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Final Report
Demonstration and Field Test of Airjacket Technology

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1. INTRODUCTION

There are approximately 600,000 paint spray workers in the United States applying paints and coatings with some type of sprayer. Approximately 5% of these spray workers are in the South Coast Air Quality Management District (SCAQMD). These spray workers apply paints or other coatings to products such as bridges, houses, automobiles, wood and metal furniture, and other consumer and industrial products. The materials being sprayed include exterior and interior paints, lacquers, primers, shellacs, stains and varnishes.

1A. Spray Painting Techniques

In the most traditional technology, often called air-powered spraying, a large jet of air exits the paint spray nozzle along with the paint. With air-powered spraying some of the paint is atomized into drops that are too small and do not have enough momentum to be delivered to the object. The result is a mist of paint particles called overspray. Also, some paint particles from air-powered spray nozzles may get entrained in the rebounding air jet from the object and bounce off the object, called bounce-back. The use of this technology is being reduced because transfer efficiencies, (the efficiency of delivering paint to the object from the nozzle,) are too low.

With increasing frequency, paint spray workers use new, alternative methods of paint spraying, the most common among them is high volume low-pressure (HVLP) spray painting, in which paint exists the nozzle at low pressures. HVLP has a better paint transfer efficiency than previously used air-powered spraying methods.

The technology of airless spray painting is commonly utilized to paint large surfaces. In airless spray painting, paint exits the spray nozzle at a high rate appropriate for painting of large surfaces. This technique is generally not used in spray booths.

The technique of powder painting is used with increasing frequency to coat metal surfaces. Solid paint particles are sprayed toward an electrically charged surface and deposited on the surface due to electrostatic forces. Subsequently, in a heated environment (e.g., an oven) the layer of particles melts and the fuse, yielding a smooth coating. Powder painting leads to reduced emissions of volatile organic compounds.

1B. Spray Booths

Fume hoods and spray booths are widely used in industry for removing airborne pollutants from localized production activity such as spray painting, washing work pieces in toxic solvent baths, or welding. Typically a fume hood or spray booth consists of a rectangular shaped enclosure, with one open side. The opposite side consists of some type of filtering mechanism beyond which is positioned an exhaust fan. Fume hoods draw air through the open side, over the process area through the filter banks, and exhaust it to the outside. The aim of the fume hood is to protect spray workers from fumes or aerosols generated during the process and to remove pollutants in the exhaust air. The air within the building containing the spray booth is drawn past the spray worker is then expelled to the outside, and replaced with fresh, filtered and thermally conditioned air, commonly referred to as the "make-up" air. This is an energy-intensive process because of the high required volumes of conditioned air. The American Conference of Governmental Industrial Hygienists (Ref. 1) recommends an air velocity at the open face of a walk-in booth of 75 - 100 fpm.

In spray booths in Southern California the make-up air for each booth annually consumes approximately 16,000 kWh of cooling electricity, and additionally the fan used in the booth itself consumes 11,100 kWh (Ref. 2). There are 10,000 industrial spray booth exhaust chimneys in the Los Angeles area (data from SCAQMD). Thus for all spray booths in SCAQMD this is an annual cost of $14.1 million (at $0.10 per kWh) per 8-hour shift.

Spray booths remove pollutants quite effectively when no spray worker is standing in the open face, partially blocking the airflow. However, when the airflow is partially blocked by a spray worker, an eddy develops in front of the spray worker that draws some of the harmful airborne pollutant (commonly generated near and in front of the spray worker) from the process area toward the spray worker's breathing zone. This eddy results in trapping the pollutant fumes from the paint, and bringing them to the spray worker's breathing zone. The presence of the eddy and its deleterious effect on exhaust hood performance are well documented (Ref. 3-5). Increasing the air speed in the spray booth strengthens the eddy, although not in proportion. As a result, a large air speed is required to reduce the concentration of the pollutant fumes at the spray worker's breathing zone.

