Lawrence Berkeley National Laboratory

California Energy Commission

“Side by Side” Fume Hood Tests Using ASHRAE 110 and “Human As Mannequin” (HAM) Test Methodology to Compare Performance of a Jamestown Conventional Fume Hood and a LBNL High Performance Hood

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INTRODUCTION and SUMMARY

Exposure Control Technologies, Inc. was contracted by the Lawrence Berkeley National Laboratory (LBNL) to conduct a series of modified ASHRAE 110 tests to compare performance of a conventional 6-ft, Jamestown Isolator fume hood (standard hood) and a 6-ft, high performance, fume hood designed by LBNL. With the assistance of Geoffrey Bell and Doug Sullivan of LBNL, the performance tests were conducted on January 11-13, 2005 in Building 63 on the LBNL campus located in Berkeley, CA. The hoods were installed side by side and exhausted by independent exhaust systems of similar design.

Both hoods were tested with the vertical sashes raised to full open that provided nearly equivalent opening areas of approximately 12 ft^2. The standard hood was tested at an exhaust flow of approximately 1200 cfm and the LBNL fume hood had an exhaust flow of approximately 670 cfm resulting in measured and calculated inflow face velocities of 98 fpm and 56 fpm, respectively. The performance tests included:

- Face velocity tests,
- Cross draft velocity tests,
- Airflow visualization (smoke tests),
- Static Mannequin tracer gas tests and
- “Human as Mannequin” tracer gas tests.

The tests were used to define the operating conditions and compare performance of the hoods when operating under similar environmental conditions. Where applicable, the tests were conducted according to the ANSI/ASHRAE 110 “Method of Testing Performance of Laboratory Fume Hoods.” However, the “Human as Mannequin” tests were unique and conducted according to procedures developed by LBNL in consultation with the California Occupational Safety and Health Administration (CAL/OSHA). The “Human as Mannequin” tests involved standing in place of the mannequin and conducting a series of choreographed procedures while generating tracer gas in the hood and sampling air near the breathing zone. Concentrations detected in the breathing zone could indicate escape from the hood and potential for inhalation and exposure. Therefore, the results of the static mannequin (SM) tracer gas tests and the “Human as Mannequin” (HAM) tracer gas tests were used to evaluate and compare hood performance. Refer to the section entitled “Methodology” for a more complete description of test procedures and performance criteria.

Summary of Results

The results indicate that when tested side by side and under the prevailing operating conditions, the performance of the LBNL hood operating at 43% less exhaust flow was equivalent to the performance of the standard or conventional fume hood. Average tracer gas concentrations from the static mannequin tests and the HAM tests were significantly less than 0.1 ppm recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) and the AIHA/ANSI Z9.5 American National Standard for Laboratory Ventilation. Average concentrations for both hoods were less than 0.05 ppm and the differences between the hoods were within the limits of instrument accuracy and expected error considering the variable challenge posed by exhaust re-entrainment and other factors. Refer to Figure 1 for results of the static mannequin tests and Figure 2 for results of the HAM tests.

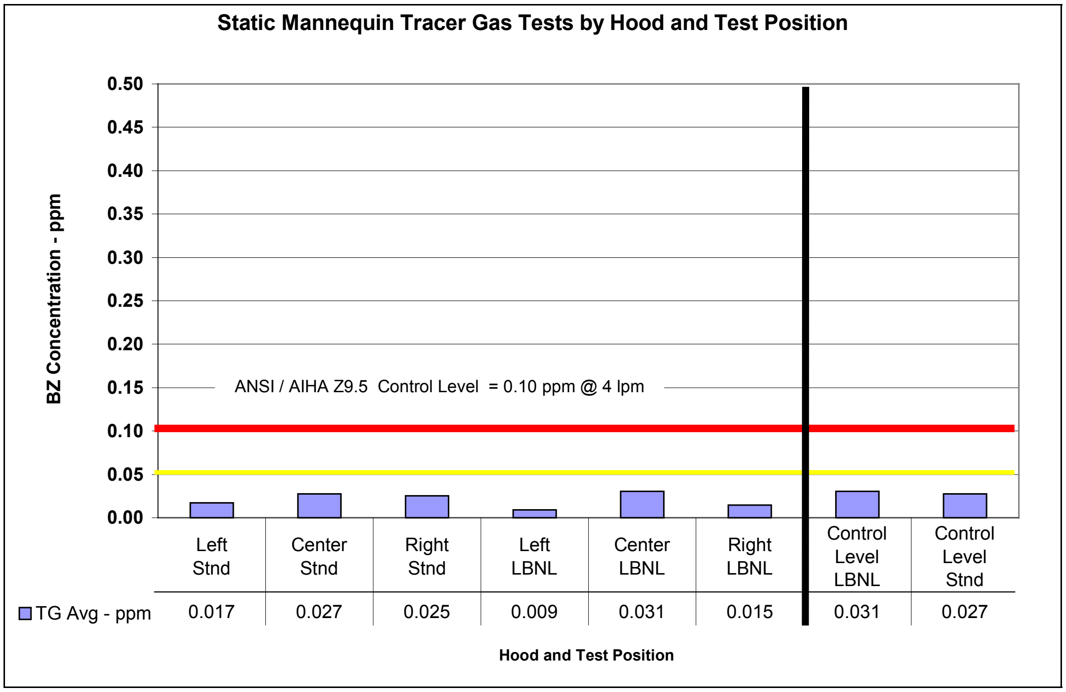

Figure 1 Results of static mannequin tracer gas test results showing average concentrations and control level for each hood and test location.

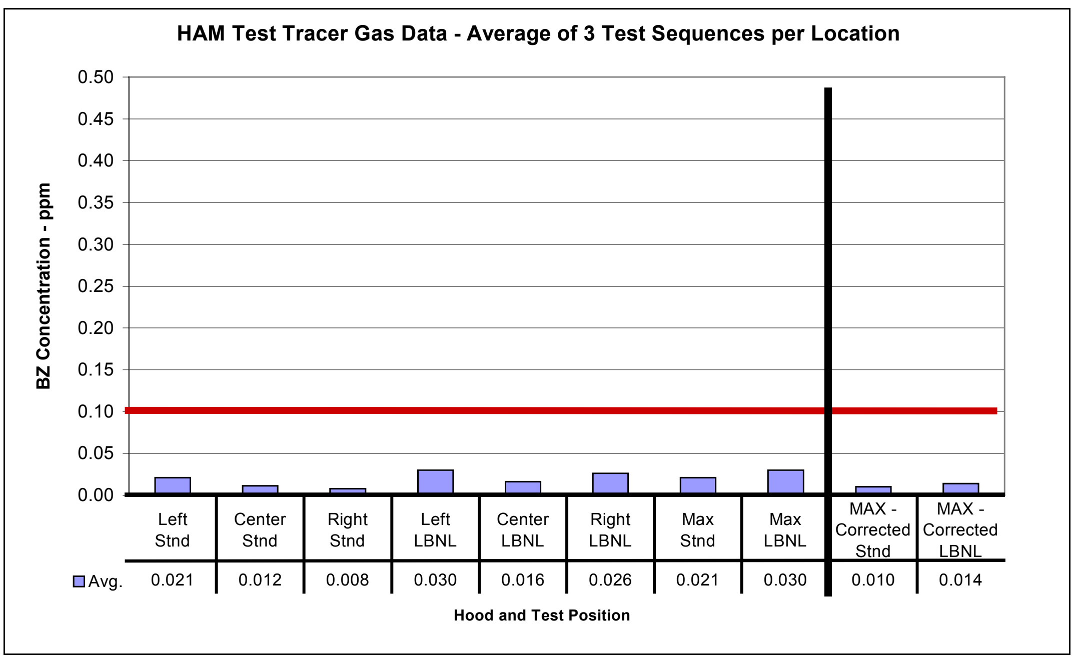

Figure 2 Results of HAM tracer gas tests showing average concentrations and control level for each hood and test location.

Despite the low average concentrations, the test results were very revealing and demonstrated the necessity of tracer gas tests to evaluate performance of a hood system. In addition, the HAM test with slight modification has particular value as a training tool to better understand the impact of work practices on hood containment.

Refer to the section "Results" for a more complete description of test results, tabulated summaries of data and plots of breathing zone concentrations for each tracer gas test.

Data contained in this report are indicative of performance of the laboratory hoods and ventilation systems at the time and date of the investigation. Any questions concerning information or conclusions contained within this report should be referred to Exposure Control Technologies. We welcome your questions, comments and suggestions concerning the report and we thank the Lawrence Berkeley National Laboratory and the California Energy Commission for the opportunity to participate in this project.

Testing and evaluation were performed by:

Thomas C. Smith
President
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METHODOLOGY

The objective of the study was to compare performance of a commercially available fume hood of conventional design and a high performance, fume hood designed by LBNL. Both hoods were fabricated by Jamestown Metal Products and installed side by side in Building 63 on the LBNL campus located in Berkeley, CA. The hood representing conventional design (Standard) was a 6-ft, Jamestown Isolator Fume Hood having a vertical sliding sash that enabled a maximum opening area of approximately 12.06 square feet (62 inches wide by 28 inches high). The standard hood was equipped with all components of a typical conventional fume hood including an airfoil sill, three slot baffle and angled entries. The face velocity for the standard hood was approximately 98-fpm with a calculated exhaust flow of approximately 1180-cfm.

The LBNL hood was of similar size but of different design. The opening area with the vertical sash full open was approximately 12.01 square feet (61.75 inches wide by 28 inches high). Air is supplied at the top and bottom of the opening using four small fans that draw air from the room to provide an air curtain (air divider) near the plane of the sash. In theory, the air curtain helps to prevent escape of materials generated within the hood and thereby reduces the need for high face velocities to provide capture and containment. The intent of this design is to reduce energy use by reducing the total volume of exhaust required to maintain containment. The exhaust flow for the LBNL hood was approximately 670 cfm or 43% less flow than the standard hood. However, the supply of air at the plane of the sash obviates the typical measurement of face velocity due to the non-perpendicular velocity vectors produced by the air curtain. Dividing the exhaust flow by the opening area provides an equivalent face velocity of approximately 56-fpm.

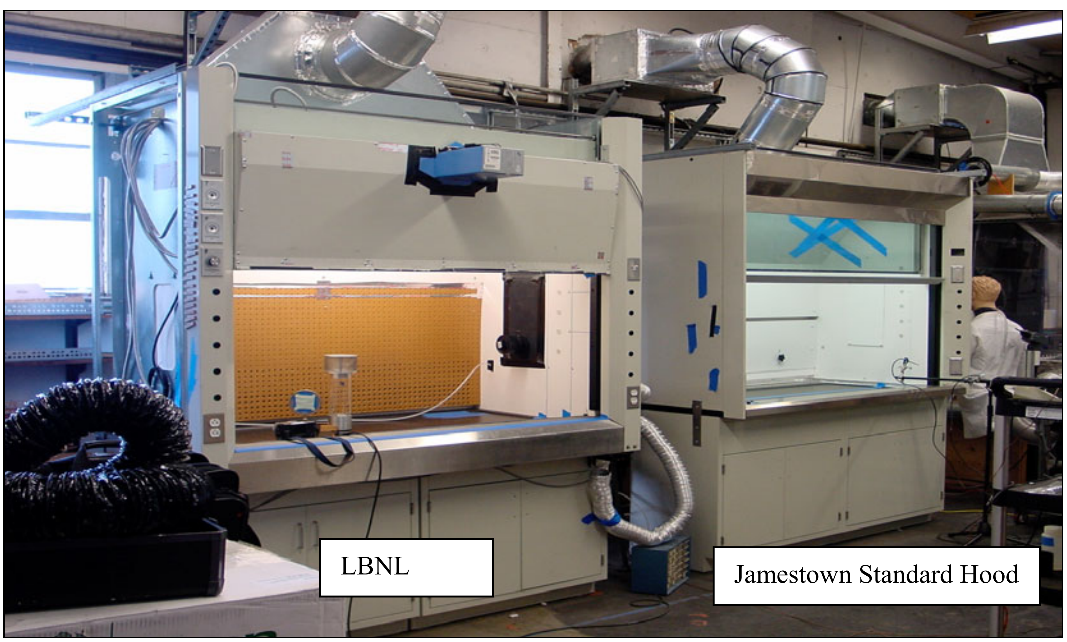

Figure 3 Photo of the LBNL hood and the Jamestown Standard Hood installed for side by side testing in the LBNL test lab.

Hood Performance Tests

The performance tests were conducted on both hoods over several long days from January 11, 2005 through January 13, 2005. The performance tests included:

- Measurement of Face Velocity
- Measurement of Cross Draft Velocities
- Visualization of Airflow Patterns
- Measurement of Tracer Gas Containment
  - Static Mannequin Tests
  - Human as Mannequin Tests

The test lab is located in a metal-sided building that was cold in the morning and warmed as the day progressed. It was suspected that the test results could be affected by the changing climatic conditions. To minimize differences between operating conditions and reduce potential variables associated with changing climatic conditions, attempts were made to conduct each test sequentially on both hoods. With the exception of the Human as Mannequin Test, the tests were conducted according to procedures described in the ANSI/ASHRAE 110 "Method of Testing Performance of Laboratory Fume Hoods." The Human as Mannequin Tests were conducted according to the LBNL procedure developed in consultation with CAL/OSHA. The individual test procedures are briefly described below.

Face Velocity Tests

Face velocity is measured to determine the speed of air entering the hood opening. The face velocity tests were performed by dividing the sash opening into equal area grids of no more than one square foot and measuring the velocity using a fixed probe located at the center of each grid (Figure 4). Air velocities were recorded every second for twenty seconds at each grid location using a calibrated thermoanemometer. The means of the grid velocities were averaged to determine the overall average face velocity. Although face velocities were measured on the LBNL hood, the perimeter air supply prevented accurate measurement and determination of average face velocity. Therefore, the equivalent face velocity for the LBNL hood was determined by dividing the exhaust flow by the opening area. The supply velocities at the top and bottom of the opening were not measured as it was assumed that the supply flow was adjusted to LBNL specifications.

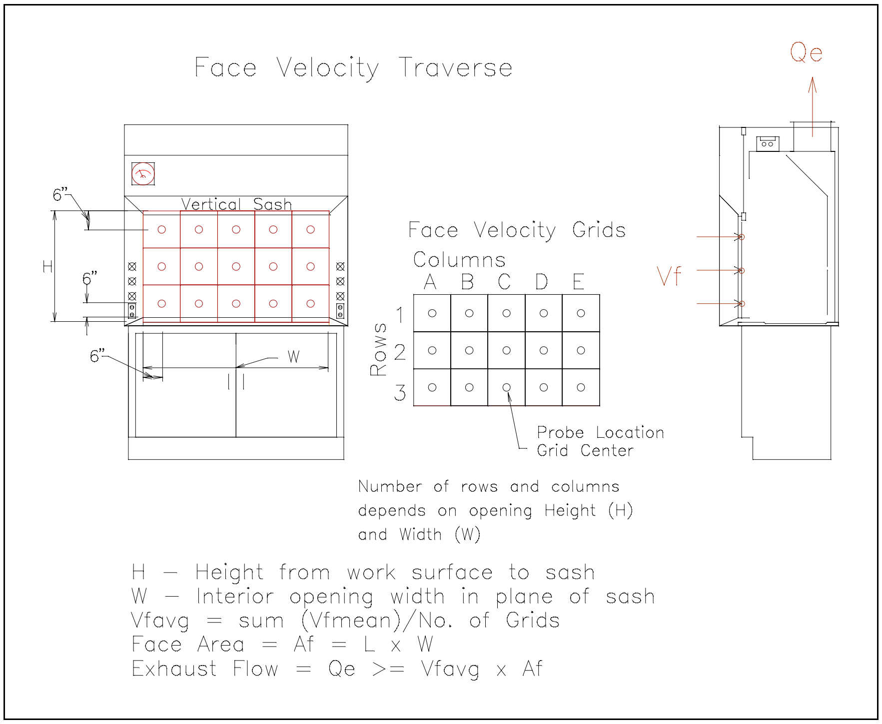

Figure 4: Diagram of hood opening showing face velocity traverse locations

Cross Draft Tests

Room air currents can pose a significant challenge to hood performance. Cross draft air velocities are measured to provide an indication of comparable operating conditions. Vertical and horizontal cross drafts were measured in front of the hood openings using two calibrated thermoanemometers. Measurements were made with the probes positioned parallel to the side edge of the hood approximately five feet above the floor and approximately 18 inches in front of the hood opening. Cross draft velocities were recorded every second for thirty seconds at each test location.

Airflow Visualization Tests

Smoke was generated in the hood and around the periphery of the opening using a Rosco Fog Generator and $TiCl_4$ smoke sticks. Smoke was generated along the periphery of the opening and inside the hood at approximately six inches inside the plane of the sash. Smoke patterns were observed to identify escape and reverse flow zones. Observations were rated subjectively based on the subjective ECT rating table provided in the following section "Recommended Performance Criteria."

Static Mannequin Tracer Gas Tests

The static mannequin tracer gas containment tests were conducted to evaluate and quantify the potential for escape with a mannequin located in front of the hood opening. A mannequin is used to simulate the presence of a hood user. The mannequin was positioned at the left, center and right side of the hood opening with the nose approximately three inches in front of the plane of the sash. The mannequin height was approximately 67 inches.

A tracer gas, Sulfur Hexafluoride, was released at 4 liters per minute (lpm) through an ASHRAE 110 ejector. The ejector was located approximately 6 inches behind the plane of the sash directly in front of the mannequin. Breathing zone concentrations were measured every second for five minutes in each test location using a calibrated ITI Model 200 Leakmeter. The Leakmeter was calibrated against a calibration gas standard immediately prior to the start of tests. The limit of detection was 0.01 ppm with a maximum scale reading of approximately 1.9 ppm (actual concentrations may be higher than the maximum scale reading of approximately 1.9 ppm).

The static mannequin tracer gas tests were repeated various times at the center test position to evaluate stability of performance, impact of environmental conditions and to characterize exhaust re-entrainment. The results of all tests on the center hood were averaged for the comparison of hood performance. The highest average concentration found at any test location is reported as the control level.

