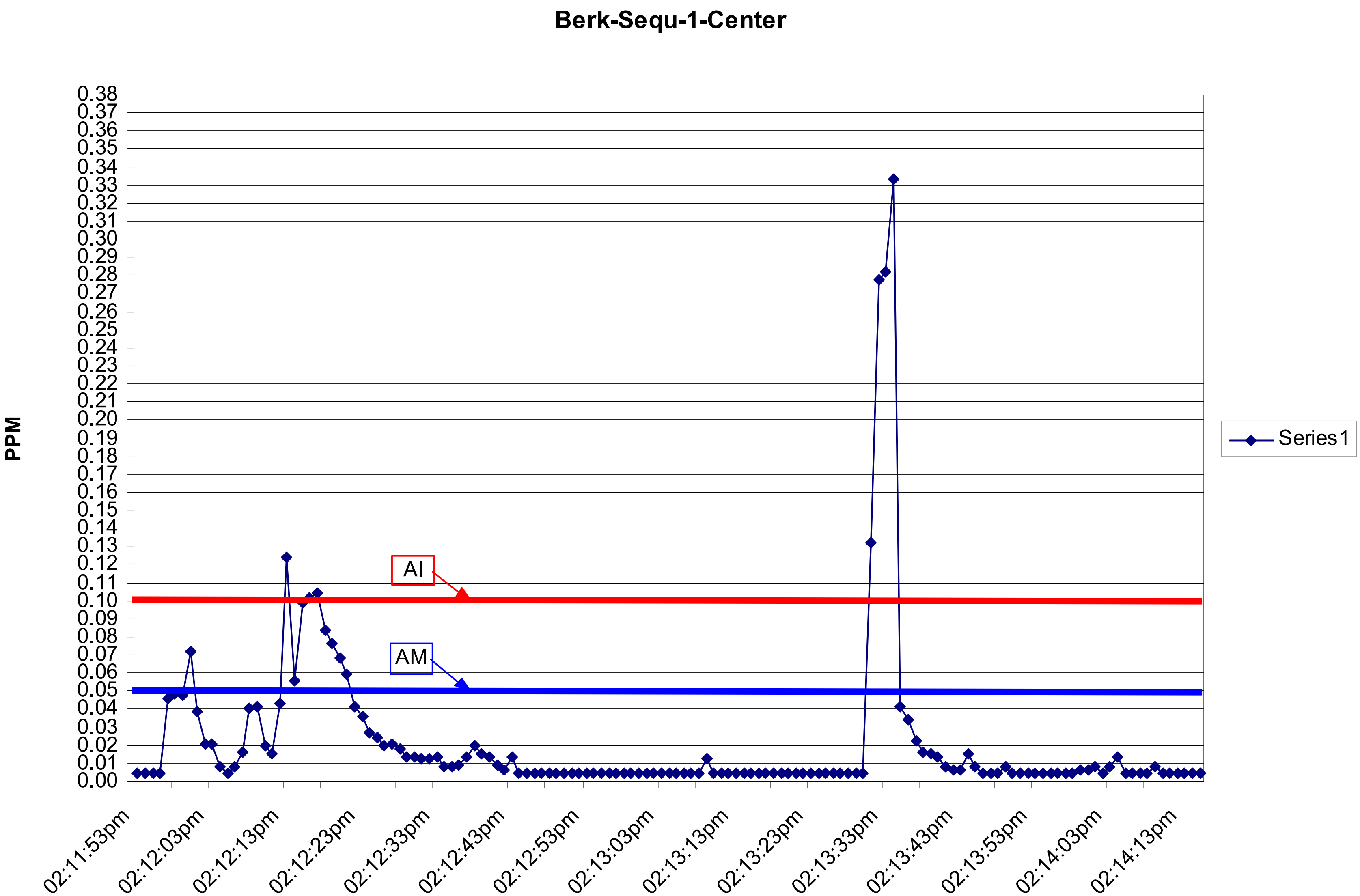
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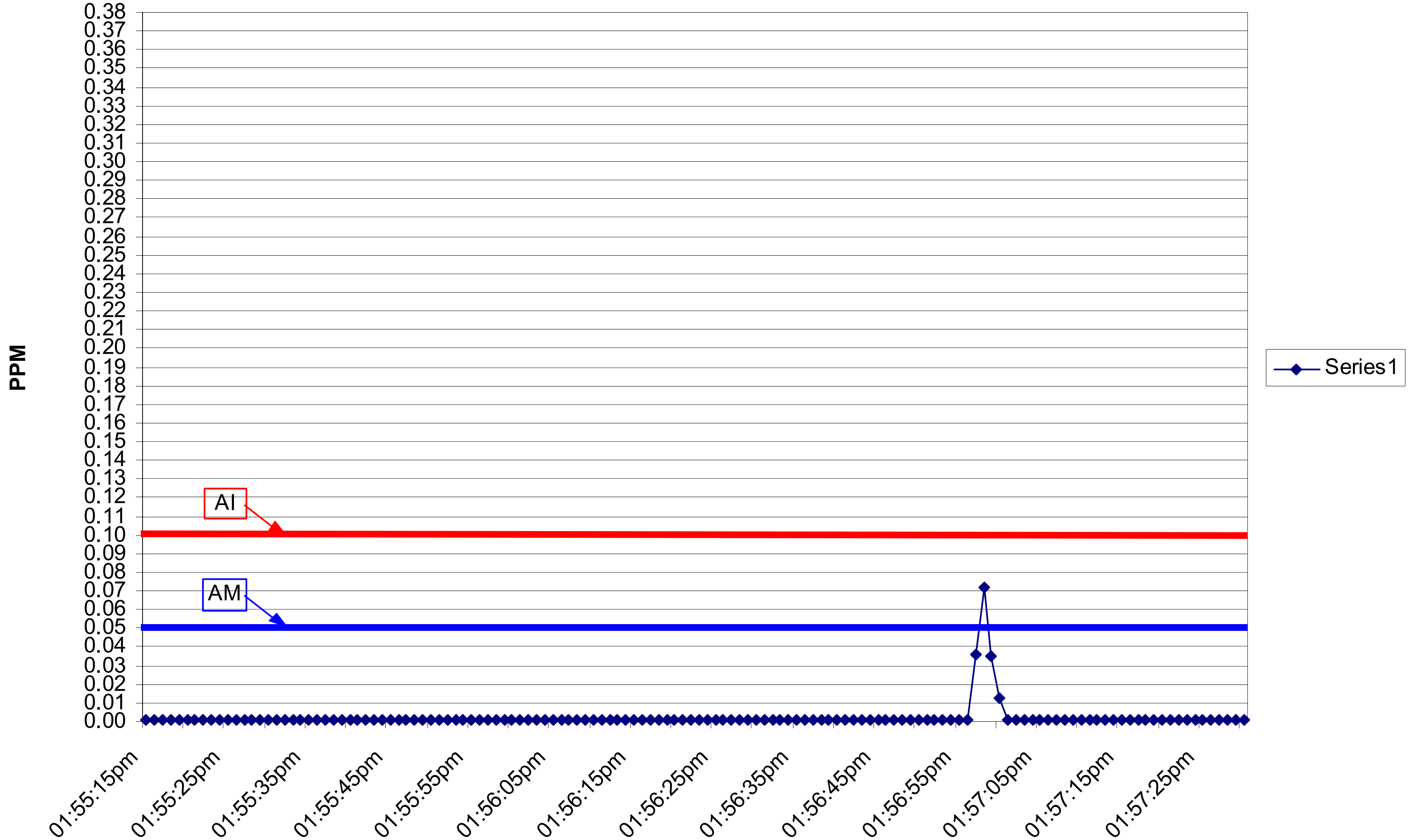
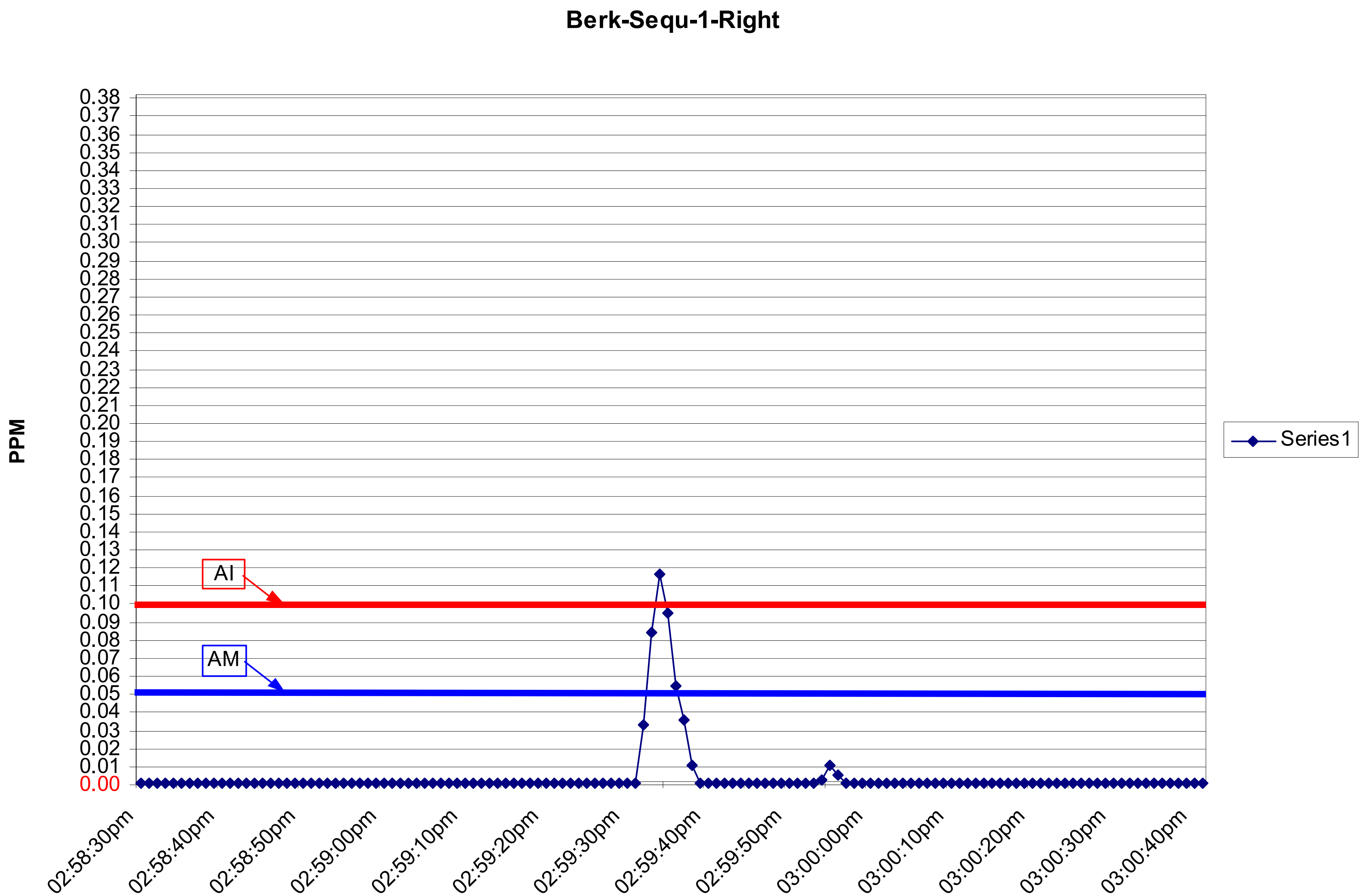
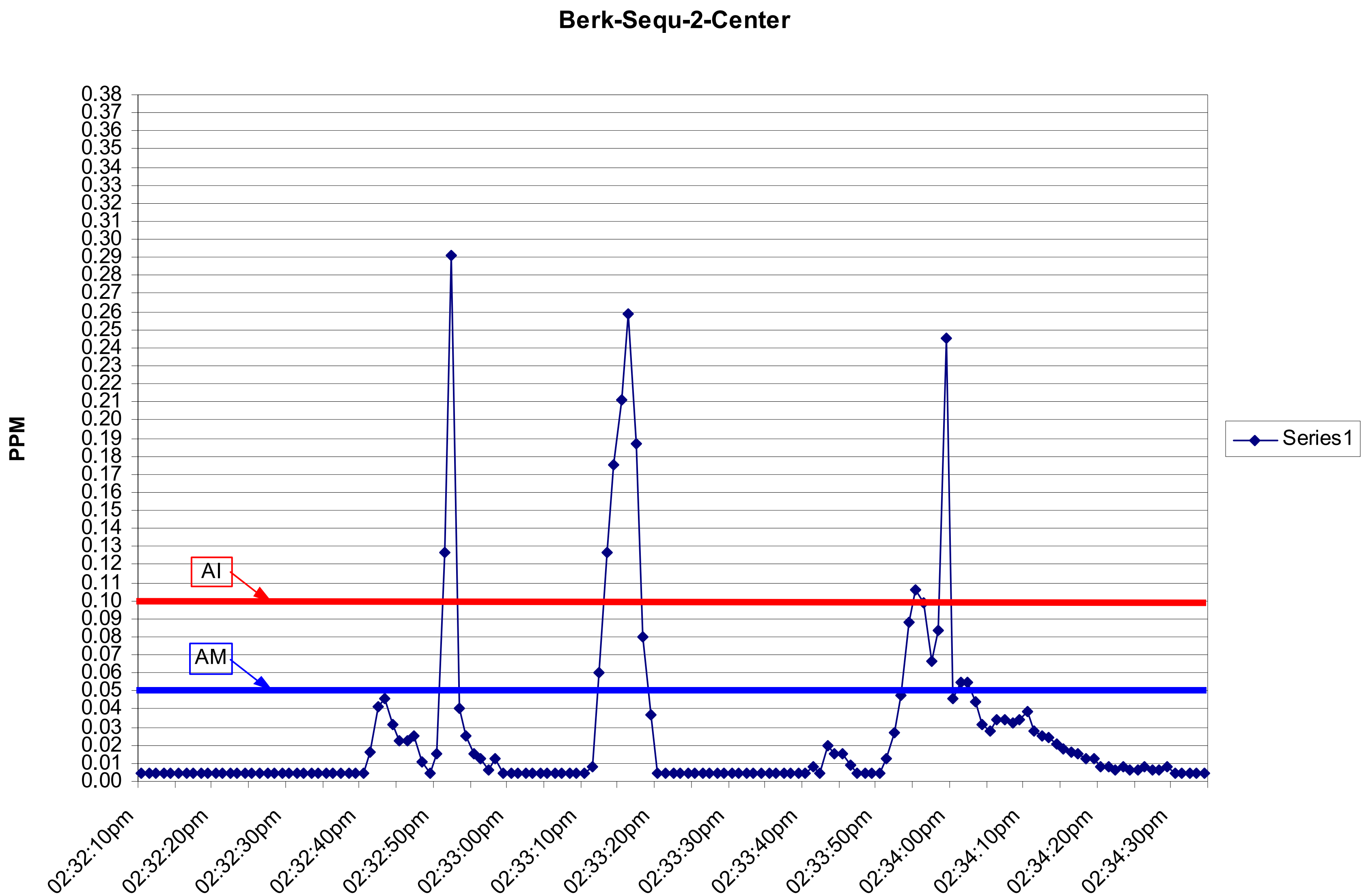
Series1

Berk-Sequ-1-Left




Berk-Sequ-1-Right
PPM
0.38
0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
AI
AM
02:58:30pm