During spraying, paint exits the gun as a high velocity jet of droplets plus air. The velocity may be high enough to cause the paint droplets to bounce off the object being painted and be redirected back into the breathing zone. This phenomena is called bounce-back and is minimized at lower nozzle exit velocities.

1C. Worker exposures to spray fumes

References 6-10 include some of the literature concerning exposures of paint spray workers to aerosols from paint. In general, the aerosols deposit in the respiratory region, the tracheobronchial airways, and the extrathoracic region. These exposures can produce long and short term health problems which may be irreversible. Problems included decrements in central nervous system function; acute neurological symptoms; decrease in forced expiratory volume in 1 second (FEV) and forced vital capacity (FVC); and increased bronchial hyperresponsiveness. A contributory cause could be exposure to volatile organic compounds or other volatile compounds emitted from water-based paints. One study found statistically significant differences for psychiatric parameters indicative of cerebral lesion. Also, statistically significant differences were found for reaction time, manual dexterity, perceptual speed and short-term memory. Some of these results were from exposure levels measured at modern places of work, and were considerably lower than the valid threshold limit values.

2. History of the Airjacket technology

The Airjacket is a new invention (a patent was issued on January 11, 1994) intended to reduce the exposures of paint-spray workers to paint fumes, and simultaneously make it possible to lower the required rates of air flow in paint spray booths, leading to energy savings and reduced costs for air pollution control equipment used with spray booths. The Airjacket concept was based on literature (Ref. 3-5) indicating that a paint spray worker's exposures to paint fumes was largely a result of the formation of a recirculating eddy in front of the spray worker. The eddy develops because the spray worker's body acts as a bluff obstruction to the high velocity air flow into the paint spray booth. The eddy leads to a higher concentration of paint fumes in the breathing zone. The basic idea of the Airjacket is simple: we make the spray worker "transparent" to the airflow by expelling a small amount of air from the chest region of the spray worker in the direction of the air stream, so the air flow patterns in front of the spray worker are the same as if the worker were absent. As the name implies, the spray worker wears a compact light-weight jacket, which is supplied with air. The Airjacket has holes facing the front surface, from which the air is expelled. Air can be supplied to the Airjacket by a stationary fan on the floor, connected with a flexible hose.

Prior to this research project, the Airjacket technology was evaluated by simulating the emissions of pollutants during spray painting and by measuring the concentrations of the simulated pollutant in the breathing zone of a heated mannequin (Ref. 11). A tracer gas (sulfur hexafluoride) and methyl alcohol in water were used to simulate the actual pollutants emitted during spray painting. Two prototypes of the Airjacket were tested on a life-size, heated mannequin located in front of a paint spray booth. A tracer gas was released in front of the mannequin to simulate the release of pollutants during painting. The results of the experiments indicated that it may be possible to reduce spray worker exposure to pollutants in the breathing zone by about a factor of 50 while concurrently reducing the flow through the spray booth by 50%.

3. Scope of this research effort

The primary thrust of this research was to design and build a new Airjacket and test it in use at three field sites. Also available background information was to be collected concerning the number and use patterns of spray paint booths in the South Coast Air Quality Management District as well as the types of paints used and their pollutants. An advisory committee was formed and consulted for the planning of the field studies. Permissions were obtained from the University of California Human Subjects committee (see Appendix). Periodic reports and a final report (this document) on the results of the field studies were to be written.

A detailed list of the tasks related to this project are listed below in Table 1.

Table 1. List of tasks for Airjacket field studies.