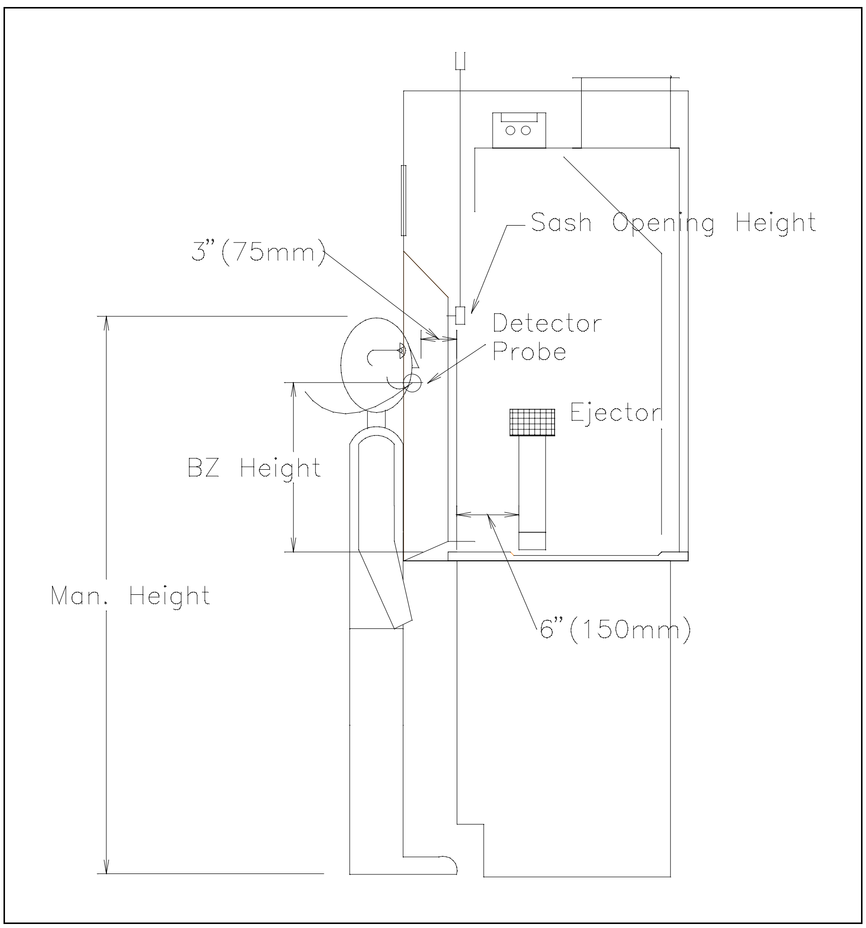

Figure 5 Configuration of mannequin at hood opening during tracer gas tests.

Human as Mannequin Tracer Gas Tests (HAM)

The HAM tests were conducted to provide a dynamic challenge to hood performance by using a person in place of a mannequin and conducting a series of choreographed activities in the hood. Tracer gas is generated using the ASHRAE 110 ejector in the same locations and at the same rate as the static mannequin tests. A short length of tubing is connected to the tracer gas detector and fixed near the mouth of the person using the microphone boom on a hands-free telephone headset. The photos in Figures 6 and 7show Thomas Smith of ECT conducting the HAM test.

The HAM tests involve conducting a series of choreographed activities using objects located within the hood. The objects consist of a beaker, two bottles and a small box that are arranged in specific patterns depending on the test location and manipulated according to a scripted sequence (See photo of objects in Figure 8). The timed sequence of activities includes:

1. Stand at hood opening with arms to side.
2. Insert and remove hands and arms
3. Move objects from six inch line to twelve inch line
4. Exchange position of objects
5. Transfer liquid from 250 ml bottle to 500 ml beaker
6. Grasp bottle, remove from hood and rotate 90 degrees from opening.

Each sequence of activities is conducted over a period of approximately 150 seconds. For more information refer to the LBNL HAM Test procedures described in the September 8, 2004 LBNL report entitled *Side by Side Fume Hood Testing: Human-as-Mannequin Report*.

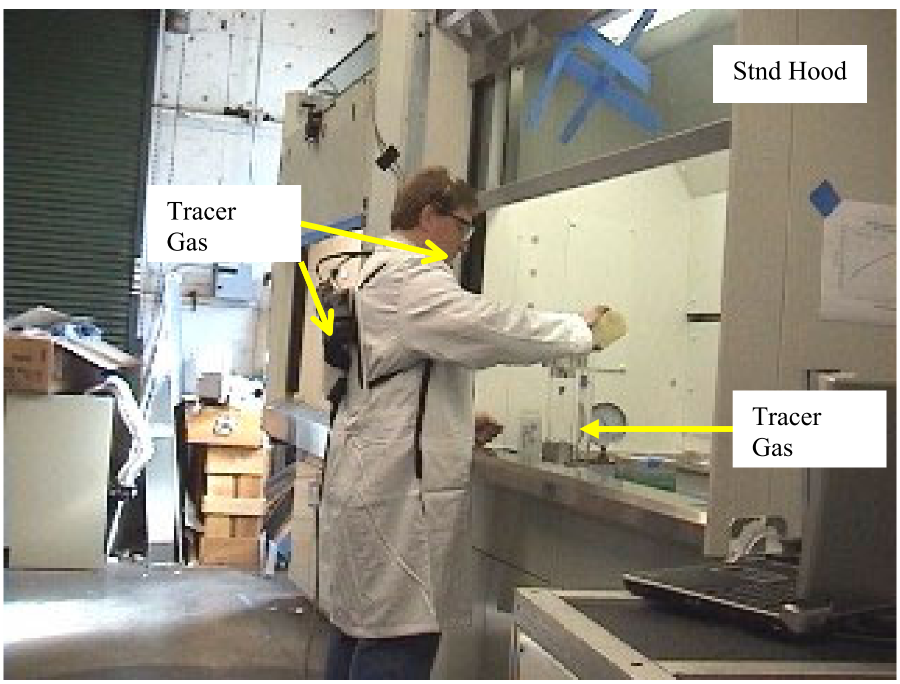

Figure 6 Photo of Tom Smith of ECT pouring liquids during a HAM test.

Each test sequence is timed and concentrations of tracer gas are measured every second for the duration of the test sequence. The sequence of tests is repeated three times at the left, center and right test locations. The data from the three test sequences are combined and analyzed to determine the average breathing zone concentration for each test location. For academic purposes, the procedures were reversed at the completion of each 150 seconds sequence to extend the test over five-minutes so that data could be compared to the static mannequin tests. Future modification of the HAM test procedure should consider a sequence of activities that require five minutes to complete.

Figure 7 Photo of Tom Smith moving objects in hood during HAM Test.

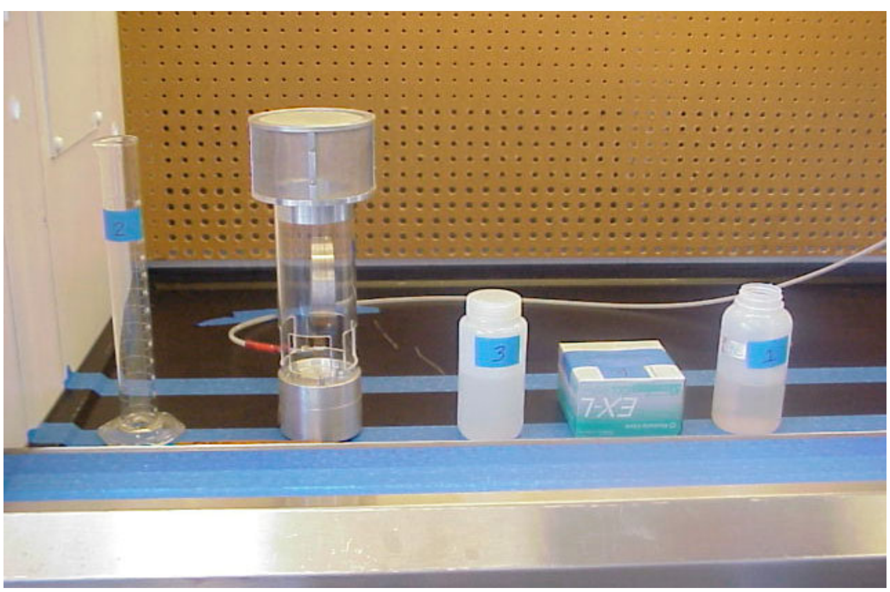

Figure 8 Photo of objects located in hood and manipulated during HAM Test procedures

RECOMMENDED PERFORMANCE CRITERIA

The following criteria were gathered from industry consensus standards (ANSI Z9.5, ACGIH and ASHRAE) or used by ECT in the evaluation of hood performance. The criteria are provided here to assist with evaluating test data and define the criteria used to evaluate and compare performance. The criteria apply to the following tests:

Smoke Visibility Test - Hood must provide complete containment of the smoke generated within the hood. Containment is determined visually and in the absence of the mannequin. ECT rates the observations of airflow patterns as a qualitative judgment of airflow distribution according to the following rating guide:

Table 1. ECT qualitative smoke visualization rating chart

RATING	DESCRIPTION
FAIL	• Smoke was visually observed escaping from the hood
POOR (Low Pass)	• Reverse flow of smoke is evident within six inches of the plane of the sash when generated at least six inches behind the plane of the sash. • Lazy flow into hood along openings • Slow capture and clearance – greater than two minutes for clearance • Observed potential for escape
FAIR (Pass)	• Some reverse flow in hood not within six inches of opening • Smoke is captured and clears readily from interior of hood – less than two minutes • No visible escape
GOOD (High Pass)	• Good capture and relatively quick clearance – approximately 1 minute or less • No Reverse Flow Regions • No Lazy Flow • No visible escape

Face Velocity Test – Ventilation system should be capable of maintaining stable exhaust flow (no more than ± 5% variation) and achieve the target average face velocity within 5 fpm. The face velocity readings should not vary more than 20% of the mean between grid locations.

Cross Draft Test – Room air currents within the lab should not exceed 30 fpm within 24 inches of the hood opening.

Tracer Gas Challenge Test - Hood should provide containment of tracer gas below an average of 0.1 ppm measured for a period of five minutes in the breathing zone of a stationary mannequin positioned directly in front of the ejector location.

Human as Mannequin Test – There are no industry standards or published criteria for HAM tests. During consultation with Cal/OSHA, it was agreed that criteria for a high performance hood not meeting the face velocity requirements was to perform at least as well as a standard hood meeting the face velocity requirement or to provide containment below an average of 0.1 ppm.

TEST RESULTS

The results of the performance tests indicated that both hoods met industry recommended criteria for ASHRAE 110 tracer gas tests (static mannequin tests) and provided comparable performance during the HAM tests. The average concentrations for all tracer gas tests were below 0.1 ppm with average concentrations for many tests equal to or below the minimum limit of detection (approximately 0.01 ppm). The test results are summarized below.

Face Velocity Tests

The standard hood was operating at a face velocity of 98 fpm and a calculated exhaust flow of approximately 1,180-cfm. The LBNL hood was operating at approximately 670 cfm with a calculated face velocity of 56 fpm. The exhaust flow for the LBNL hoods was approximately 43% less than the Standard Hood.

Cross Draft Velocity Tests

The hoods were tested side by side in the test lab. The cross draft velocities were comparable with average velocities less than 30 fpm near the hood openings. The highest velocity was 25 fpm in the horizontal direction in front of the LBNL hood and the highest velocity was 22 fpm in the vertical direction near the Standard hood.

Smoke Tests

Both hoods provided containment of smoke generated at least six inches inside the plane of the sash. According to the subjective ECT rating scheme, the Standard hood rated “low pass” during both the low volume and the high volume smoke tests. The LBNL hood rated “low pass” during the low volume challenge and had a rating of “pass” during the high volume challenge.

Observation of the airflow patterns in the LBNL hood indicated reasonably uniform flow and capture at the baffle perforations and slots. The hood received a low pass rating during the low volume challenge as some minor reverse flow was observed within six inches of the opening when generated at the work surface (primarily due to the recess in the work surface). In addition, a vortex was observed inside the top of the hood with relatively slow but satisfactory clearance. Entrainment of smoke in the vortex region required generation of smoke in the top of the hood.

Observation of smoke patterns in the Standard hood indicated rather poor airflow patterns with considerable reverse flow above the work surface and some eddying above the airfoil sill. In addition, a very turbulent vortex was observed behind the raised sash with significant eddying observed below the sash pull. Furthermore, smoke generated at the work surface was entrained in the vortex region at the top of the hood.

Static Mannequin – Tracer Gas Tests

Table 2 (below) provides a summary of the results from the static mannequin tracer gas tests and Figures 9-15 show the plots of breathing zone concentrations for each test. The results indicate that both hoods met the performance criteria with average concentrations less than 0.1 ppm. The highest concentration for both hoods occurred at the center test position producing equivalent control levels of 0.031 ppm for the LBNL hood and 0.027 ppm for the Standard Hood. The difference between average concentrations is not significant as the results are well within expected error considering the minimum limit of detection for the tracer gas detector was approximately 0.01 ppm and the results were confounded by re-entrainment of exhaust that varied depending on ambient wind conditions. Re-entrainment caused higher background concentrations during tests on the LBNL hood and slightly higher average concentrations. Refer to the section below entitled "Analysis of Re-entrainment" for more information about the impact of re-entrainment on test results.

Human As Mannequin Tests

The results of the HAM tests are provided in Table 3 and the plots of breathing zone concentrations are shown in Figures 16-33. The results indicate that the LBNL hood provided comparable performance to the Jamestown Standard hood during the HAM tests. The maximum series averages for the LBNL hood and the Standard hood were 0.030 ppm and 0.021 ppm, respectively. To account for the bias caused by re-entrainment; a correction factor was applied to both hoods resulting in a maximum average breathing zone concentration of 0.014 ppm for the LBNL hood and 0.010 ppm for the Jamestown Standard hood. Average concentrations found during the HAM tests were less than the static mannequin tests due to the impact of exhaust re-entrainment and the limited duration of the test sequences.

Analysis of Re-entrainment and Impact on Hood Performance

Although all of the tracer gas results indicated that average breathing zone concentrations were less than 0.10 ppm, re-entrainment of exhaust caused the average concentrations to be higher on the LBNL hood than the Standard hood. In addition, the magnitude of re-entrainment and the impact on average concentrations varied depending on the ambient wind conditions. A limited analysis of several tests conducted on both hoods was undertaken to determine the significance of the difference between average concentrations for the two hoods. The results were used to determine a correction factor that was applied to the results of the HAM tests.

The exhaust systems serving the hoods were of similar design and had the same stack height and stack discharge diameter. However, the LBNL hood was operating at approximately 43% less exhaust flow than the standard hood. The reduced flow resulted in a higher discharge concentration and a 43% lower stack velocity (Refer to Table 4). The increasing background concentrations were attributed to re-entrainment of the exhaust and the variability was attributed to changes in wind speed and wind direction. Wind speed and direction were affected by weather conditions and the time of day.

Smoke was used to visualize the exhaust plume from the individual exhaust stacks serving each hood. The photo in Figure 34 shows the upward directed plume discharged from the exhaust stacks under relatively calm wind conditions. The plume from the standard hood system was discharged with higher momentum and had less potential to envelop the building. The photo in Figure 35 shows the plume from both stacks with the wind blowing the plume over the building. The plume from the LBNL hood appears to have a higher potential to envelop the building and increase the potential for re-entrainment. The re-entrained concentrations are variable but the impact is to increase or bias the average tracer gas concentration.

Data from a series of tracer gas tests were analyzed to determine a correction factor that could be applied to the results of the HAM tests. The results of the limited analysis indicated that concentrations from re-entrainment could increase background concentrations on average of 0.016 ppm for the LBNL hood and 0.011 ppm for the standard hood during the 150 second HAM test sequence. The data used to determine the correction factor are plotted and tabulated in Figure 36. The plot in Figure 37 shows the potential difference between re-entrained concentrations for the LBNL hood and the standard hood.