02:58:40pm
02:58:50pm
02:59:00pm
02:59:10pm
02:59:20pm
02:59:30pm
02:59:40pm
02:59:50pm
03:00:00pm
03:00:10pm
03:00:20pm
03:00:30pm
03:00:40pm
Series1


Berk-Sequ-2-Center
PPM
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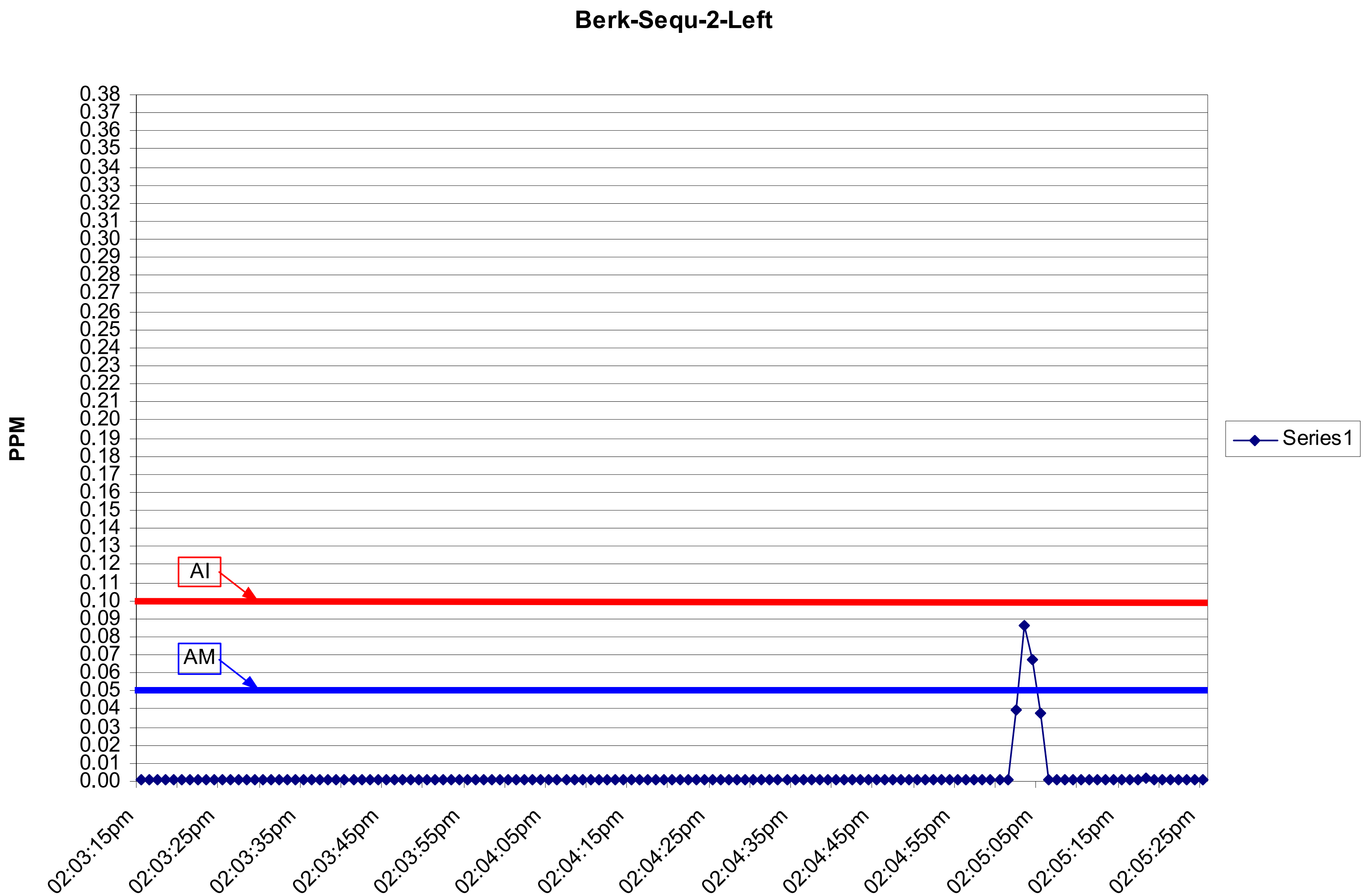
0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
AI
AM
Series1