Task	**Description**
1	Form a scientific advisory panel to consult on the research plans
2	Collect background data on spray booths in the South Coast Region
3	Collect data on pollutants emitted from paint used in spray-booths
4	Select and evaluate measuring technique for marker compound(s) in paint to be used
5	Setup measuring system
6	Evaluate measuring system
7	Visit field sites used for evaluating Airjacket
8	Design and fabricate Airjacket
9	Obtain permission to use field sites
10	Obtain permission from the Human Subjects Committee of the University of California
11	Collect background measurements of concentrations of marker compound(s) at field sites
12	Conduct field tests of the Airjacket
13	Perform data analysis of measurements collected at field sites
14	Periodic reports and a final report will be made

4. Research Methods

4A. Background Information

One task in the work scope was to collect available background information on paint spray booths and paints used in the South Coast Air Basin. The SCAQMD is the only known source for this information. We identified the types of information desired and asked the SCAQMD project manager to identify the SCAQMD staff that can be contacted to obtain this information. The only information available from the SCAQMD was a distribution of spray booths in the district by size (small and large) and type of business. Information was also requested of Southern California Edison, but no response was received.

4B. Advisory Panel

Another task was to form a technical advisory panel to review the preliminary research plans and provide comments. These and other comments were incorporated into the final sampling plan.

The advisor panel members included:
Jim Cole: Director of California Institute for Energy Efficiency (CIEE)
Ranji George: Program Supervisor at the SCAQMD
Paul Stonas: former Supervisor of Paint Shop at Lawrence Berkeley National Laboratory
Les Michael: California-Occupational Safety and Health Administration (Cal-OSHA)
Eric Auer: United States Environmental Protection Agency (USEPA) Region 9

4C. Review of paint spray practices

To design the Airjacket and the subsequent field studies, we obtained information about spray painting practices. Visits were made to facilities with spray booths and spraying practices observed. The operators of the facilities were questioned about spraying techniques and practices. Experts were consulted about various spray painting techniques and spray nozzle design including advantages and drawbacks and the most likely configuration in which each technique would be used.

In addition to investigating paint spraying methods, the procedures used by actual paint spray workers were observed during visits to spray booths and discussed with spray booth managers. We found that actual spray paint procedures differ considerably from the "ideal" procedures discussed in the literature. In the ideal procedure, the spray worker stands only upstream of the object to be painted and sprays paint only downstream and the object painted is rotated as needed. In actual spray painting, we found that the spray workers sometimes walked around the object to apply spray paint from all directions, thus the spray was sometimes directed perpendicular to or opposite to the direction of air flow. We also noted that spray workers sometimes did not wear protective equipment. Finally, we observed that spray workers' exposures was strongly influenced by the bounce of the air/paint jet of the object being painted, leading to a cloud of paint around the spray worker.

In addition to investigating spray painting techniques, we also investigated the coatings used while spray painting. The coatings used with the technique of powder coating have lower VOCs than conventional liquid coatings and paints. This is the main reason the painting industry is shifting to this method of coating. But not all surfaces, (for example wood) can be coated with this method. For these two reasons, (low VOCs and use on limited materials) powder coating was not chosen to test with the Airjacket.

The technique of airless spraying is mostly used on large objects which will not fit into a spray booth, thus this spray technique was not a candidate for the Airjacket.

Air-powered spraying as compared to air-assisted methods is being used less often because of bounce-back and low transfer efficiency of paint. The Airjacket was not designed to overcome bounce-back , but to eliminate the eddy that forms in front of the spray worker due to the air velocity of the spray booth. HVLP spraying methods are the most common method of spraying in the South Coast District. Also air-powered spraying is no longer permitted in the South Coast District.

Based on the above discussion of paint spraying methods, on the test results for air-powered painting, and on fluid-dynamic principles, the Airjacket is most appropriate for use with HVLP paint spraying and is only appropriate for facilities with a horizontal airflow through the spray booth. Thus, we decided to limit field studies to this type of painting.