Table 2 Summary of Static Mannequin Tracer Gas Test Data

Hood ID	Sash Opening	Sash Open Area - sq ft.	Avg. Fvel fpm	Calc. Exh. Flow-cfm	Left TG Avg ppm	Left TG Peak ppm	Center TG Avg ppm	Center TG Peak ppm	Right TG Avg ppm	Right TG Peak ppm	Horiz CD Max Avg fpm	Vert CD Max Avg	Smoke Rating	Other Notes
6-ft LBNL HP Hood	Vertical Full Open	12.01	56	670	0.009	0.081	0.045	0.111	0.015	0.150	25	17	Pass (Fair)	1/11/05 - Very Windy Conditions – Test 1
							0.017	0.042						1/13/05 – Cold in lab. – Test 2
Multiple Test Average							0.031	0.076						
6-ft JT STND Hood	Vertical Full Open	12.06	98	1181	0.017	0.150	0.098	1.974	0.025	0.150	11	22	Low Pass (Poor)	1/11/05 - Very Windy Conditions - Test 1
							0.016	0.032						1/12/05 at 10:30 a.m. – Test 2
							0.006	0.186						1/13/05 -9:25 a.m. Overcast, cool and relatively calm winds. – Test 3
							0.012	0.533						1/13/05 -9:25 a.m. Overcast, cool and relatively calm winds. – Test 4
							0.005	0.224						1/13/05 - 11:25 a.m. - Still cold in lab and outside but becoming windier. – Test 5
Multiple Test Average							0.027	0.590						

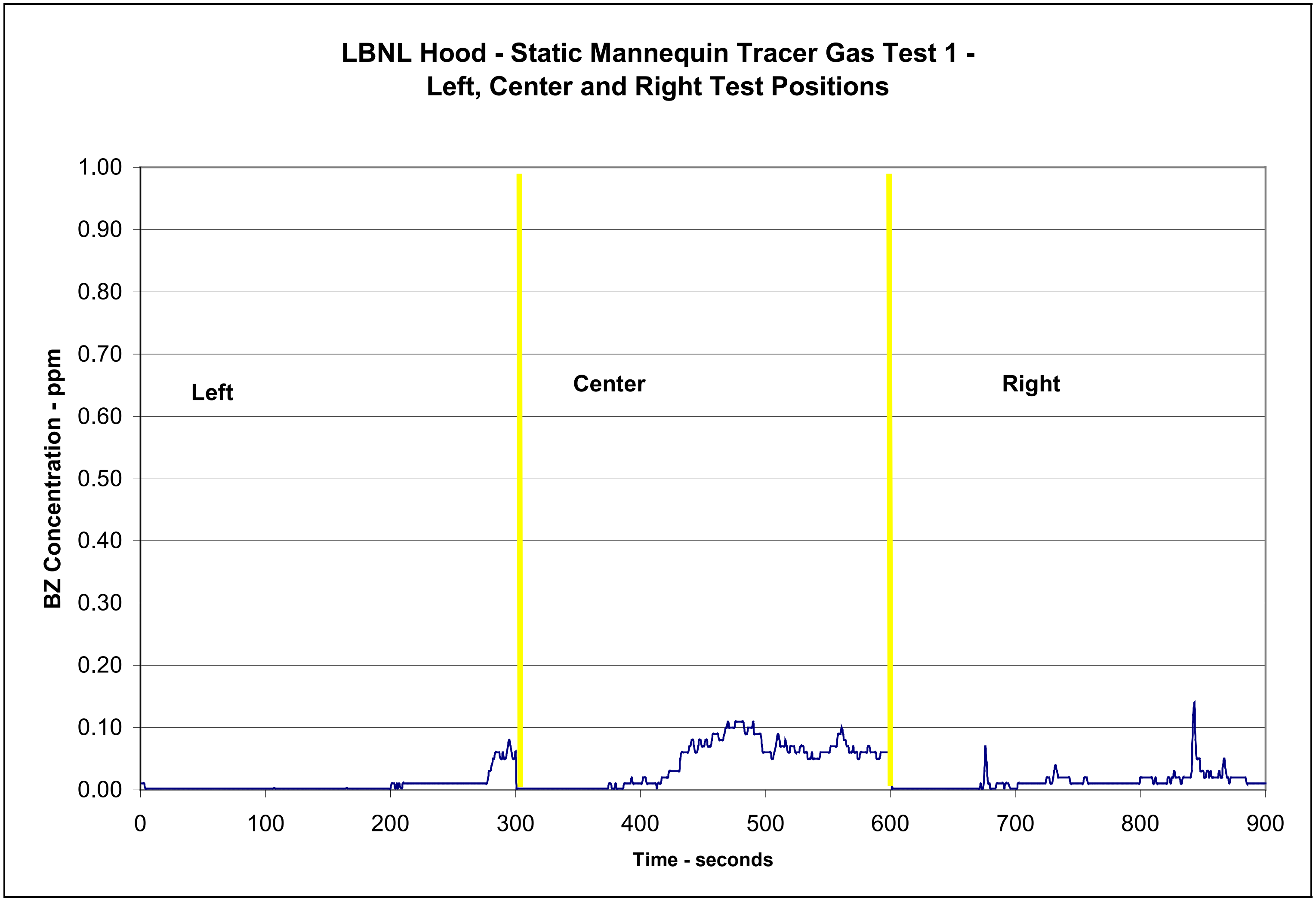

Figure 9 Plot of concentrations measured at each test position during a static mannequin tracer gas test on the LBNL hood.

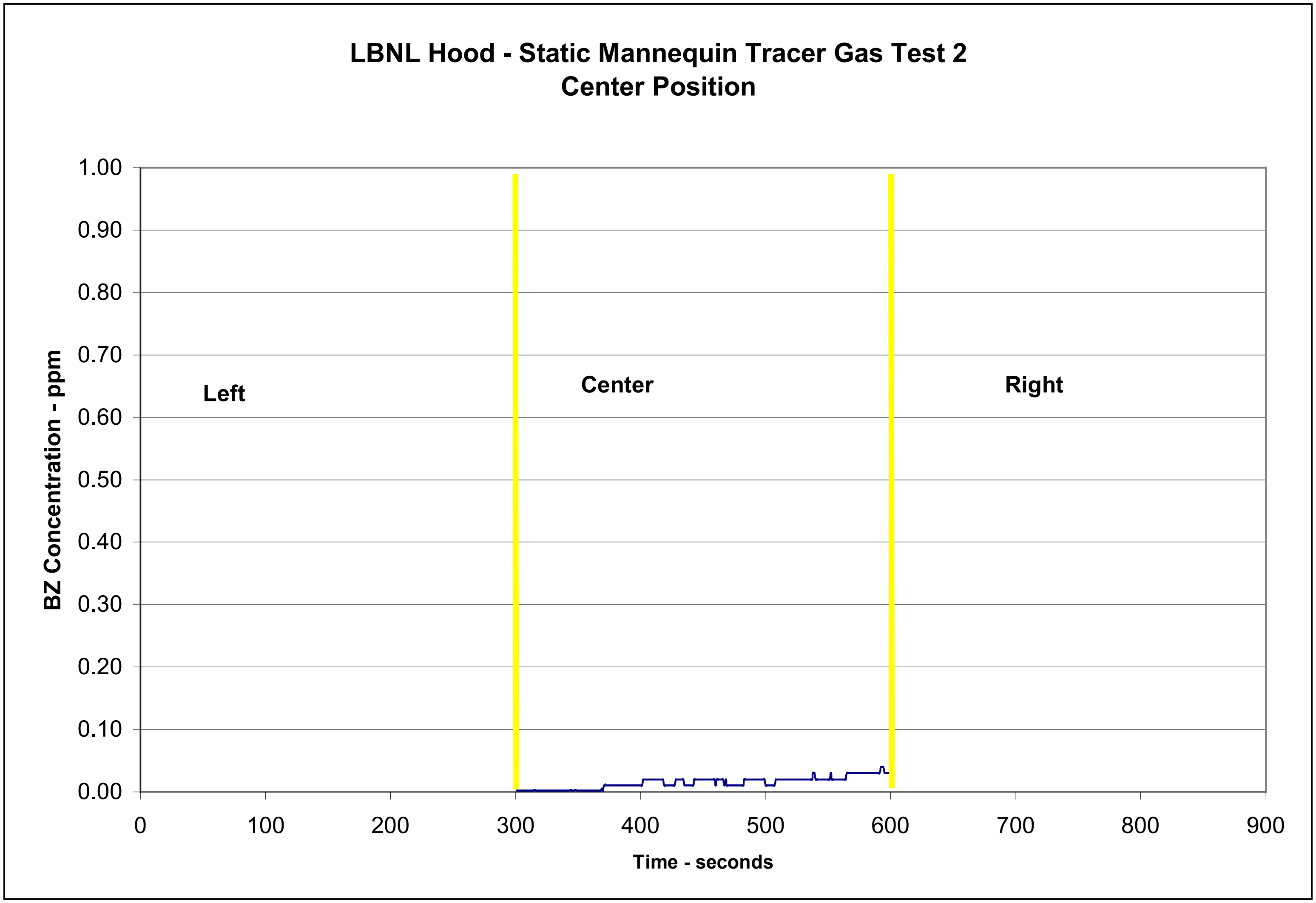

Figure 10 Plot of concentrations measured during a re-test at the center position during a static mannequin tracer gas test on the LBNL hood.

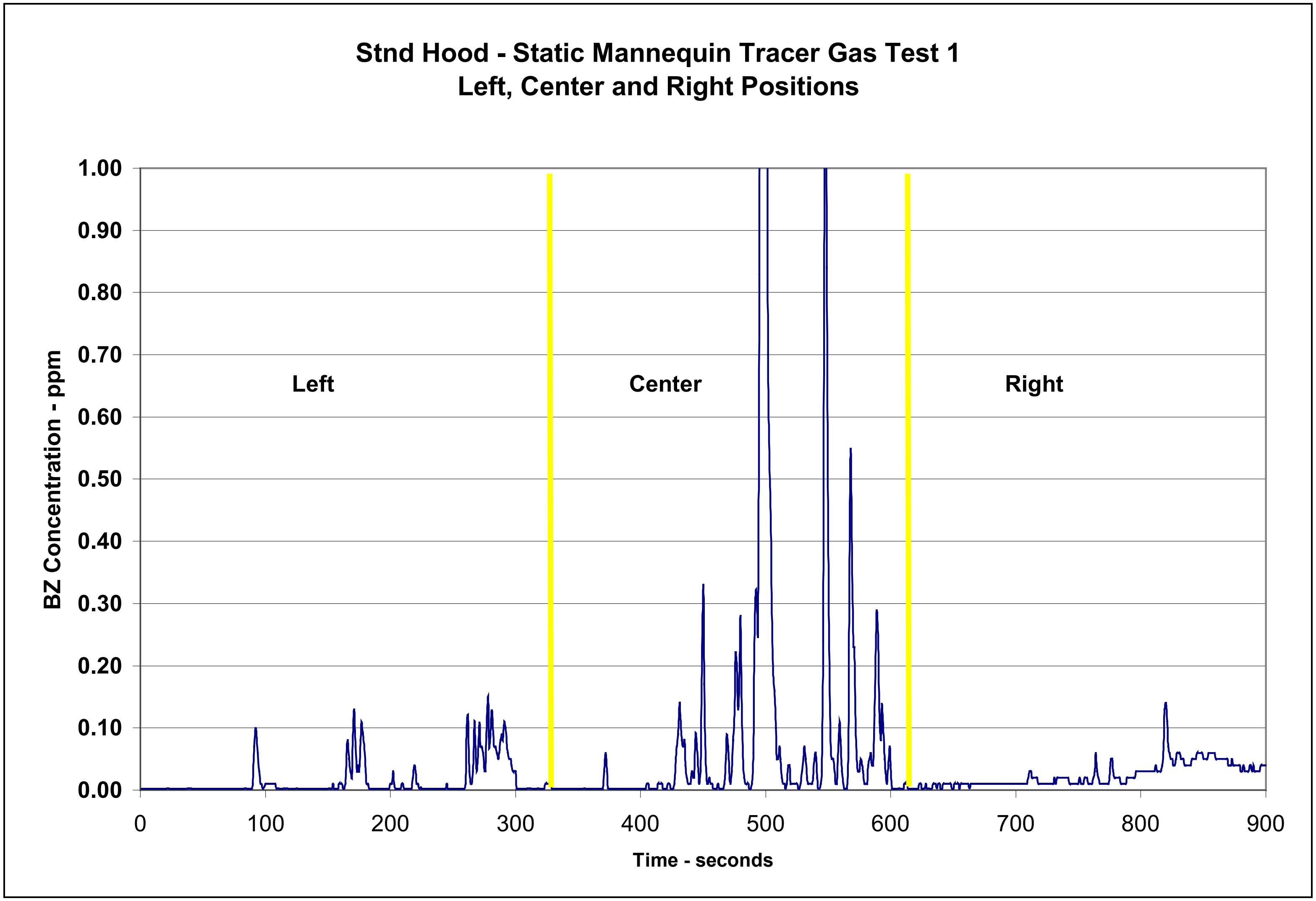

Figure 11 Plot of concentrations measured at each test position during a static mannequin tracer gas test on the standard hood.

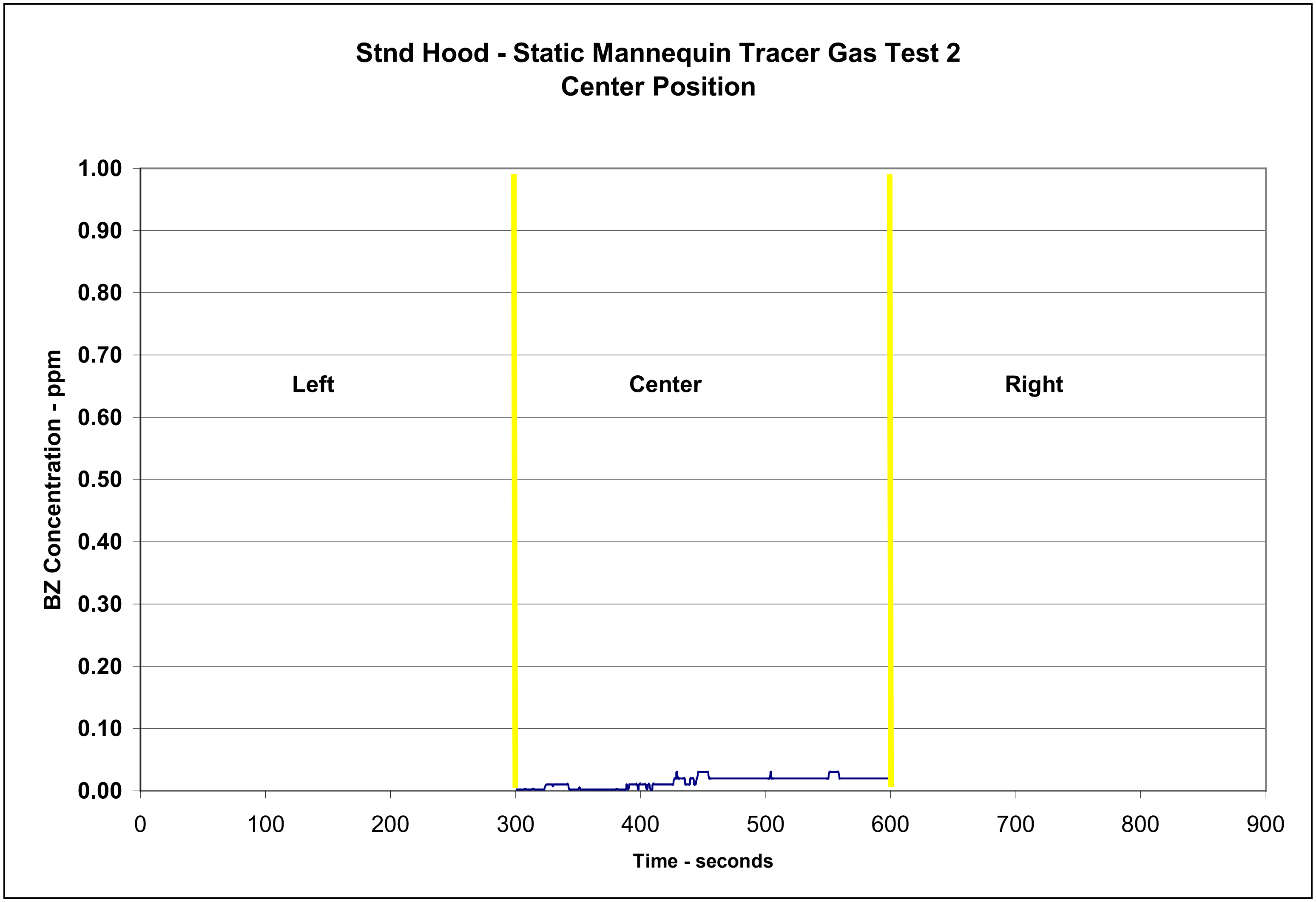

Figure 12 Plot of concentrations measured during a re-test at the center position during a static mannequin tracer gas test on the standard hood.

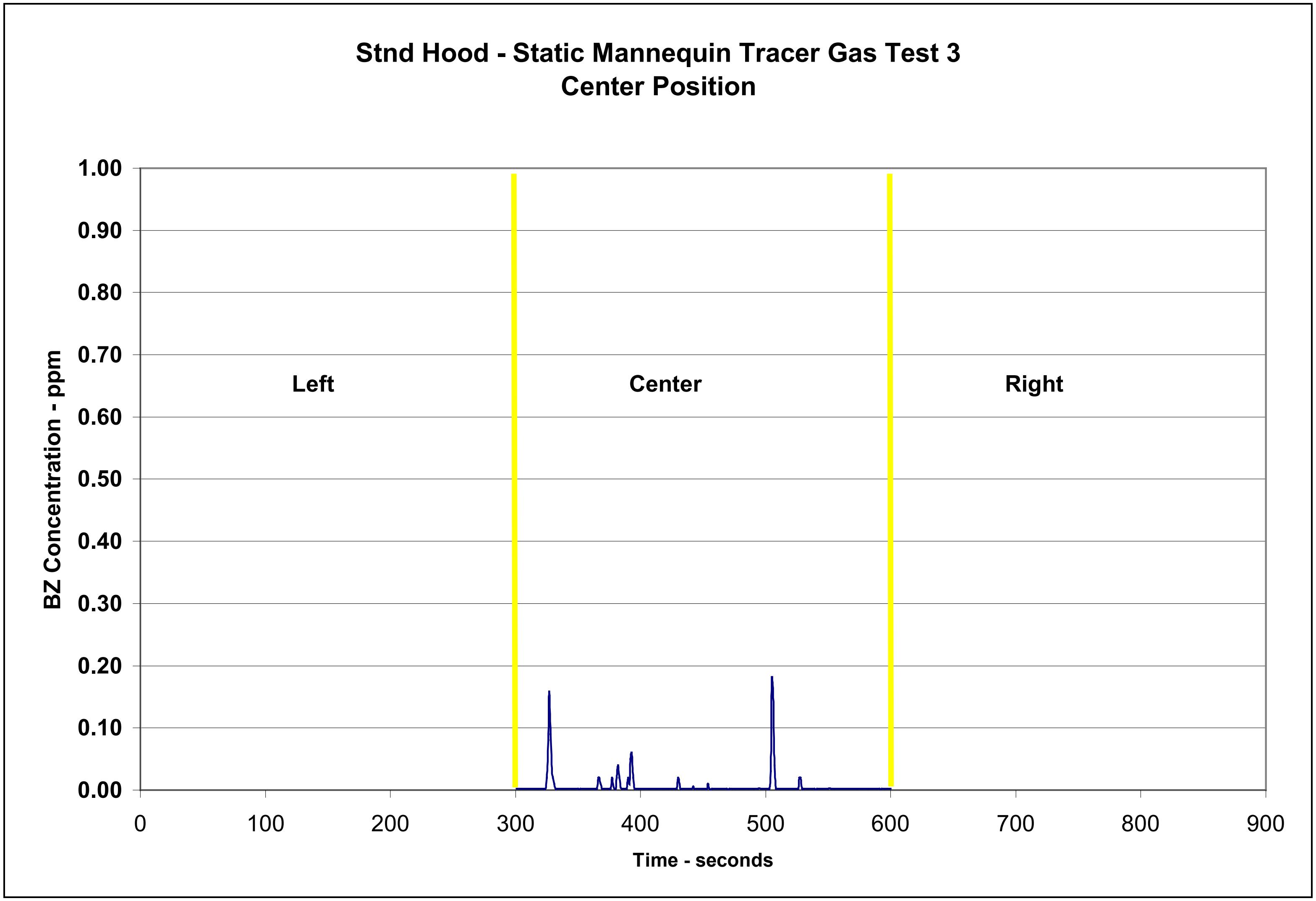

Figure 13 Plot of concentrations measured during a re-test at the center position during a static mannequin tracer gas test on the LBNL hood.