02:32:10pm
02:32:20pm
02:32:30pm
02:32:40pm
02:32:50pm
02:33:00pm
02:33:10pm
02:33:20pm
02:33:30pm
02:33:40pm
02:33:50pm
02:34:00pm
02:34:10pm
02:34:20pm
02:34:30pm


Berk-Sequ-2-Left
PPM
0.38
0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
AI
AM
Series1
02:03:15pm
02:03:25pm
02:03:35pm
02:03:45pm
02:03:55pm
02:04:05pm
02:04:15pm
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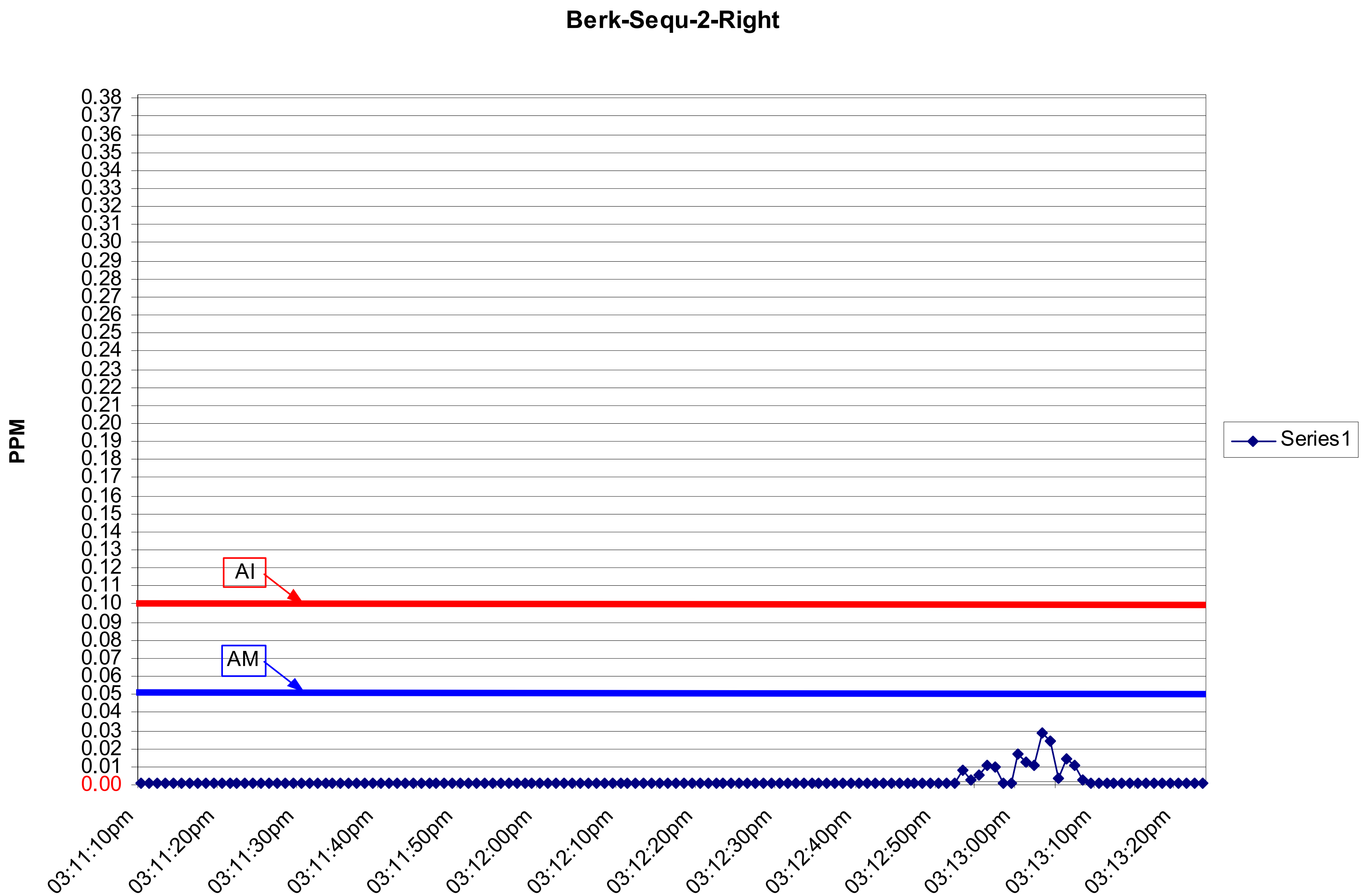
02:04:35pm
02:04:45pm
02:04:55pm
02:05:05pm
02:05:15pm
02:05:25pm


Berk-Sequ-2-Right
PPM
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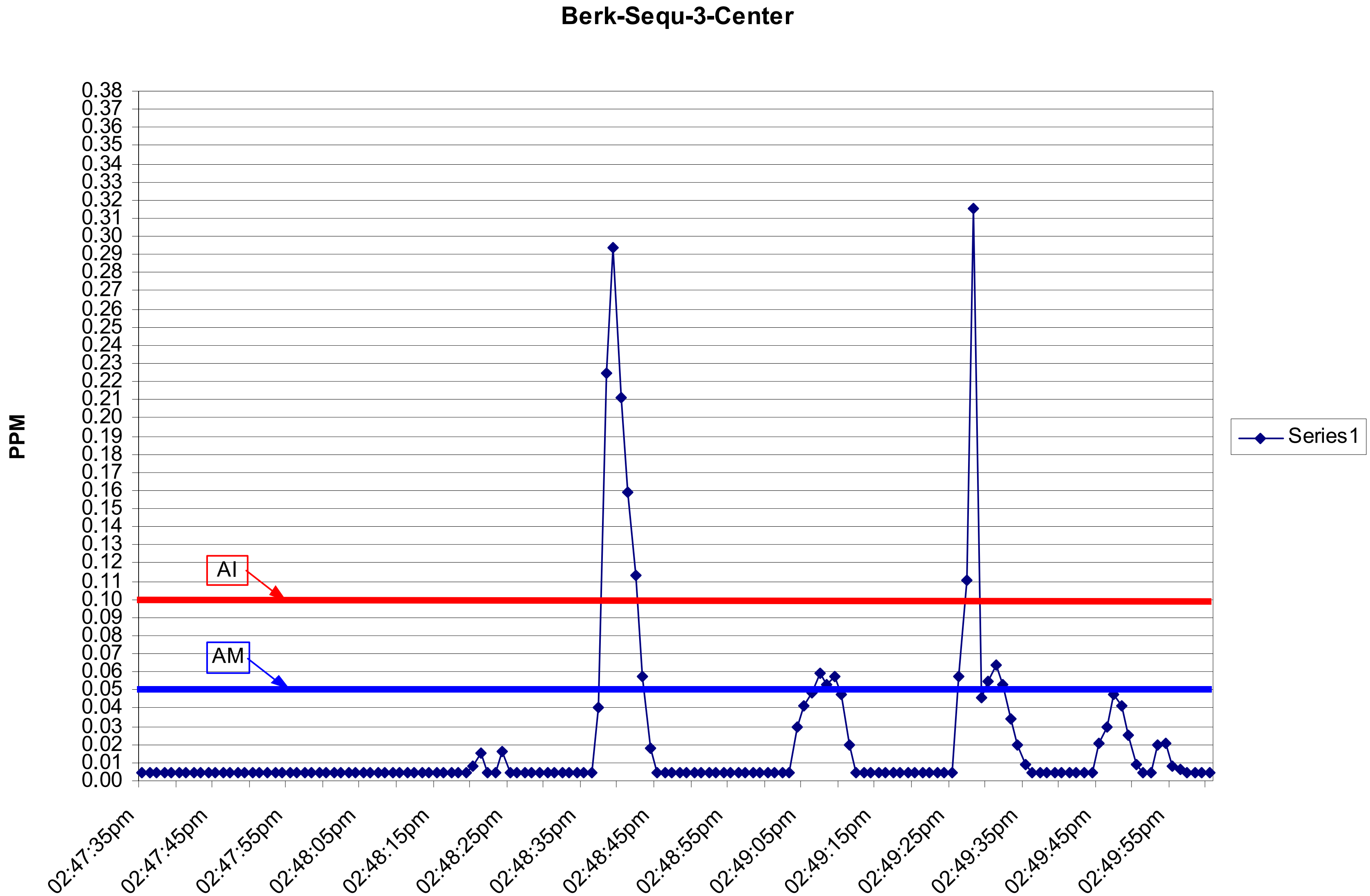
0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
AI
AM
Series1