4D. Airjacket Design

One of the tasks for this project was the development of a user-friendly Airjacket for use in the field experiments. The design needed to supply air to the chest region at a flow rate of about 15 - 20 cfm and exit at a uniform velocity. The Airjacket needed to be comfortable to wear and to not restrict the movements of the paint spray worker. We experimented with different prototype designs, evaluating comfort, noise level, uniformity of air flow from the Airjacket. Smoke was released in front of prototype Airjackets to observe the effect of the Airjacket airflow on pollutant transport in front of the spray worker.

4E. Analytical Methods

To evaluate the Airjacket performance in field studies, measurements of the breathing-zone concentrations of one or more constituents of paint fumes was required. We investigated the composition of paints and other spray coatings through discussions with a chemist familiar with the emissions of volatile organic compounds from paints, discussions with the managers of paint spray facilities, and reviews of product literature and material safety data sheets. It became obvious that a very large range of paints and coatings are used and that the constituents of paint fumes will vary with the type of paint. If different paints or coatings were used at different field sites, it would be necessary to develop and evaluate distinct sampling and analytical procedures for each study site. Therefore, the decision was made to standardize the type of coating.

After discussions with the manager of a paint spray facility, a commonly-utilized lacquer was selected as a prototype coating for the field studies. This lacquer has three volatile compounds which were evaluated for suitability as marker compounds. The compounds are 2-butoxyethanol (CAS # 111-76-2); 1-methoxy-2-propanol (CAS # 107-98-2); and 2-(2-ethoxyethoxy) ethanol (CAS # 111-90-0). Pure sources of each compound were used to check each compound for use as a marker. Each compound was tested with an infrared analyzer for minimum detection concentration, linear response and spectrum response. The spectrum response for all three compounds were similar and had one peak in common near 3.45 micrometers. After these experiments, this lacquer was determined to be suitable for the field studies.

The sampling and analyses procedures used in the field study to quantify a spray worker's exposure to paint fumes had to be appropriate for the expected large temporal variations in pollutant concentrations at the breathing zone and a very wide range of possible time-average concentrations at the breathing zone.

To obtain near real-time data indicating how spray workers' exposures vary with time a stream of sample air was continuously collected from the breathing zone and passed through an infrared analyzer (variable wavelength infrared spectrometer) with a 20 m path for the infrared beam and with an adjustable infrared wavelength. The infrared analyzer was set at a wavelength of approximately 3.45 micrometers, which, based upon laboratory experiments, gave the best response of the infrared analyzer to volatile marker compounds in the lacquer being sprayed. The primary drawback to this procedure is that the marker compounds have overlapping absorption bands at this wavelength, so we can not determine the concentrations of individual marker compounds. Thus, this technique provided real-time information on the relative magnitude of exposure, but not absolute concentrations, to lacquer fumes associated with the combined presence of these marker compounds with and without Airjacket use. The real-time data provided information on the activities that led to high exposures.

The infrared analyzer has a 5 liter sample cell. To measure real-time fluctuations in, but not absolute levels of, the marker compound concentrations, this cell was continuously flushed with sample air at a high rate of flow of 20 lpm. During sampling, data were logged every second over a range of 0 - 1 volt (1 volt is equivalent to 100% IR transmittance) to a precision of 0.002 volts. For concentrations of approximately 30 parts per million of the marker compounds (approximately equal to their Threshold Limit Value- TWAs), the infrared absorbance (decrease in infrared transmission) is approximately 30 to 40 times greater than estimated precision of the absorbance measurement. To check the operation of the analyzer, air samples were drawn at the beginning and end of each day's sampling, with and without a volatile organic compound (VOC) filter. The infrared analyzer was checked by the manufacturer before field measurements.

To measure the absolute concentrations of each of the three marker compounds, for each configuration tested, the continuously sampled air was passed through glass tubes with solid sorbent. The sorbent tubes would later be analyzed to obtain time-integrated concentrations values for comparison to exposure limits such as threshold limit values, TLV, set by various agencies. Also, the influence of the Airjacket on spray workers exposures to paint fumes were assessed by comparing the time integrated concentrations measured with Airjacket operation to the time-integrated concentrations without Airjacket operation.