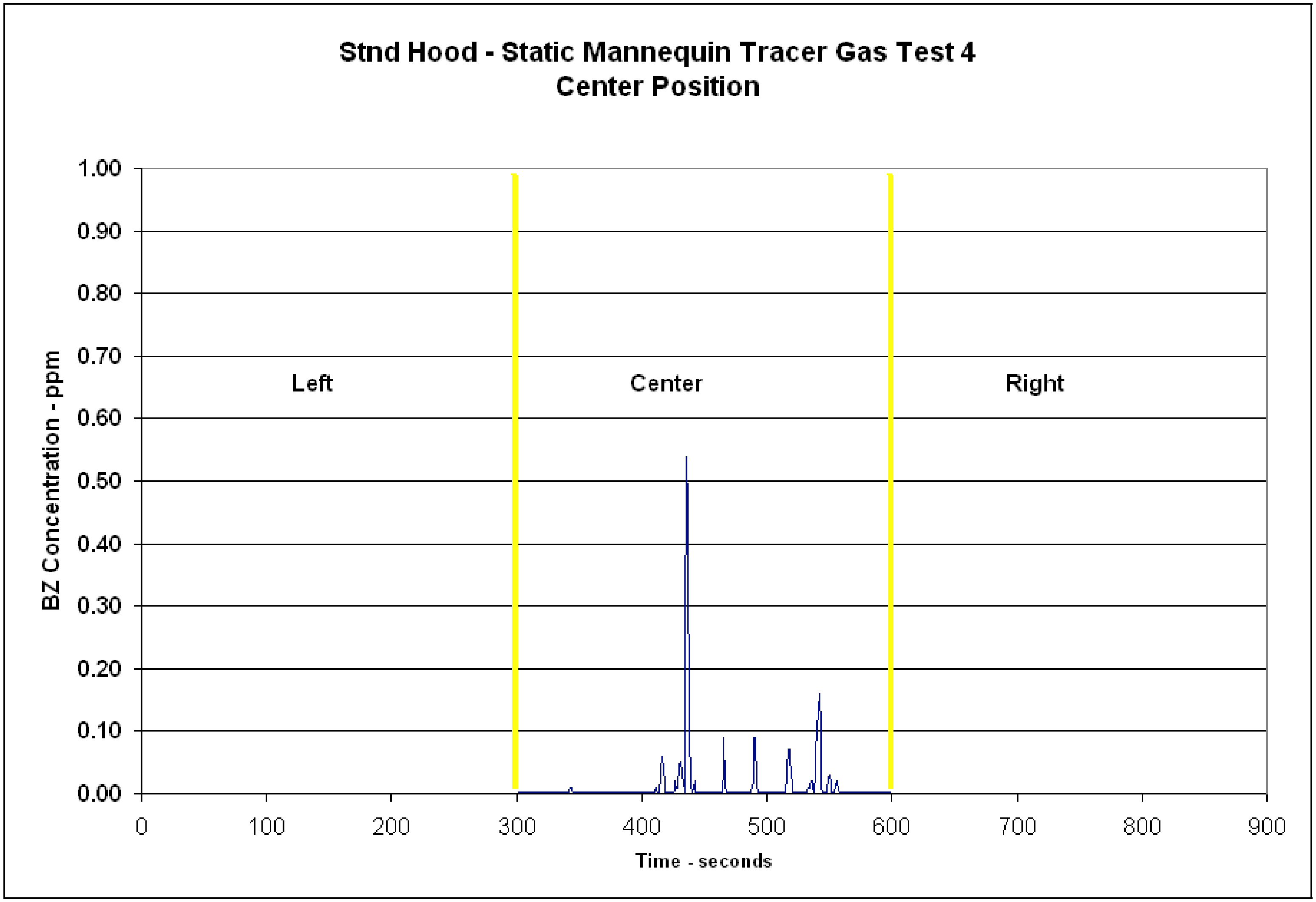

Figure 14 Plot of concentrations measured during a re-test at the center position during a static mannequin tracer gas test on the LBNL hood.

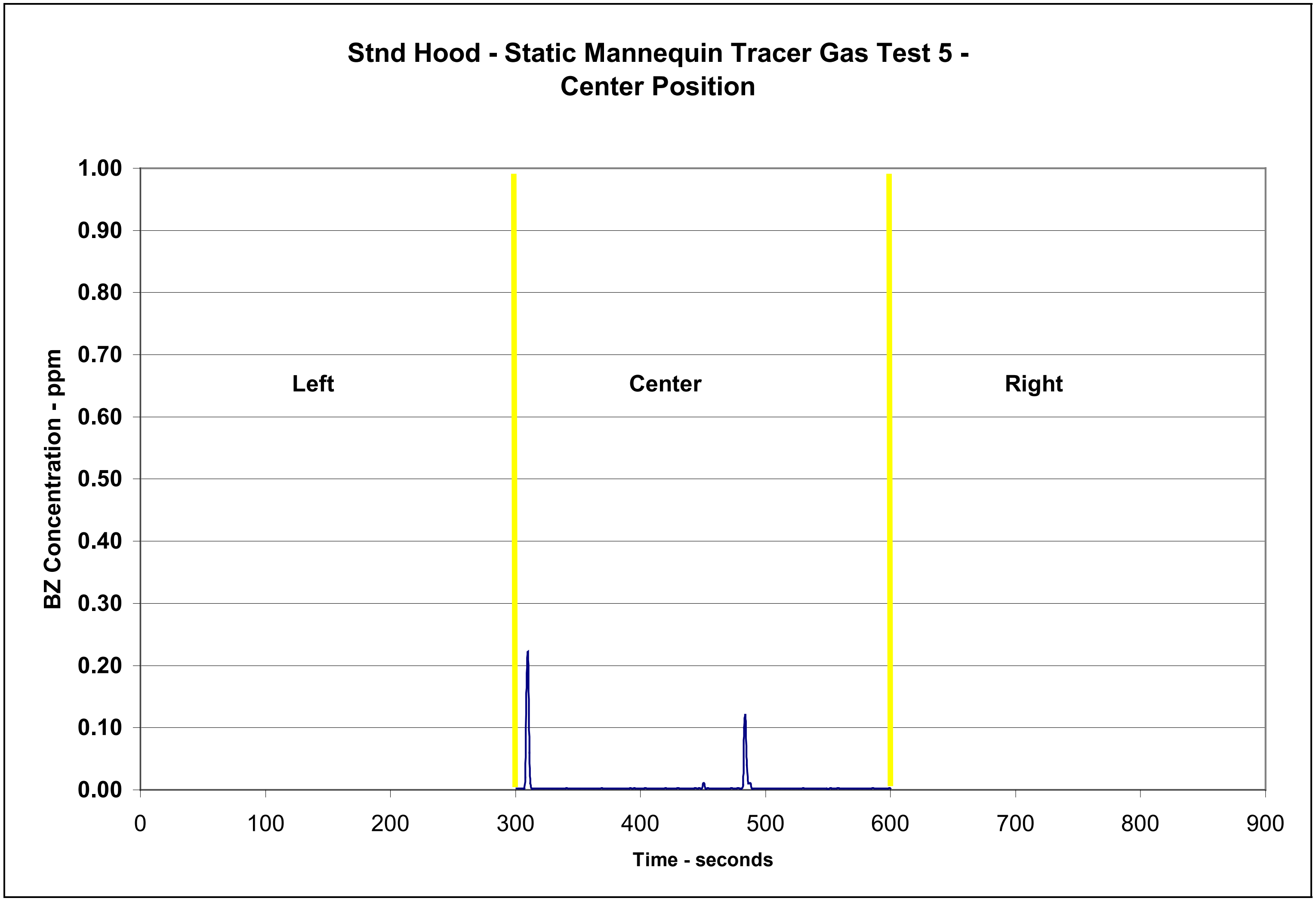

Figure 15 Plot of concentrations measured during a re-test at the center position during a static mannequin tracer gas test on the LBNL hood.

Table 3 Summary of tracer gas data and sequence time for HAM tests for each hood and test location

		Left		Center		Right		MAX Breathing Zone Concentration (Uncorrected) - ppm	MAX Breathing Zone Concentration (Corrected) - ppm
		BZ Conc. ppm	SEQ Duration Time-sec.	BZ Conc. ppm	SEQ Duration Time-sec.	BZ Conc. ppm	SEQ Duration Time-sec.		
LBNL - HP	SEQ 1	0.011	153	0.024	154	0.037	160	0.030	0.014
	SEQ 2	0.052	159	0.013	160	0.027	153		
	SEQ 3	0.027	147	0.012	169	0.015	155		
Series Avg. / Total Time		0.030	459	0.016	483	0.026	468		
Standard Hood	SEQ 1	0.036	154	0.007	163	0.010	156	0.021	0.010
	SEQ 2	0.015	135	0.007	157	0.006	150		
	SEQ 3	0.011	145	0.020	158	0.007	148		
Series Avg / Total Time		0.021	434	0.011	478	0.008	454		
Aggregate SEQ Time (MAX) - mm:ss		7:39		8:03		7:48			
Aggregate SEQ Time (AVG) - mm:ss		7:27		8:01		7:41			
Aggregate SEQ Time (MIN) - mm:ss		7:14		7:58		7:34			

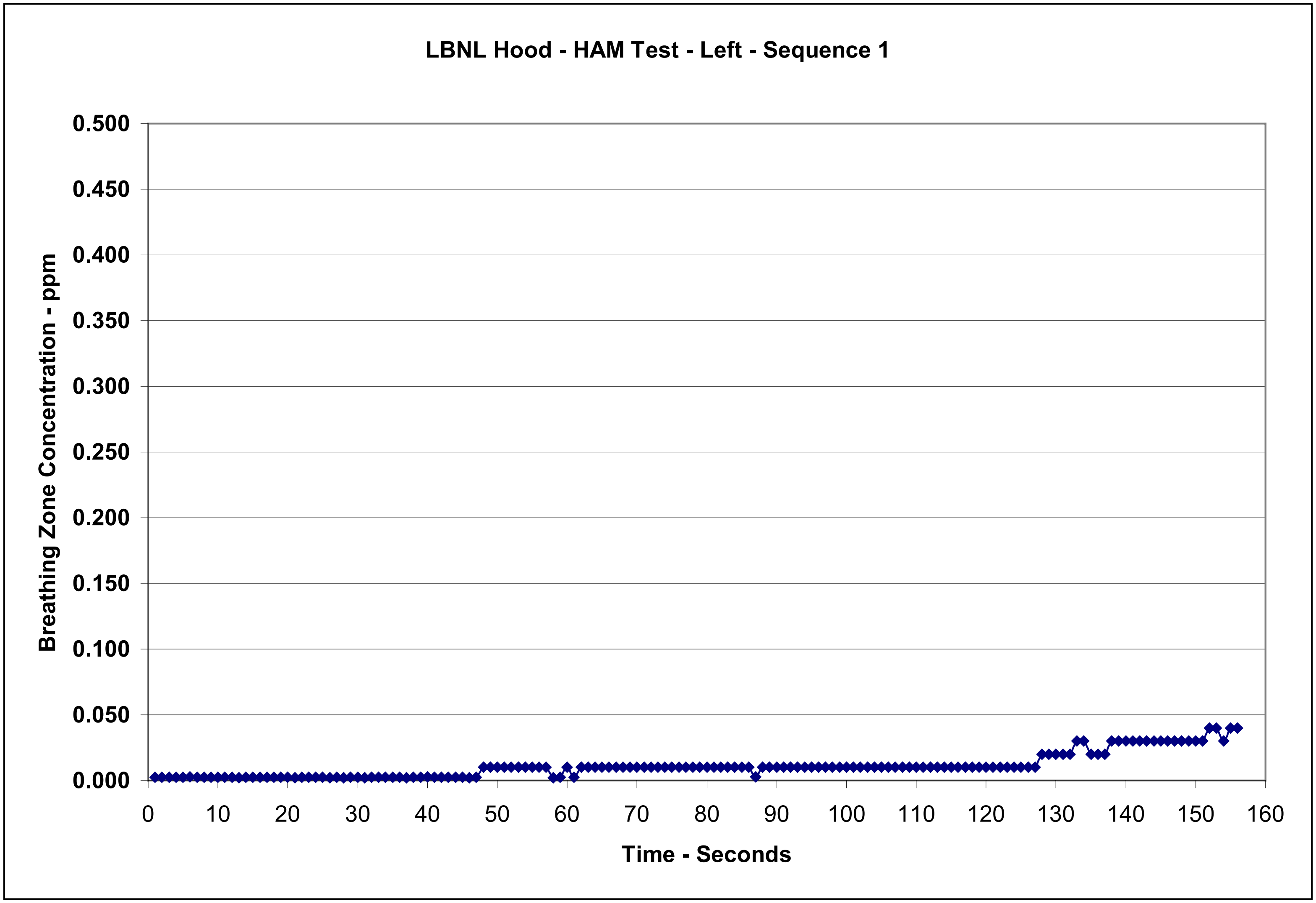

Figure 16 Tracer gas concentrations measured during test sequence 1 on the left side of the LBNL hood

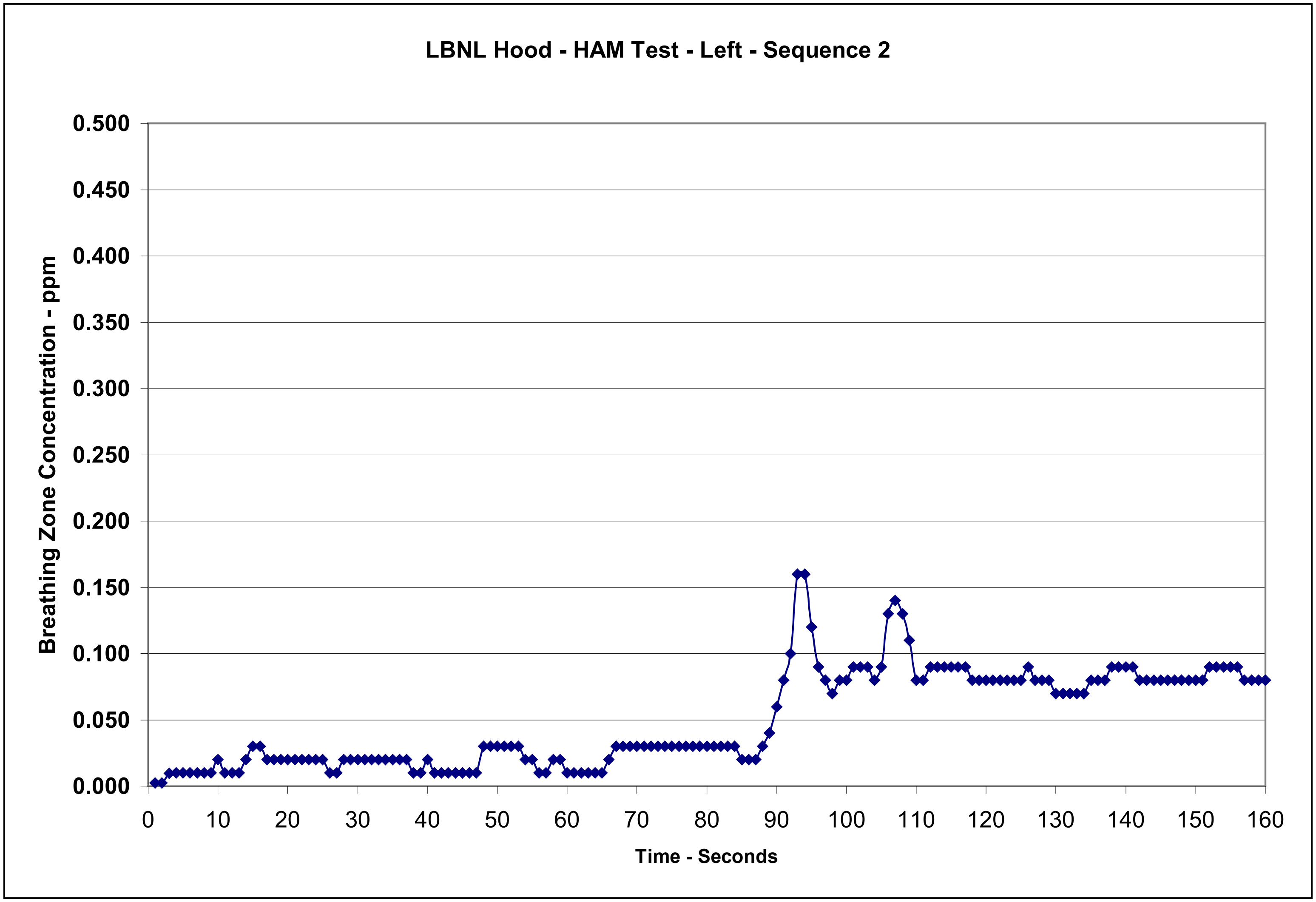

Figure 17 Tracer gas concentrations measured during test sequence 2 on the left side of the LBNL hood