03:11:10pm
03:11:20pm
03:11:30pm
03:11:40pm
03:11:50pm
03:12:00pm
03:12:10pm
03:12:20pm
03:12:30pm
03:12:40pm
03:12:50pm
03:13:00pm
03:13:10pm
03:13:20pm


Berk-Sequ-3-Center
PPM
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0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
AI
AM
Series1
02:47:35pm
02:47:45pm
02:47:55pm
02:48:05pm
02:48:15pm
02:48:25pm
02:48:35pm
02:48:45pm
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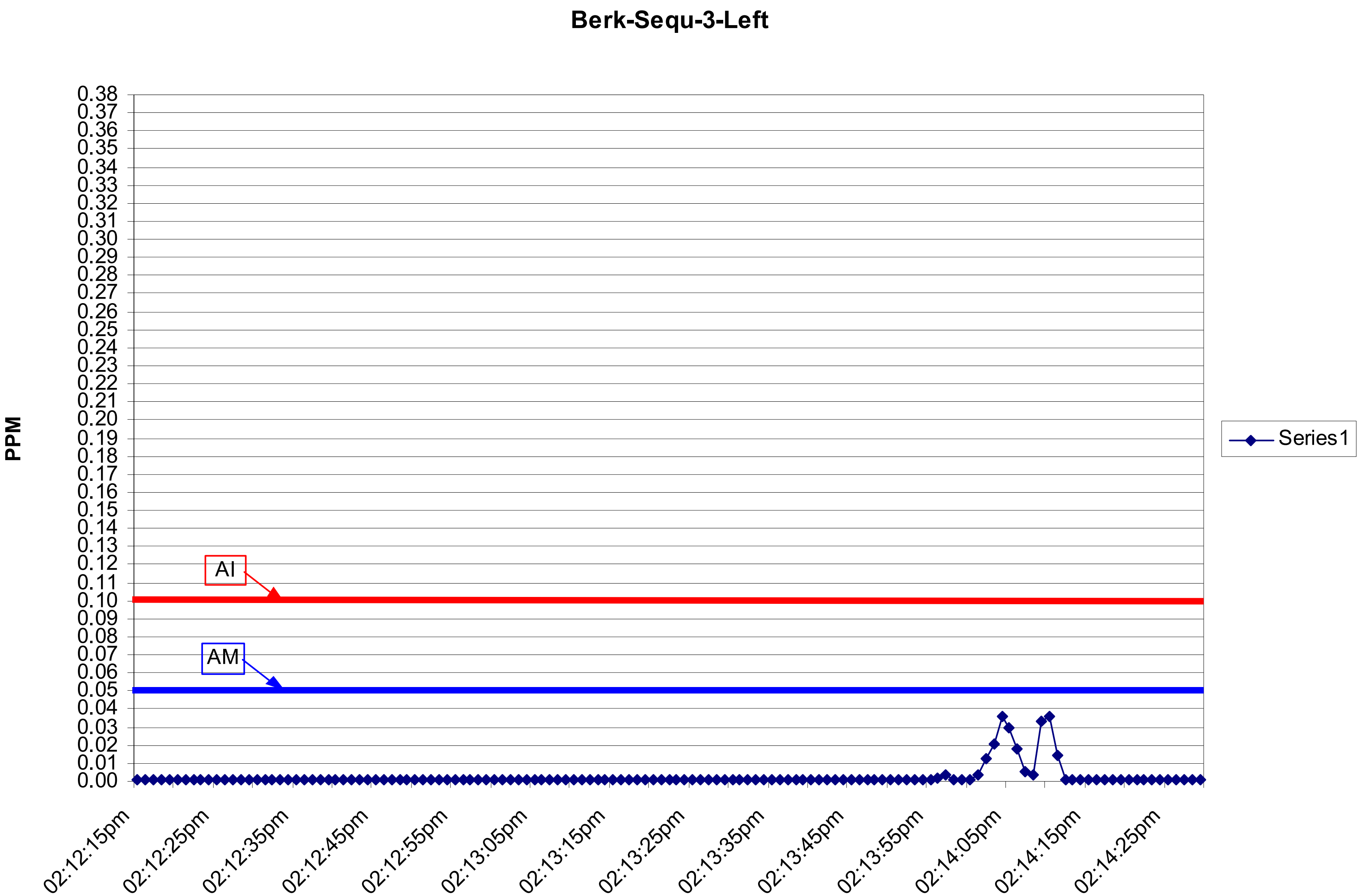
02:49:45pm
02:49:55pm


Berk-Sequ-3-Left
PPM
0.38
0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
AI
AM
Series1
02:12:15pm
02:12:25pm
02:12:35pm
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02:13:05pm