For all configurations tested, backup and duplicate samples on sorbent tubes were collected. The tubes were analyzed using gas chromatography with a flame ionization detector (GC-FID). For quality control, sample blanks and spiked tubes were analyzed with each batch of samples tubes. Blank tubes were made by opening the tube ends and then immediately capping them. Three sorbent tubes were spiked by injecting different known dilute concentrations of a mixture of the three marker compounds.

The overall sampling plan is shown in Figure 1. Air was sampled from the breathing zone of the spray paint booth worker with and without the Airjacket operating while the spray worker was spraying the coating on an object in the spray booth. Sampling started when the spray worker commenced spraying and finished when he was done, sample periods varied from 4 to 9 minutes. The sample air was filtered for particulates, then sent through sorbent tubes and the infrared analyzer. Simultaneous sorbent tube sampling was done outside the spray booth to determine the background concentrations of the marker compounds in the air entering the spray booth. To minimize the loss of marker compounds when the sample was drawn through the sample line, all sampling was through Teflon and copper tubing.

The potential loss of marker compounds when the sample air is drawn through a sample line was investigated before field sampling. This was a potential issue when the infrared analyzer was used to collect real time data, since this instrument must be located some distance from the spray worker. Losses on sample lines would be most problematic when attempting to collect real time data during a short period of high exposure. To characterize sample line losses, we filled a large sample bag with the vapors from the lacquer and then analyzed samples drawn from this bag through a short length of metal tubing (the reference case with minimal losses) and then through a 60 ft length of Teflon tubing. To simulate a spike in concentration at the breathing zone, the infrared analyzer initially sampled room air, then sampled air from the sample bag for a period of only three minutes. The infrared absorbance at 3.45 microns was monitored over time. The correspondence of results, i.e., corresponding analyzer voltage within approximately one minute of initiating the sampling the paint fumes, with and without the length of Teflon tubing in the sample path, indicates that the sample line losses were close to negligible. We also monitored the infrared absorbance versus wavelength for samples drawn through both the short metal (reference) and long Teflon sample tube and obtained very similar results. Thus, we confirmed that this length of Teflon tubing can be used for measurements of the marker compounds.

All sorbent tube sampling was performed in duplicate for estimating measurement precision. The air from the breathing zone of the spray worker was also drawn through paired sorbent tubes in series. The second sorbent tube in series was used to check for sample breakthrough and to quantify the breakthrough if it occurred. Breakthrough occurs when high concentrations of the marker compounds saturate and, thus, passed through the first sorbent tube. The sample flow rate for the sorbent tubes, as specified in NIOSH and OSHA Air Sampling Methods, was measured during each run and was nominally 100 ml/min. All sample flowrates, were maintained and measured with an accuracy of at within ±5% except for unstable one pump at Site 1, in which sample flowrates varied by as much as 50%. (The data from the samples with an unstable sample flow rate were not utilized.)

The sorbent tubes were sent to an analytical laboratory recommended by the Lawrence Berkeley National Laboratory Environmental Health and Safety Office. This analytical laboratory is an American Industrial Hygiene Association IH Accredited Laboratory. All samples were analyzed with a gas chromatograph using a flame ionization detector (GC-FID) following NIOSH and OSHA standard methods of analysis. The concentration for all three compounds were reported in parts per million (ppm). Samples were sent to the laboratory in four batches. The first two batches were from field Site 1 and the last two batches were samples from field Sites 2 and 3. With each batch of tubes, at least one blank tube and three tubes spiked with known quantities of all three compounds were sent for analysis. The concentrations of all compounds were checked for correlations with each other. Also, the repeat measurements were compared to each other. Finally the measured concentrations of the spiked tubes were compared to predicted values. Also, plots were made of the real time data over each sample period, to look for possible relationships between breathing zone concentrations and spray worker behavior.