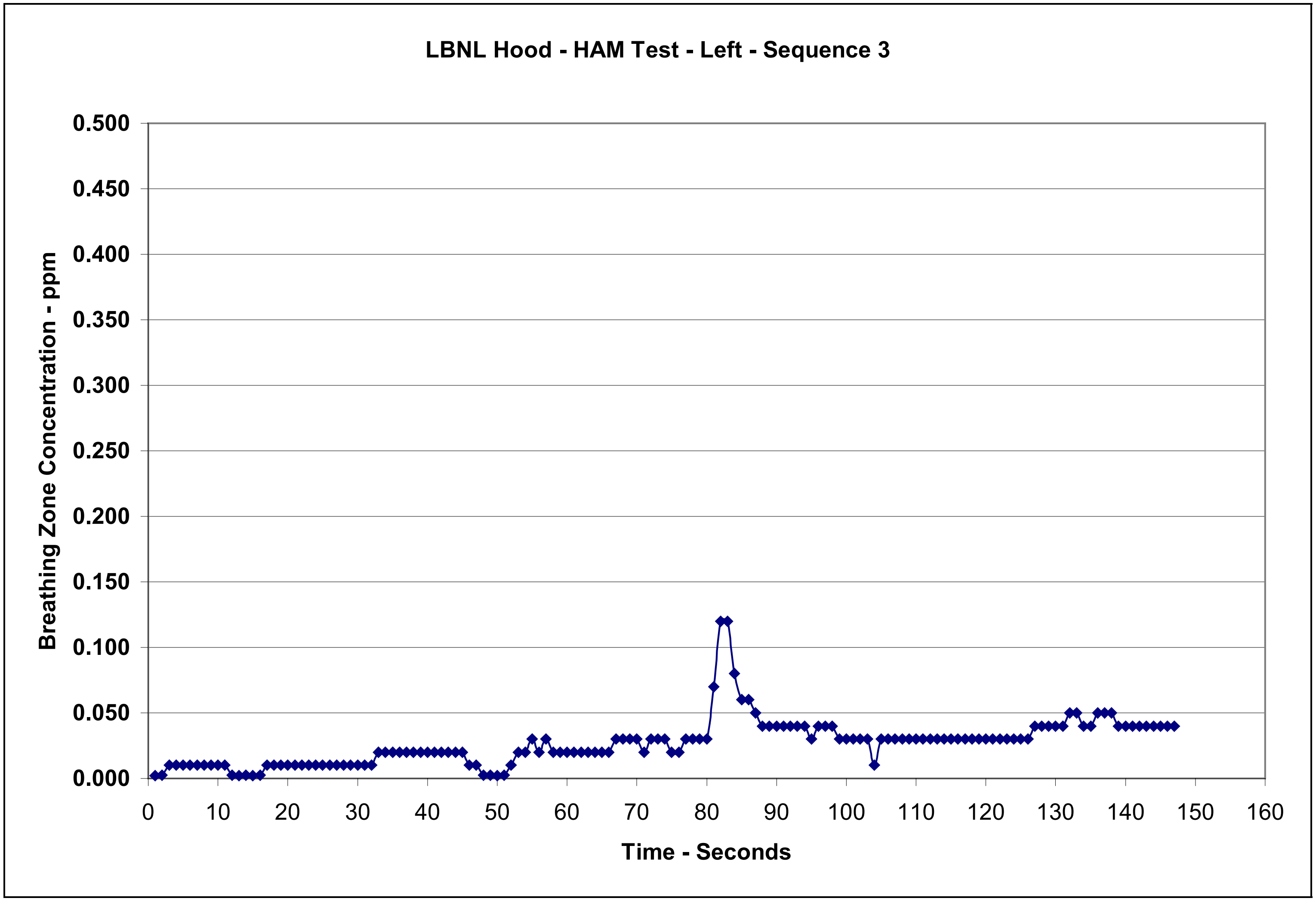

Figure 18 Tracer gas concentrations measured during test sequence 3 on the left side of the LBNL hood

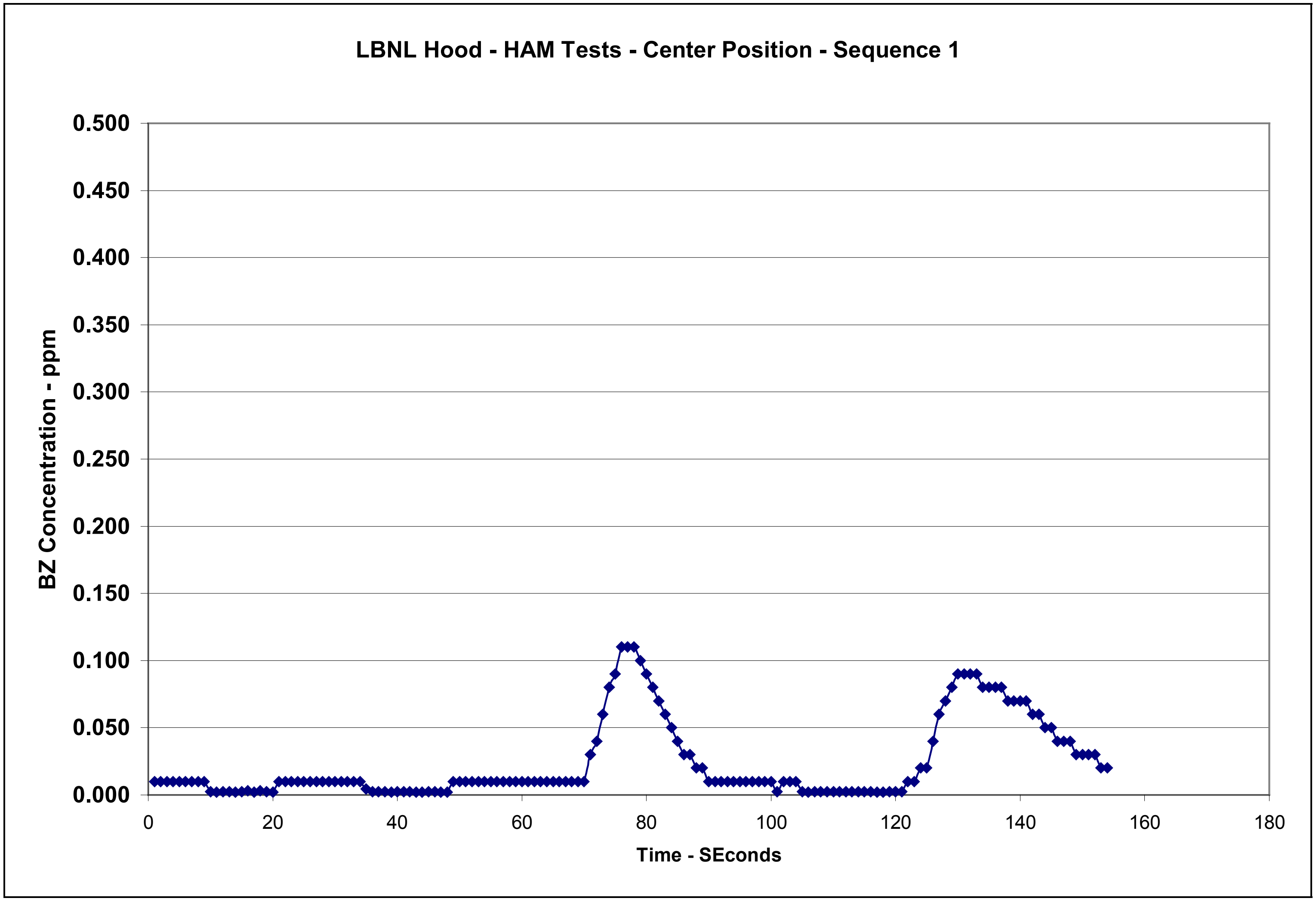

Figure 19 Tracer gas concentrations measured during test sequence 1 in the center position of the LBNL hood

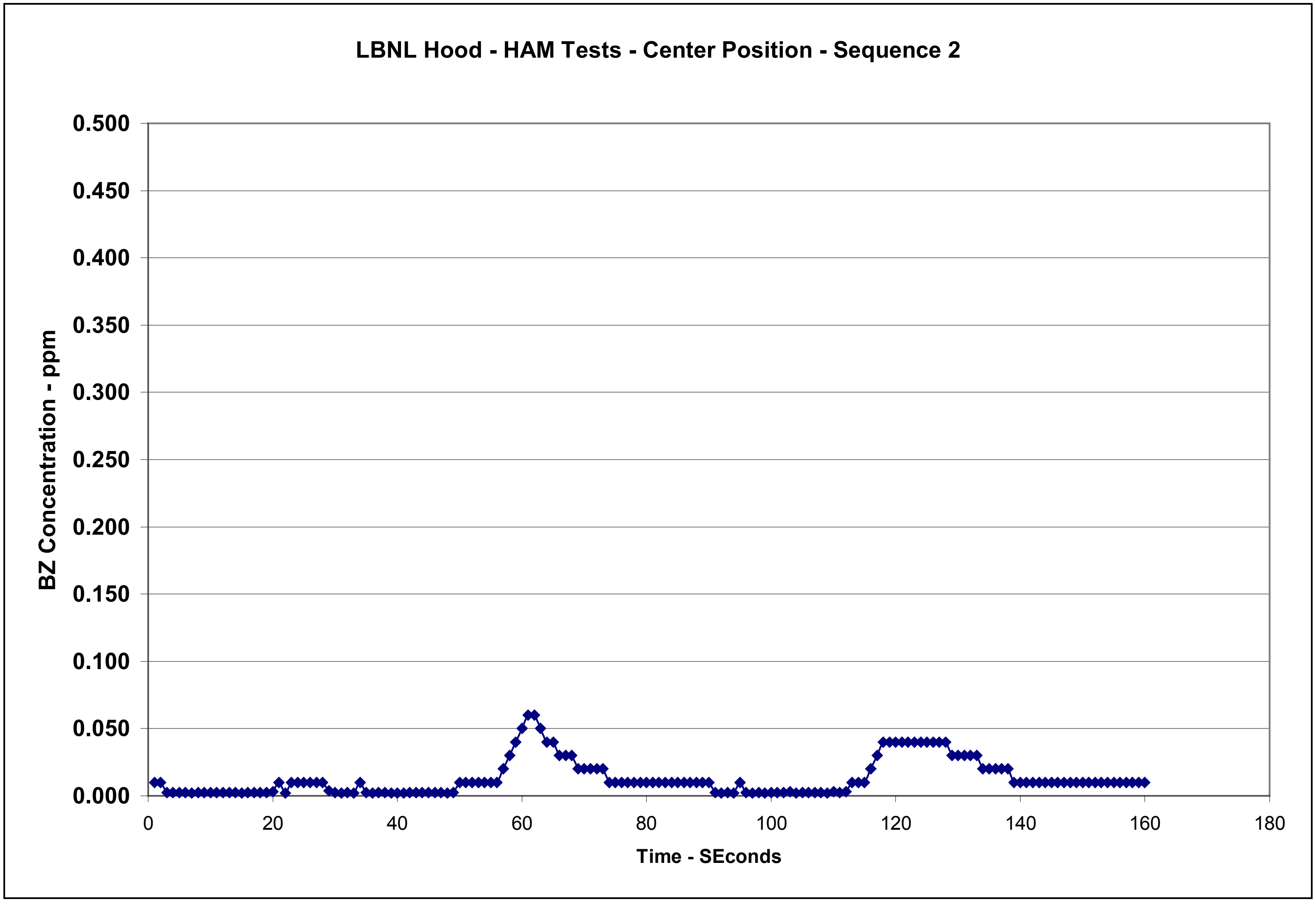

Figure 20 Tracer gas concentrations measured during test sequence 2 in the center position of the LBNL hood

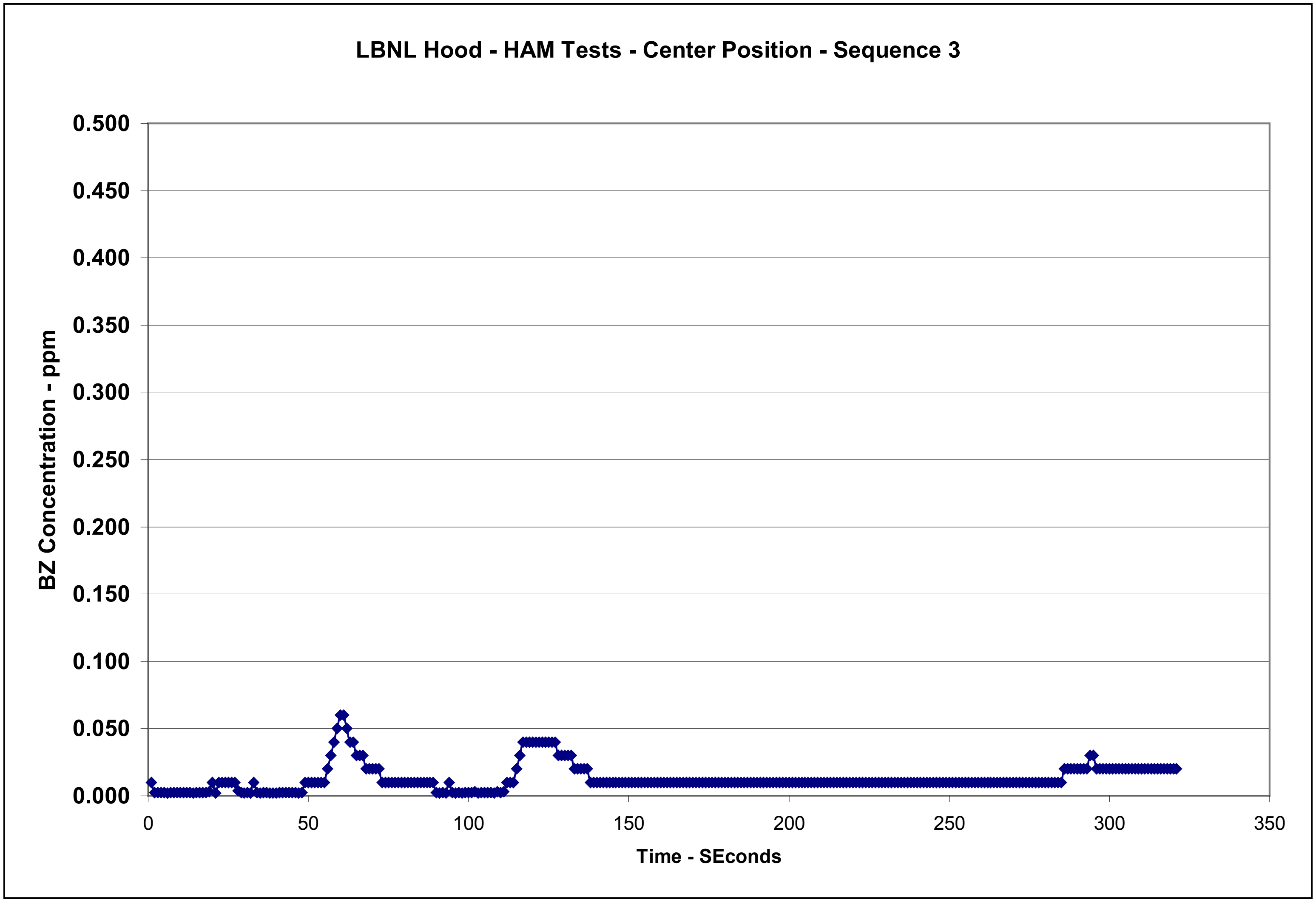

Figure 21 Tracer gas concentrations measured during test sequence 3 in the center position of the LBNL hood

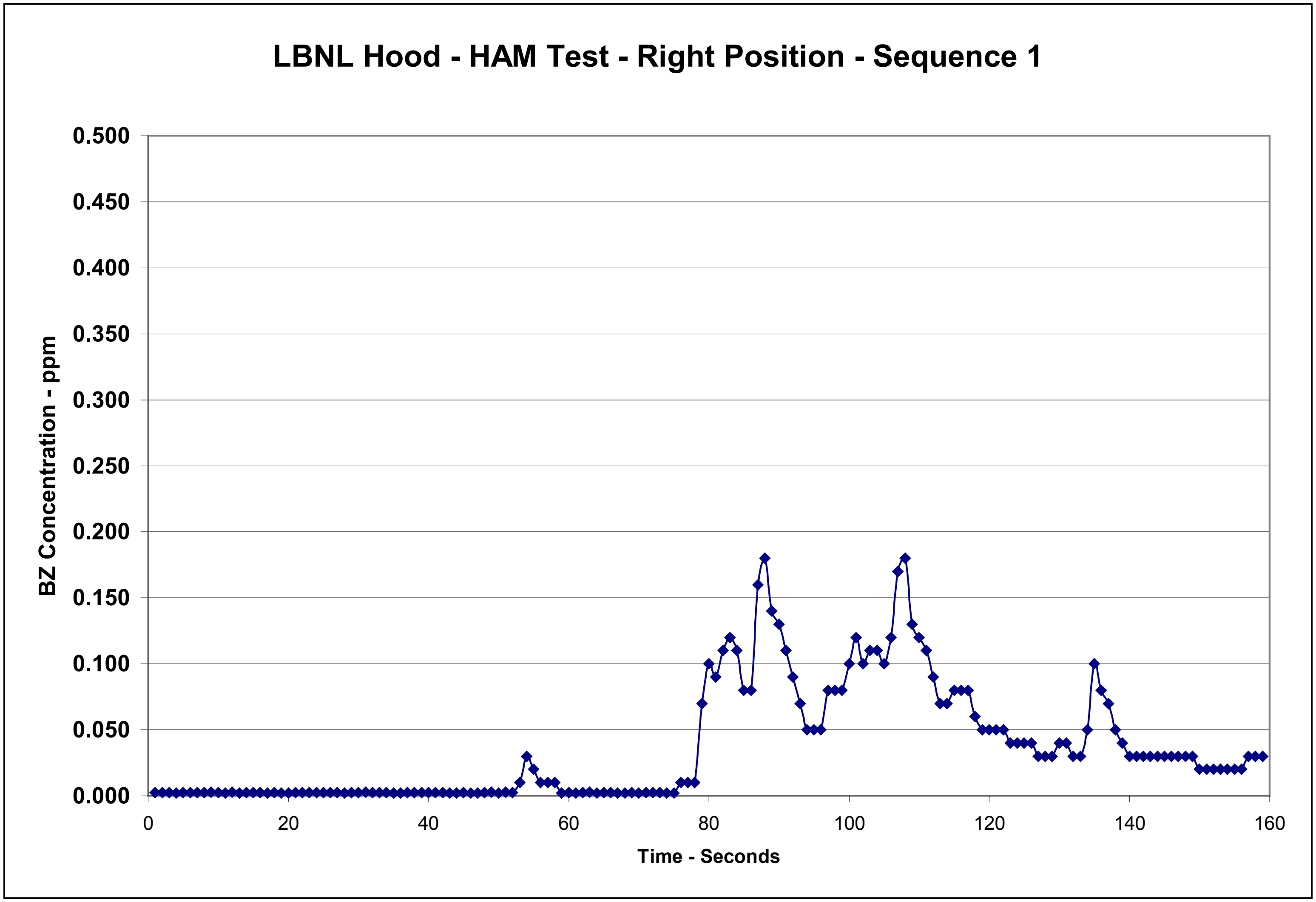

Figure 22 Tracer gas concentrations measured during test sequence 1 on the right side of the LBNL hood