02:13:15pm
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02:13:35pm
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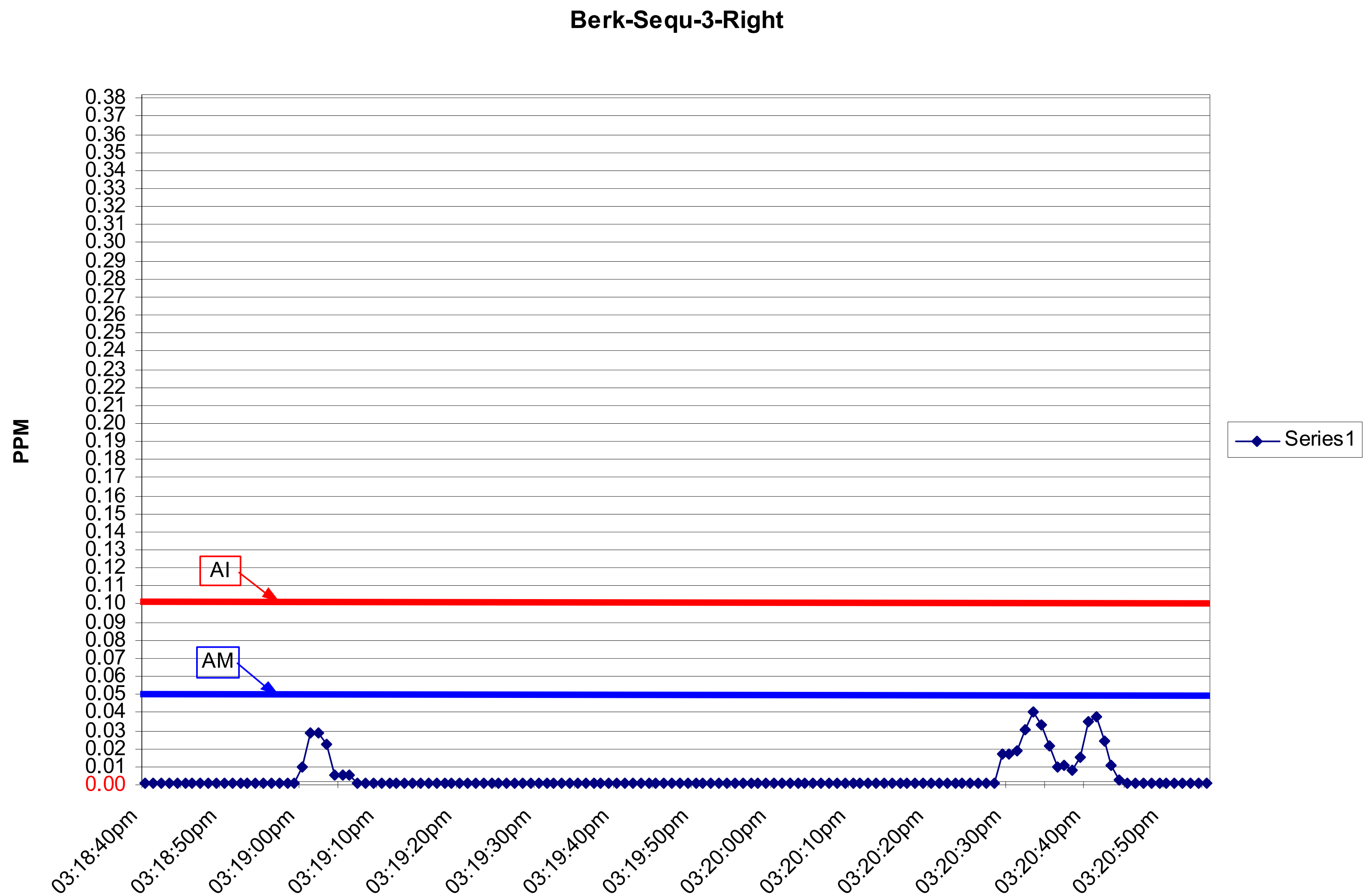
02:13:55pm
02:14:05pm
02:14:15pm
02:14:25pm


Berk-Sequ-3-Right
PPM
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0.36
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0.34
0.33
0.32
0.31
0.30
0.29
0.28
0.27
0.26
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0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
AI
AM
Series1
03:18:40pm
03:18:50pm
03:19:00pm
03:19:10pm
03:19:20pm
03:19:30pm
03:19:40pm
03:19:50pm
03:20:00pm
03:20:10pm
03:20:20pm
03:20:30pm
03:20:40pm
03:20:50pm