4F. Field Studies

The sampling methods and protocols were reviewed by the technical advisory committee. Comments concerning the proper use of sorbent tubes were incorporated into a revised sampling plan.

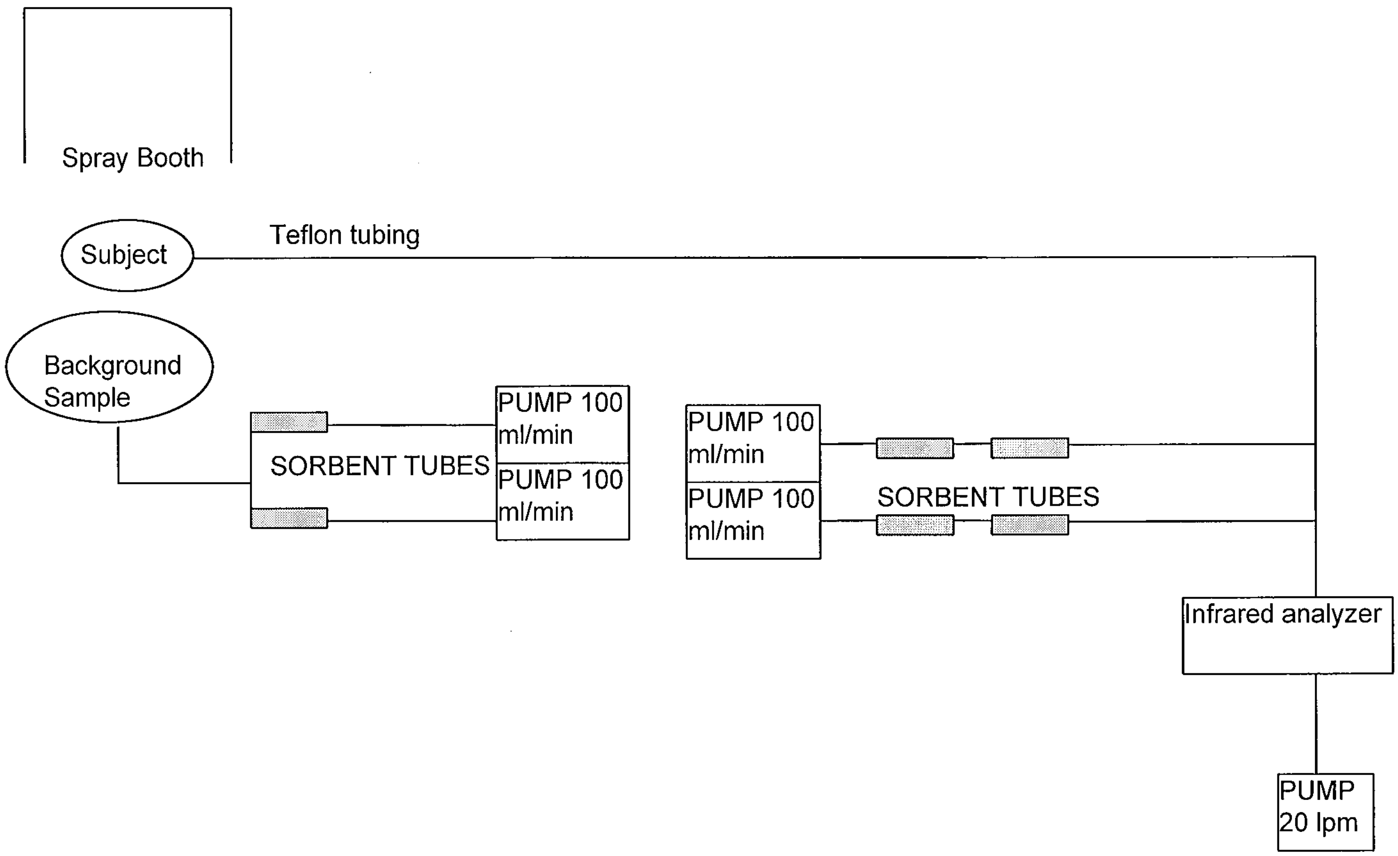

Figure 1. Diagram of measurement system

At each site, the spray booth dimensions were measured as well as inlet velocities. The velocities were measured at 12 or more equally spaced points at the inlet of the spray booth with a hot wire anemometer. Also, the flow rate through the pump supplying air to the Airjacket was measured each time it was used.