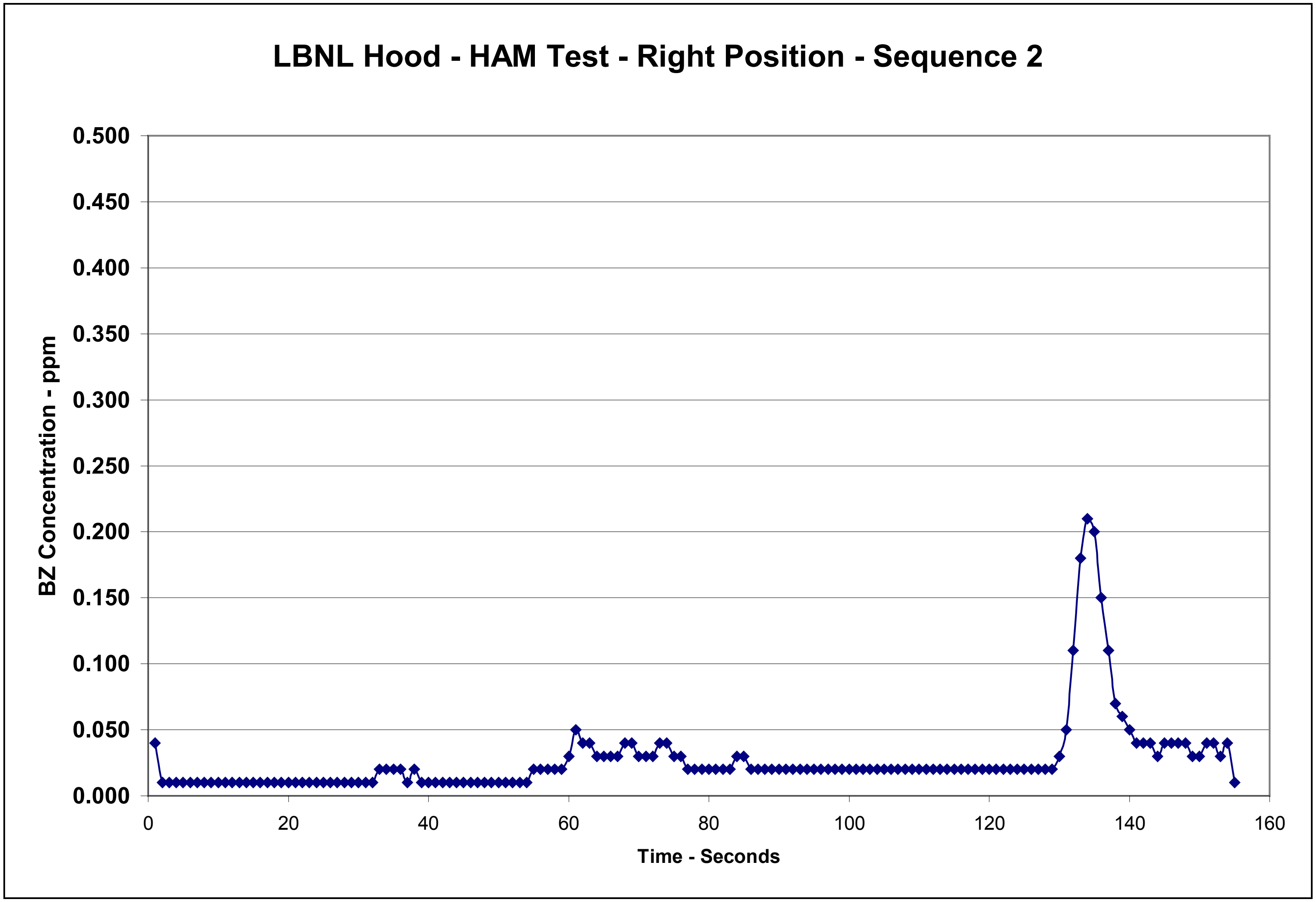

Figure 23 Tracer gas concentrations measured during test sequence 2 on the right side of the LBNL hood

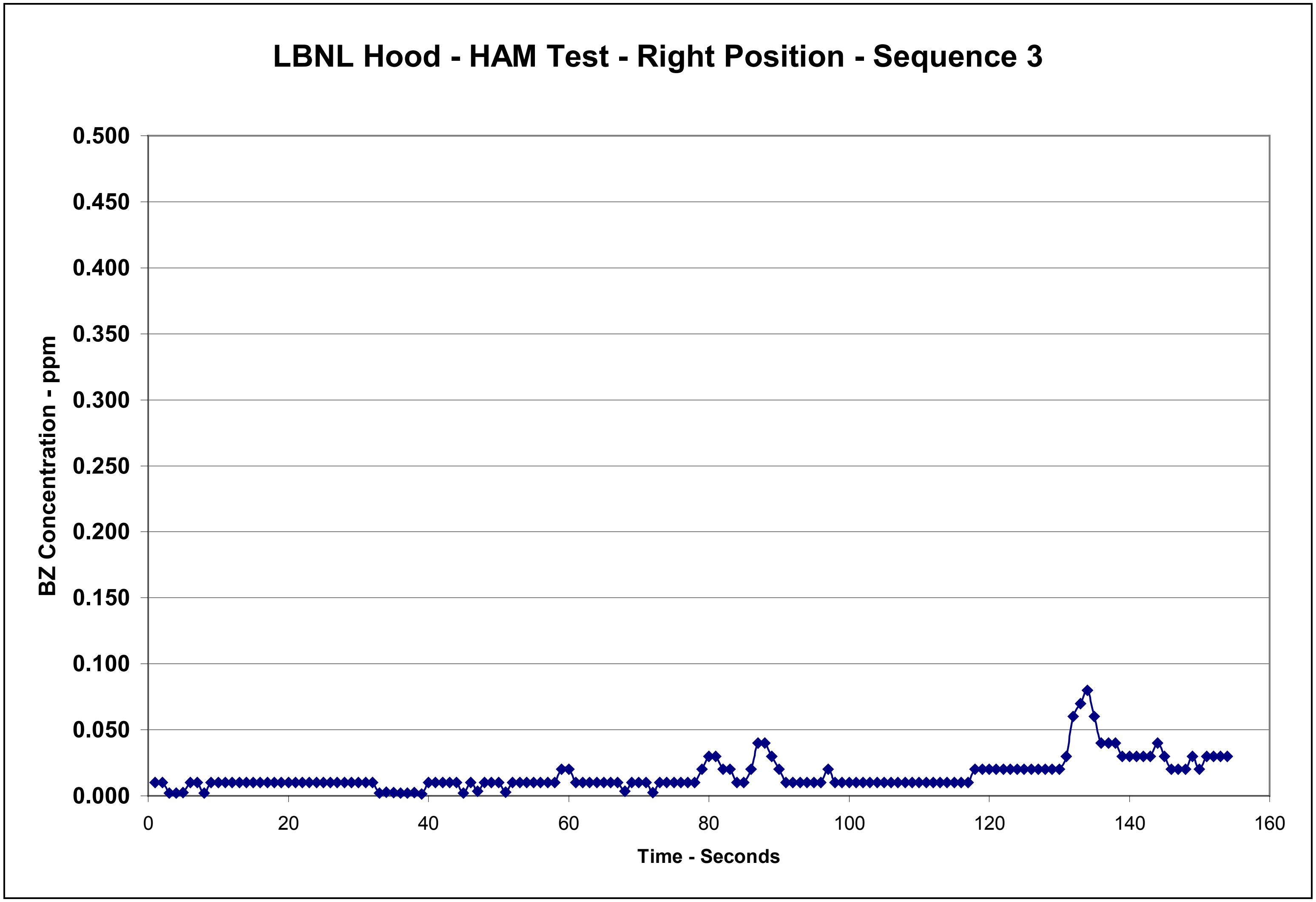

Figure 24 Tracer gas concentrations measured during test sequence 3 on the right side of the LBNL hood

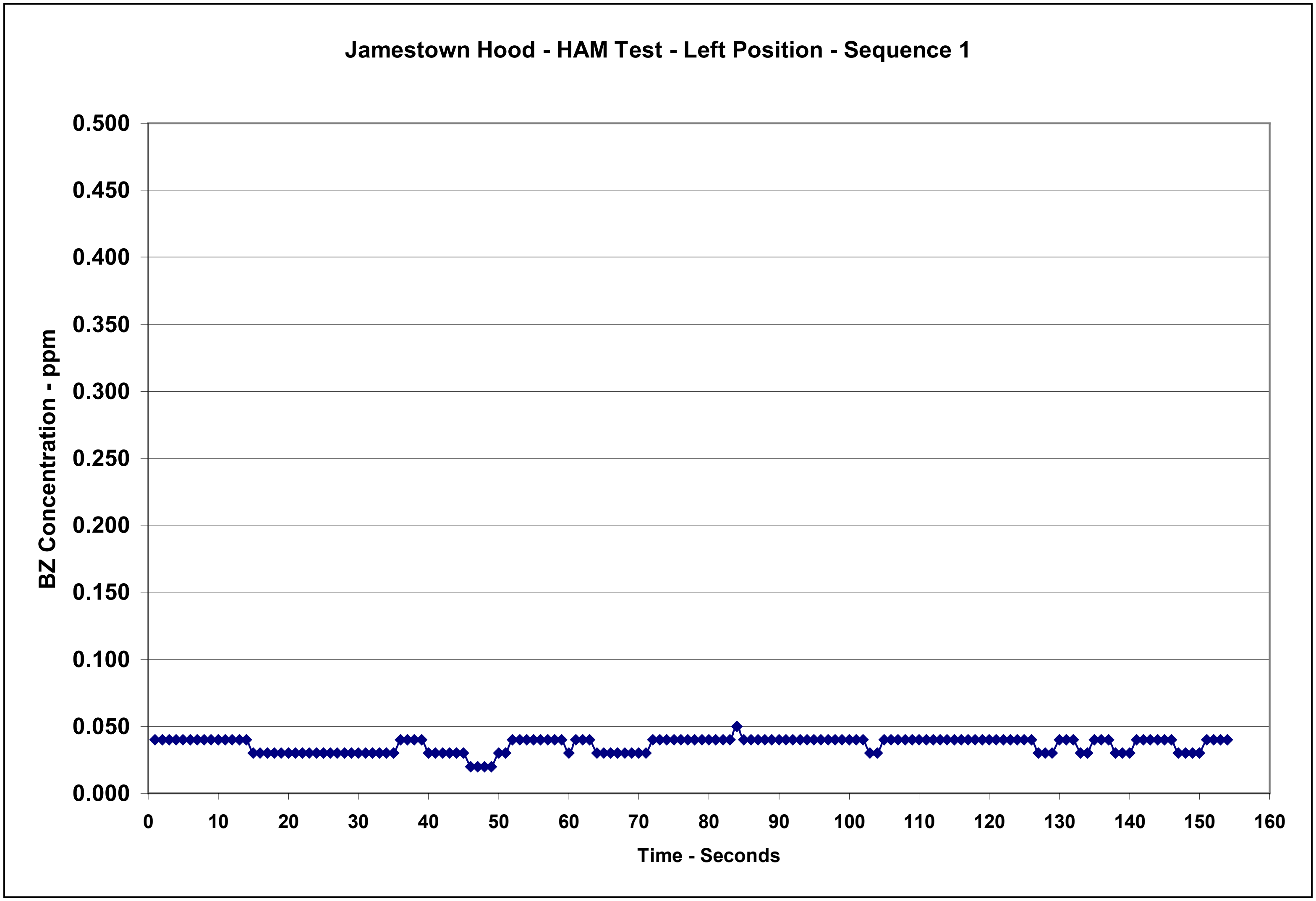

Figure 25 Tracer gas concentrations measured during test sequence 1 on the left side of the Standard hood

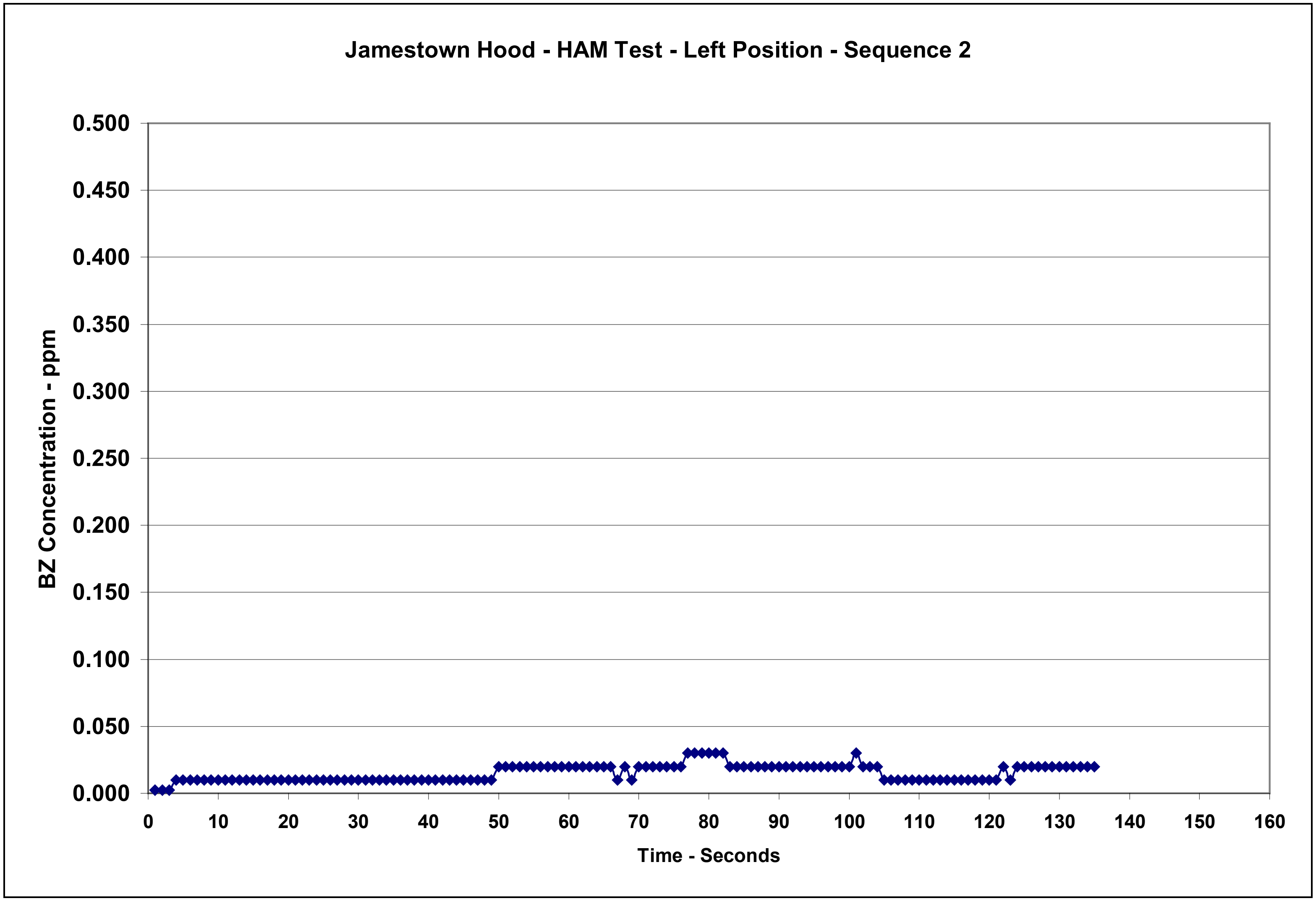

Figure 26 Tracer gas concentrations measured during test sequence 2 on the left side of the standard hood

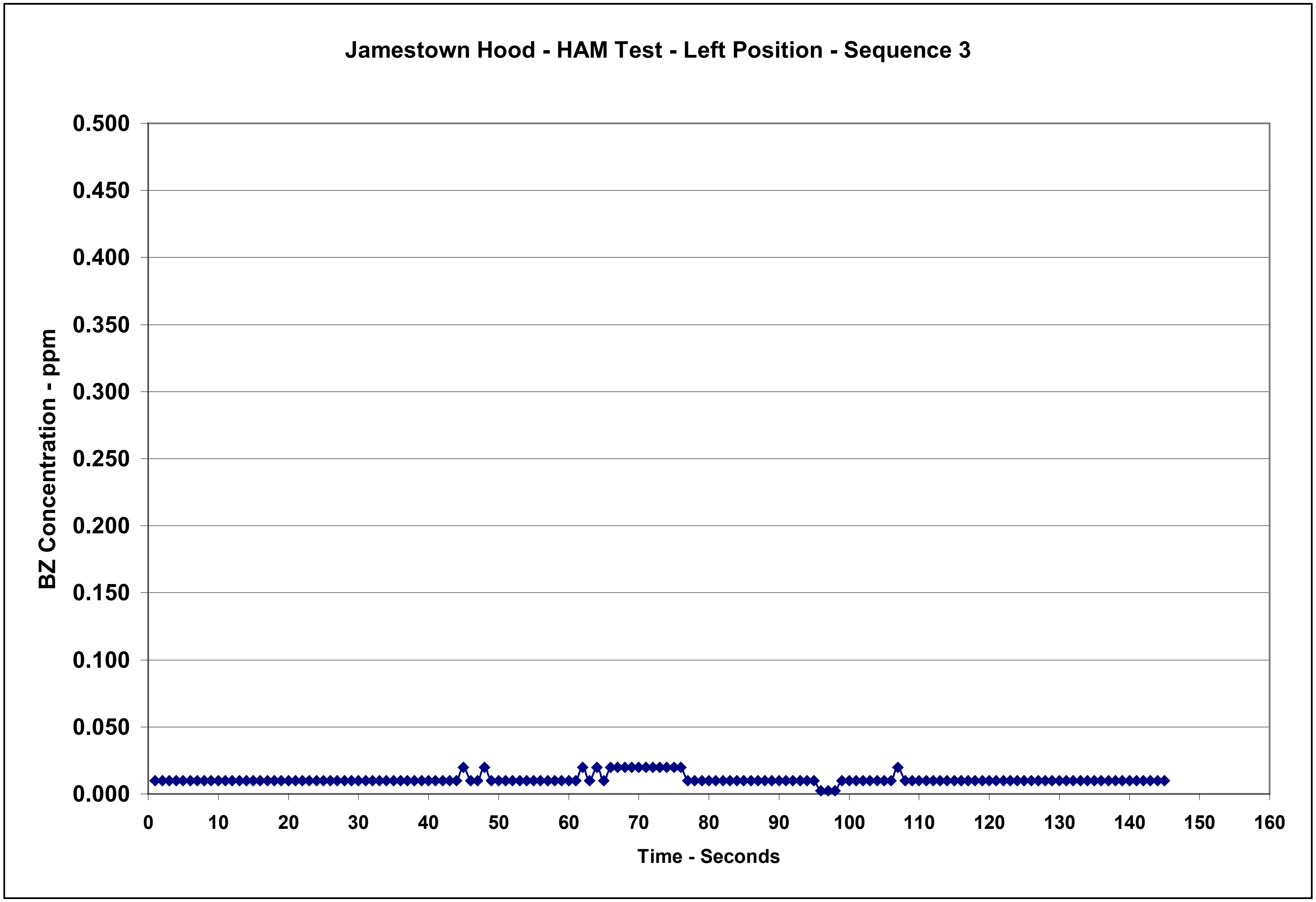

Figure 27 Tracer gas concentrations measured during test sequence 3 on the left side of the standard hood

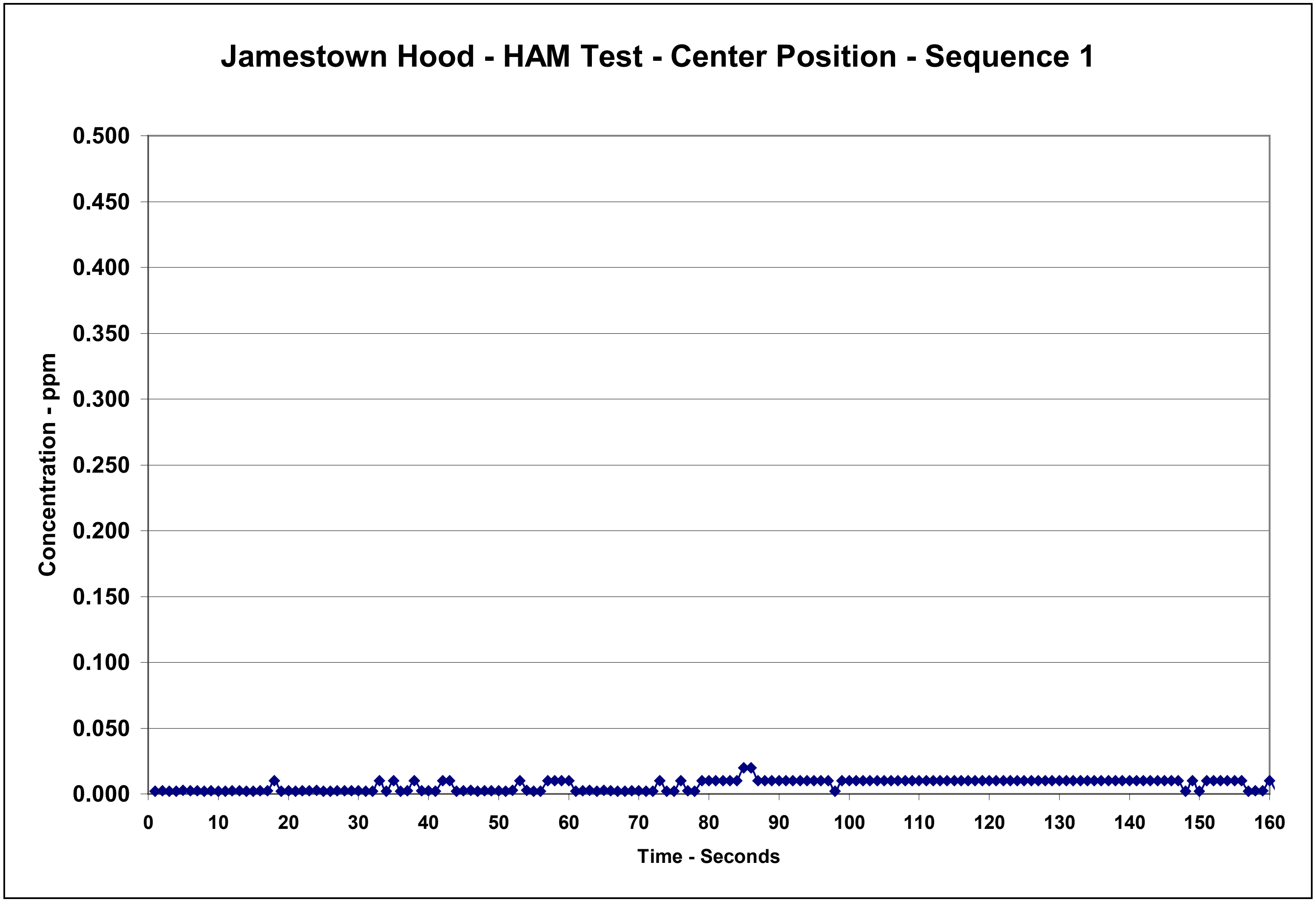

Figure 28 Tracer gas concentrations measured during test sequence 1 in the center test position of the standard hood

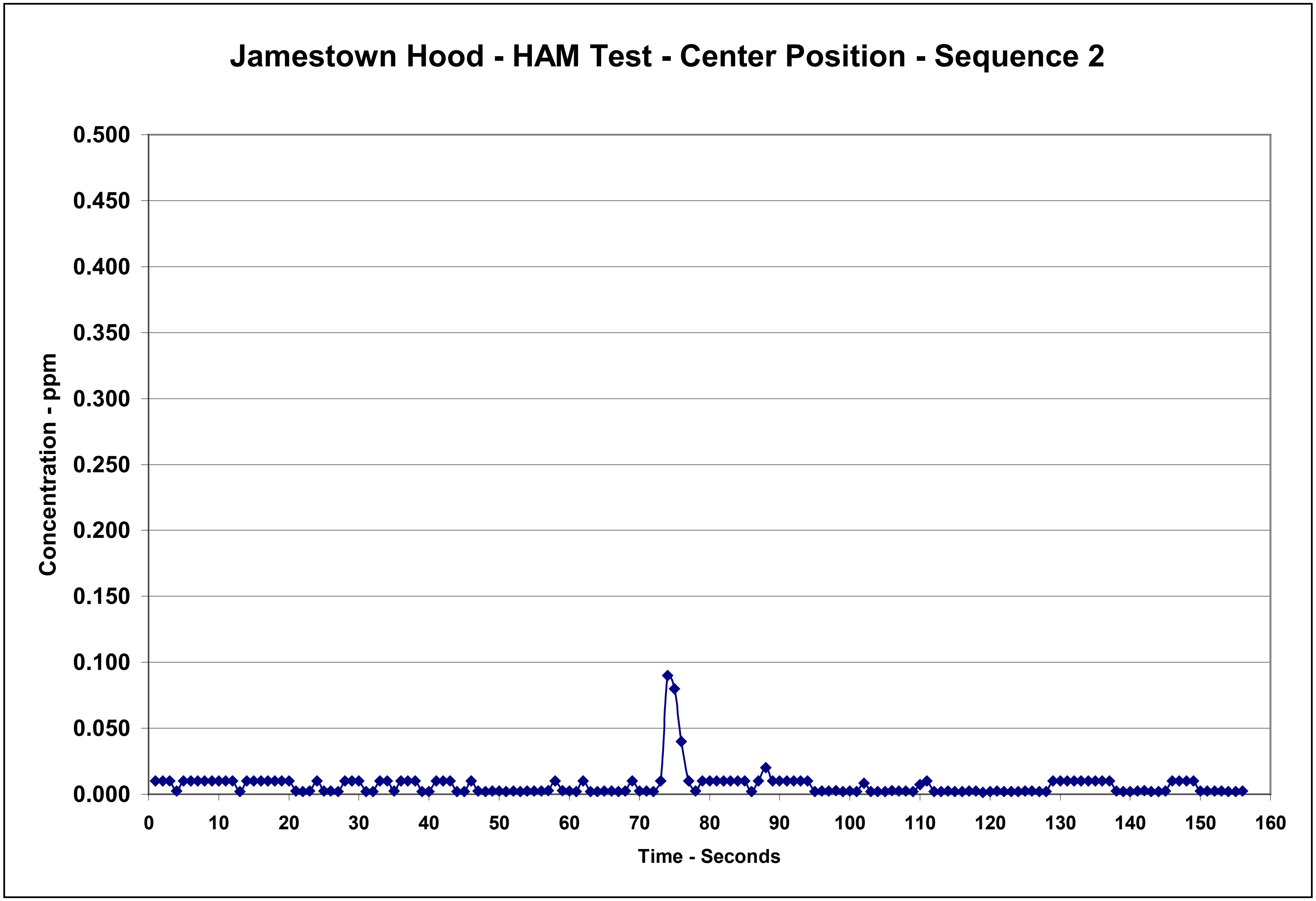

Figure 29 Tracer gas concentrations measured during test sequence 2 in the center test position of the standard hood

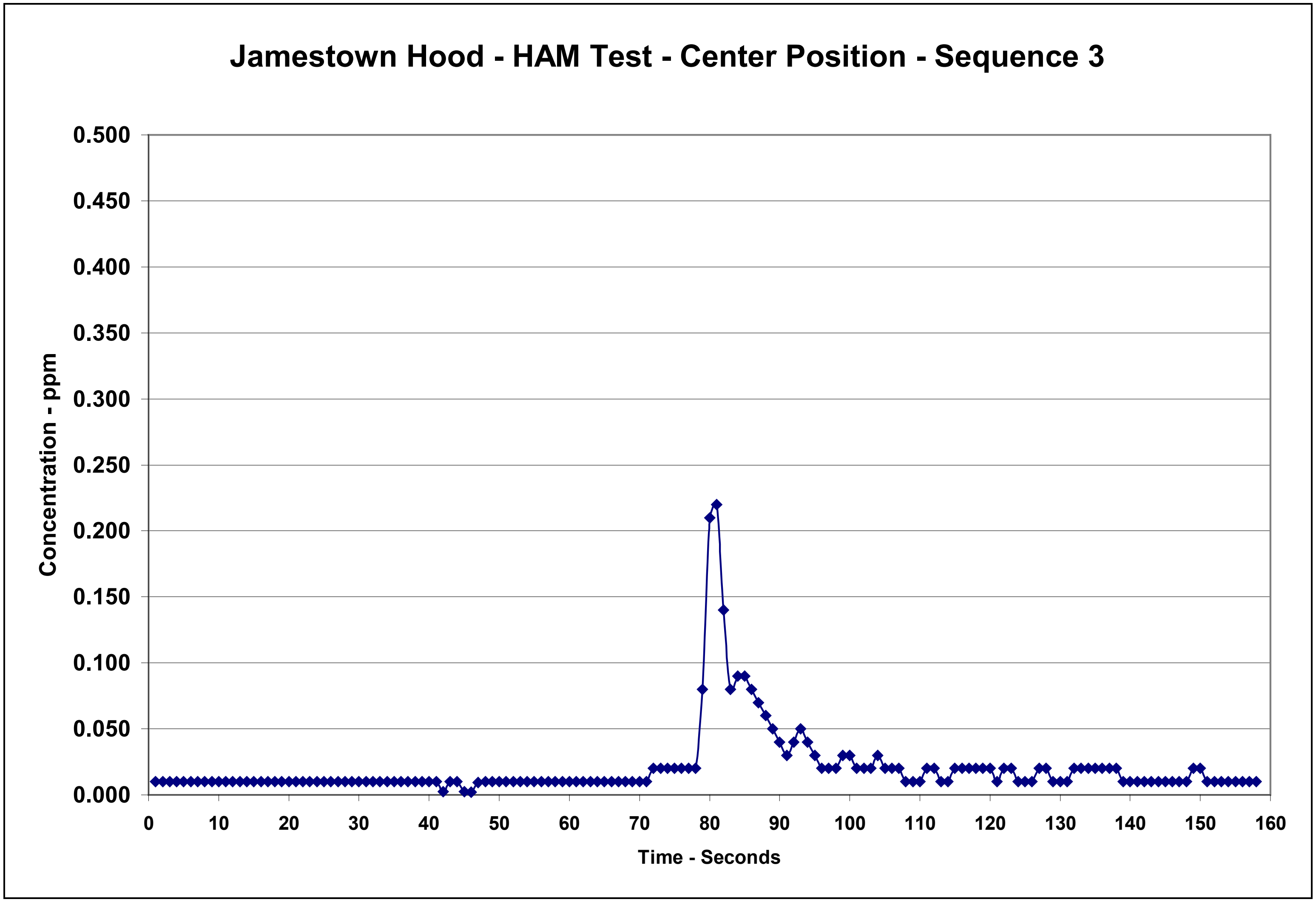

Figure 30 Tracer gas concentrations measured during test sequence 3 in the center test position of the standard hood

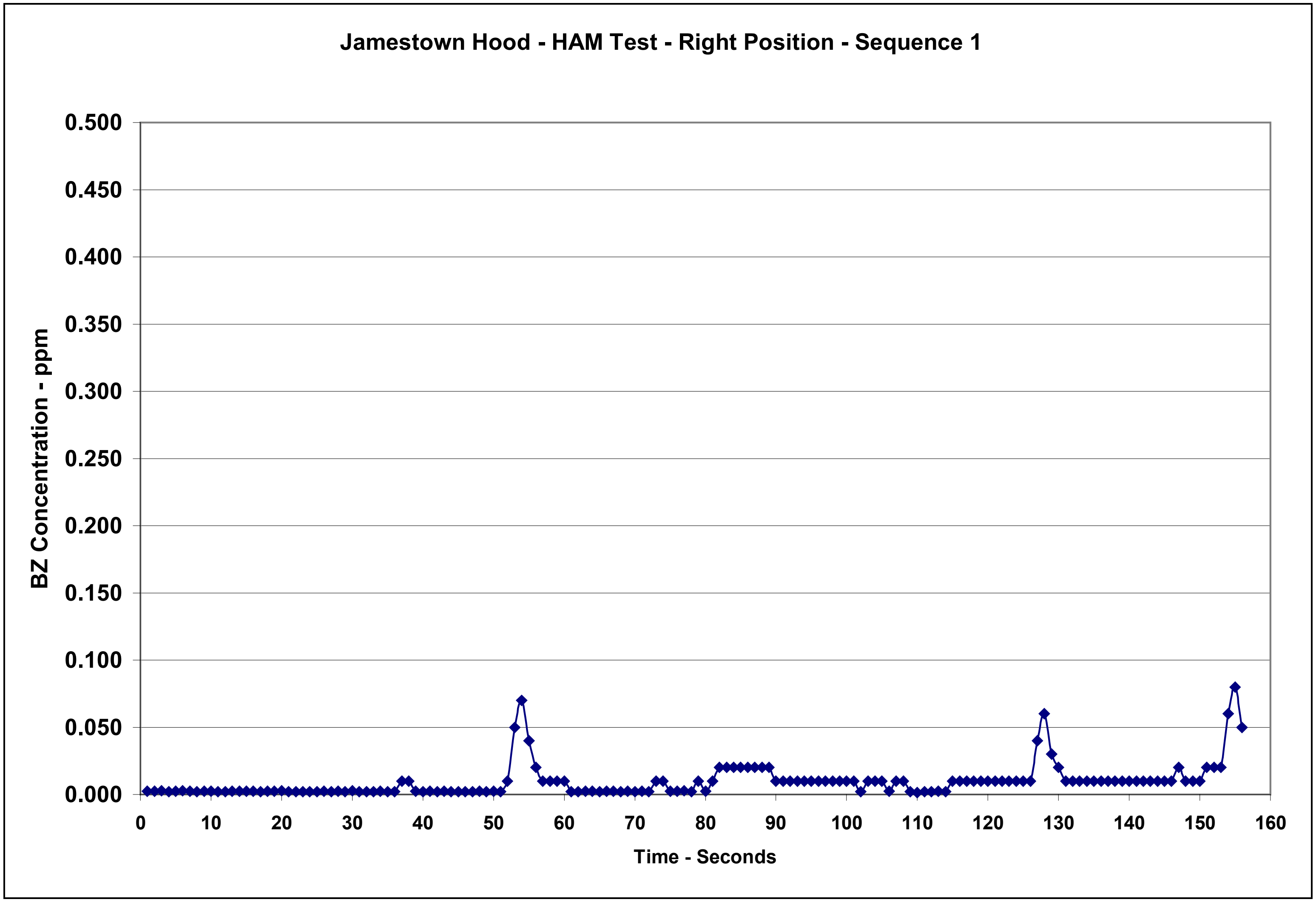

Figure 31 Tracer gas concentrations measured during test sequence 1 on the right side of the standard hood