At each field site, a set of five (three for the last two tests at Site 3) identical bookcases (2 ft wide x 5 ft high x 9.25 in deep) were sprayed with the same lacquer, using HVLP spray guns supplied by the spray workers. The spray workers always wore the Airjacket and measurements were made with the Airjacket supply air on or off. At Site 1, the flow rate through the spray booth was reduced to approximately half the normal flow rate during a subset of tests.

For the first set of tests at each site, the spray workers were given no directions as to how to orient the bookcases in the booths. The spray workers were simply asked to spray the front, sides and top of the bookcases using their normal procedure. During the second set of tests at Sites 2 and 3, the spray workers were asked to try to spray the bookcases with the spray nozzle always pointed downstream relative to the air flow in the spray booth.

Site 1 is in Northern California where the spray booth is used daily to spray wooden furniture such as bookcases, shelves and desks. The spray booth has a water spray to filter the exhaust air. During the second set of tests, the reduction in flow was accomplished by partially blocking the exhaust fan grille. Site 2 is at a university in Southern California, where the spray booth is again used daily to spray wooden and metal objects for use around the campus. This spray booth also has a water spray to filter the exhaust air. Site 3 is a small industrial shop in Southern California that does spray painting and coating of metal and wooden manufactured parts. There are two spray booths, one for powder coating and the other for HVLP spraying. The spray booth has particulate filters for the exhaust air.

All spray workers signed the informed consent form, approved by the Human Subjects Committee, prior to participating in the study. Also, all of the employers of the paint spray workers were paid for the use of their facilities, as if the experiments were a normal spray paint job.

5. *Results*

5A. Background Information

As a part of Task 2, listed above, the SCAQMD provided data regarding the number of spray booths (in the SCAQMD geographical region) sorted by SIC classification as of Feb 1993. The number of spray booths operated by small businesses was 1,052 and by large businesses was 9,995. Table 2 lists percentages for some types of businesses using spray booths in the SCAQMD.

Table 2. Percent of small and large businesses using spray paint booths by type of business.

	Small	**Large**
Undefined	27%	9%
Food and Kindred Products	1%	4%
Lumber and Wood Products	4%	3%
Furniture and Fixtures (wood related)	2%	4%
Metal coating and allied services	3%	4%
New and Used Car Dealers	2%	3%
Automotive Repair Shops	41%	25%

Overwhelmingly the largest users of spray booths in the SCAQMD are related to the automobile industry. However, for painting of automobiles the air flow in spray booths is generally vertically downward. A small but significant percentage of businesses use spray booths related to wood products such as furniture.

No data were available from the SCAQMD related to the distribution of sizes (other than large and small), operating hours, flow rates and emission controls of spray booths in the region. Also, types of paint, lacquer or other coating material were not available from SCAQMD. Southern California Edison was contacted but did not provide any information regarding energy use in spray booths in the region.

5B. Paint and Coating Pollutants

In the SCAQMD as well as many other regions of the country, the push is for low- or no-VOC paints and coatings. This is due to the Clean Air Act of 1990 requiring state and local governments to increase air quality. To comply with the Clean Air Act, paint manufacturers have been formulating fewer coatings with solvents that have high VOCs and more coatings that are water-based (Ref. 12). Paint manufacturers are trying to reduce the amount of aromatic and aliphatic solvents such as toluene, xylene and mineral spirits. These solvents are being replaced by less-hazardous solvents and solvents that are less photochemically reactive such as butyl acetate, ethyl acetate, propylene glycol-based products, some ketone-based products and dibasic esters.