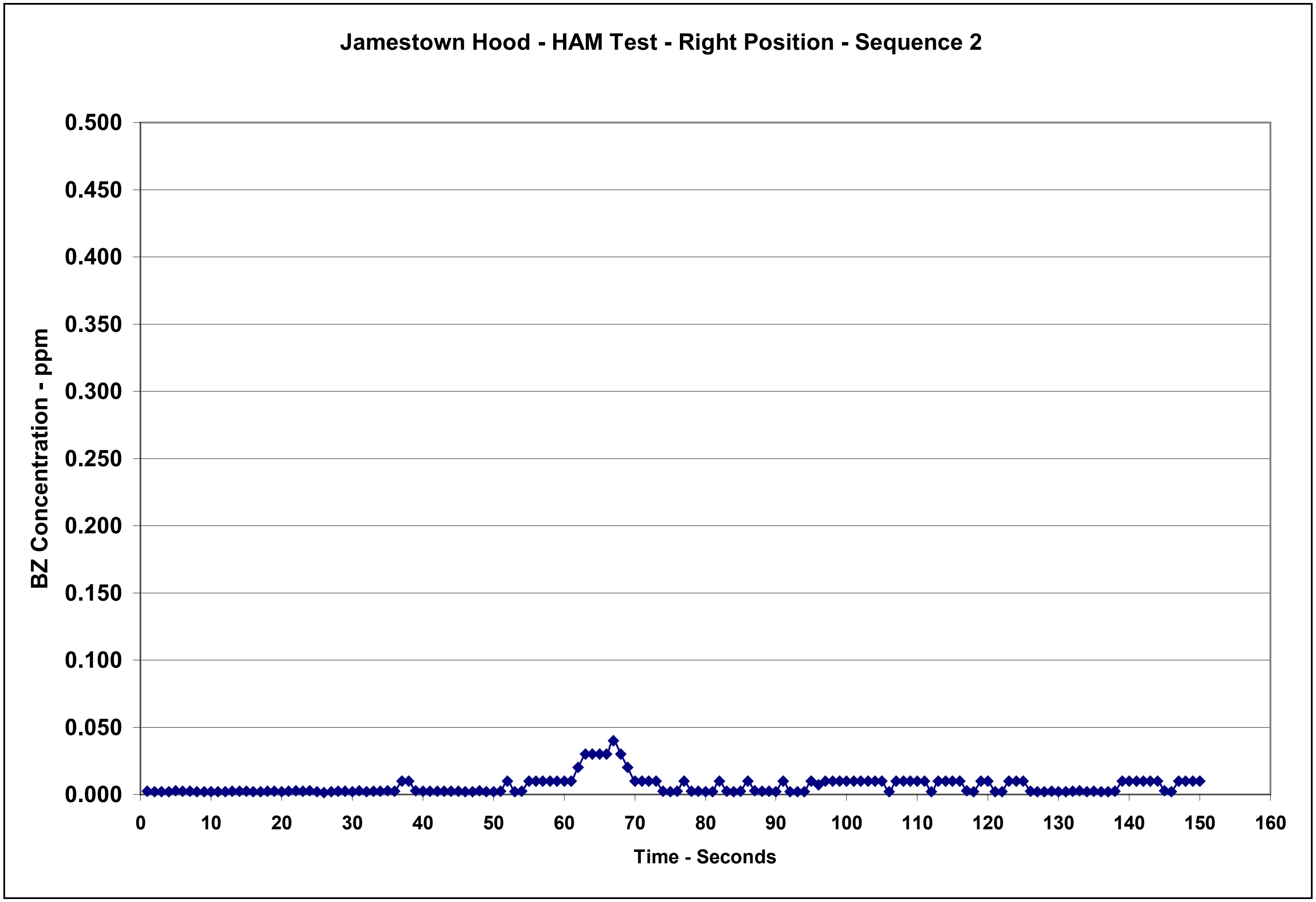

Figure 32 Tracer gas concentrations measured during test sequence 2 on the right side of the standard hood

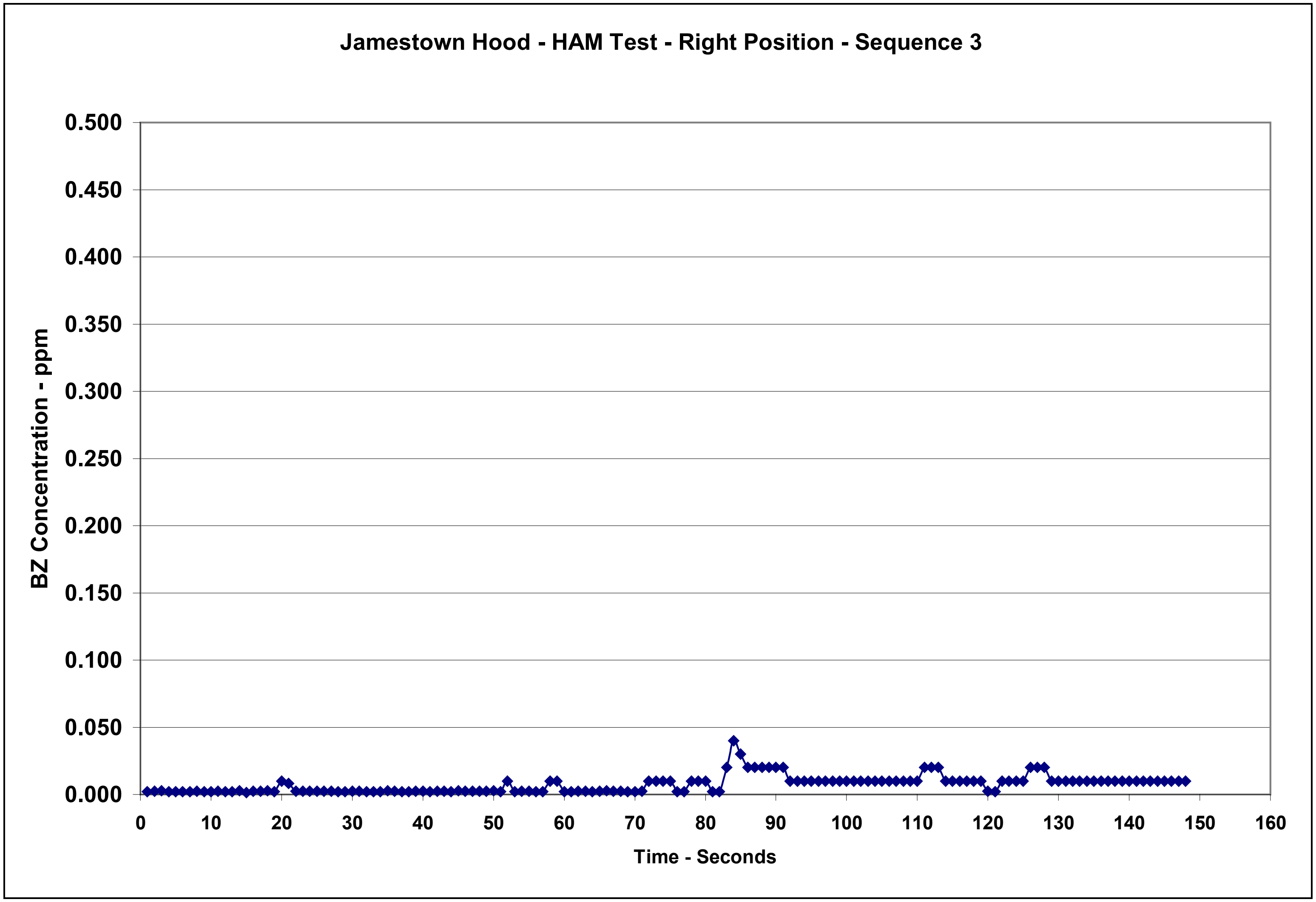

Figure 33 Tracer gas concentrations measured during test sequence 3 on the right side of the standard hood

Table 4 Calculation of exhaust flow, stack velocity and discharge concentration for each hood system

Hood	Flow cfm	Stack Velocity fpm	Exhaust Concentration ppm
LBNL	670	1228	194
Jamestown Standard	1200	2202	108

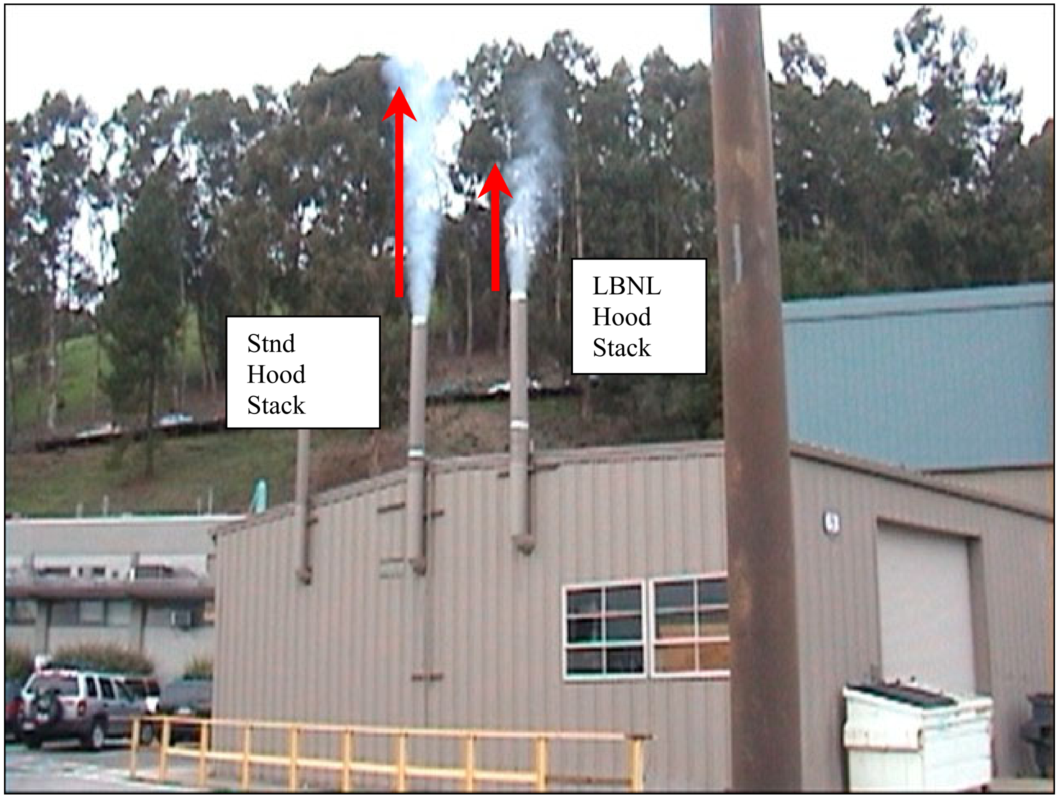

Figure 34 Photo of exhaust discharge from the exhaust stacks serving the LBNL hood and the standard hood.

Figure 35 Photo of exhaust discharge from the exhaust stacks serving the LBNL hood and the standard hood.

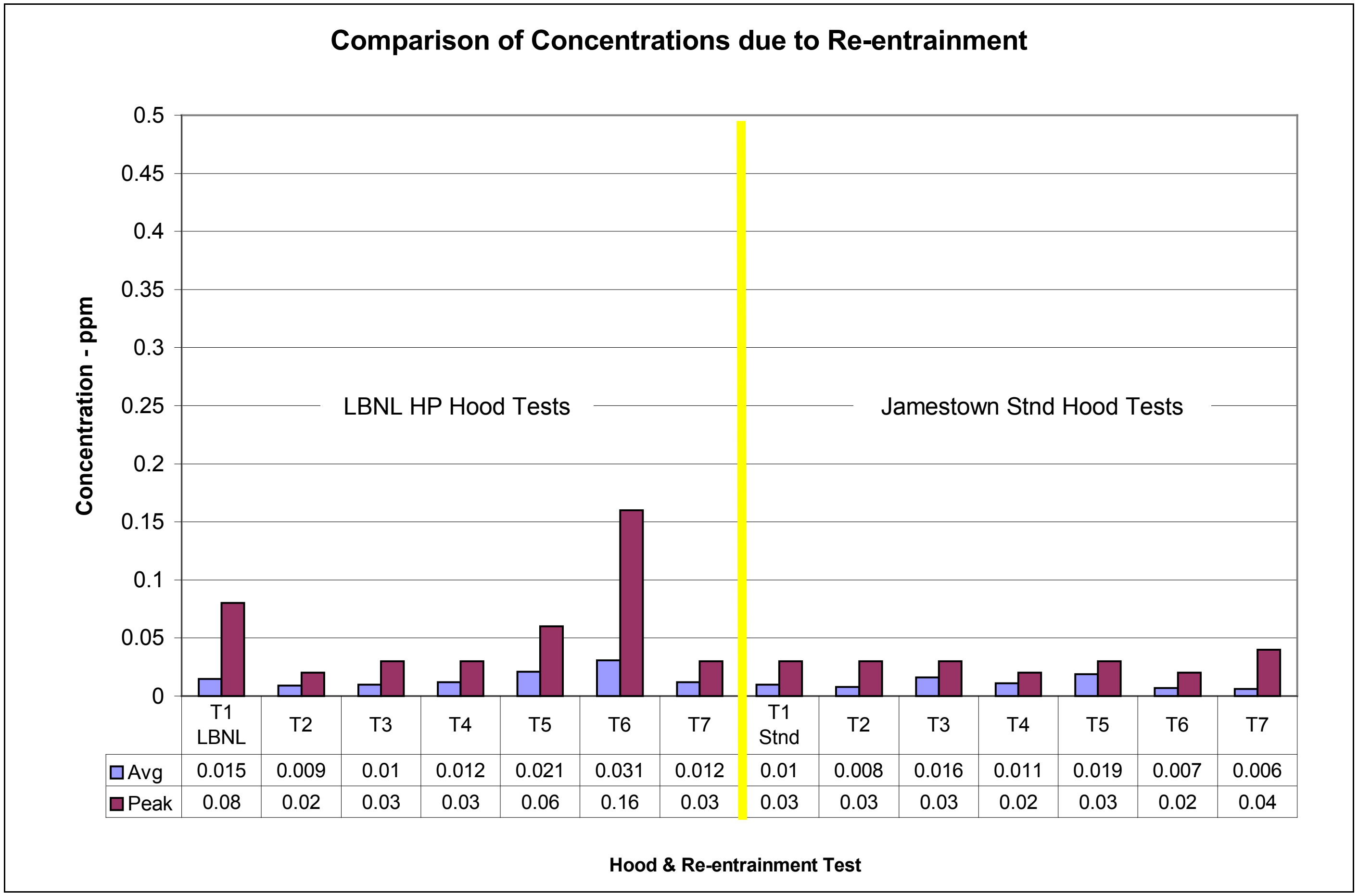

Figure 36 Tracer gas concentrations attributed to re-entrainment during a series of tests conducted on the LBNL hood and the Jamestown standard hood.

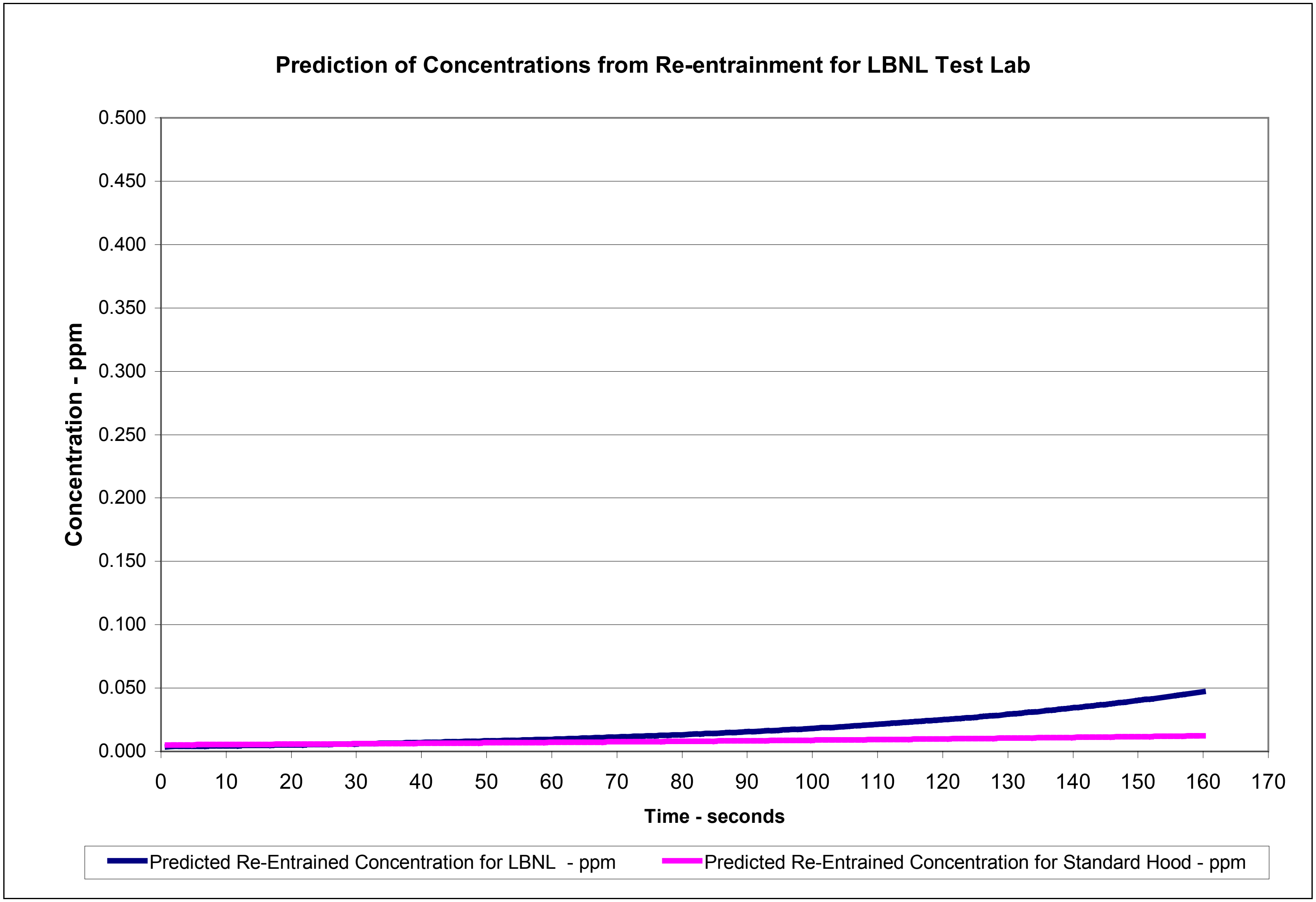

Figure 37 Curve of background concentrations predicted from a series of tests to evaluate re-entrainment.