5C. Airjacket Design

The Airjacket consists of an array of closely-spaced parallel plastic tubes with holes through which the air exits. The final Airjacket design, illustrated in Figure 2, is simple, light weight, and compact. The array constructed of plastic tubing, clips onto the shoulder straps of a small modified back-pack (with the normal storage compartment removed). The Airjacket consisted of a horizontal array 8 inches long by 6 inches high of five 0.75 inch diameter PVC tubes and spaced 1.25 inches apart. Each tube contained approximately 75 holes 0.09 inch diameter, for the air to exit.

The air supply to the Airjacket was air drawn from outside of the spray booth and delivered to the Airjacket through tubing. To obtain the desired quantity of air, greater than 15 cubic feet per minute, through a reasonably small and light weight tube, the fan had to operate overcome a large resistance (e.g., 40 inch of water). A 0.5 horsepower regenerative blower (commonly called a ring compressor) was selected and purchased for this application. With 30 feet of 0.75 inch diameter tubing between the regenerative blower and the Airjacket, the supply flow rate was approximately 20 cubic feet per minute. This flow rate was monitored during each test with the air supply operating and was nominally 20 cfm.

Spray workers were not specifically asked about the level of comfort of wearing the Airjacket, but none of them complained about wearing it.

5D. Results of Field Studies

Results of all tests with the Airjacket are presented in Table 3 which lists percent change in concentrations as compared to the average baseline concentrations for each site. For each site, the baseline configuration is defined as spraying with the air supply to the Airjacket off, the spray worker applying the lacquer as he normally would and the spray booth flow rate at the normal flow rate for each site. At Site 1 the baseline concentrations are the average values of Tests 1 and 6. At Site 2 the baseline concentrations are the average values of Tests 8 and 13. Thus the percent change from baseline for Tests 1 and 6 and Tests 8 and 13 will be equal in magnitude and opposite in sign and provide a measure of repeatability of measured concentrations at Sites 1 and 2 respectively. At Site 3, there are two baseline configurations defined, one with three bookcases and the other with five.

Figure 2. Photographs of Airjacket in use at Site 1. Sprayer is wearing Airjacket with breathing zone sample point attached to shoulder.

Table 3. Percent change in concentration from baseline at each site. Baseline is Airjacket supply flow off, standard spray technique, and normal spray booth air flow rate. Positive values indicate higher concentrations than baseline. Results for each site have been sorted by concentration.

					Percent Change from Baseline		
Test	**Site**	**Airjacket Flow**	**Spray Technique**	**Spray booth Flow**	**Compound 111-76-2**	**Compound 107-98-2**	**Compound 111-90-0**
1 (B)†	1	Off	Standard	Normal	-25%	-19%	-41%
2	1	On	Standard	Normal	-23%	-14%	-51%
3	1	On	Standard	Normal	0%	-2%	-2%
4	1	On	Standard	Reduced	3%	6%	22%
5	1	On	Standard	Reduced	8%	11%	20%
6 (B)	1	Off	Standard	Normal	25%	19%	41%
7	1	Off	Standard	Reduced	61%	75%	47%
8 (B)	2	Off	Standard	Normal	-17%	-14%	-52%
9	2	On	Standard	Normal	-3%	-5%	-40%
10	2	On	Standard	Normal	-1%	-7%	28%
11	2	On	Downstream	Normal	0%	-7%	43%
12	2	Off*	Downstream	Normal	0%	-11%	61%
13 (B)	2	Off	Standard	Normal	17%	14%	52%
14	2	Off	Downstream	Normal	23%	14%	83%
15	3	On	Downstream**	Normal	-14%	-16%	-8%
16 (B3)	3	Off	Downstream**	Normal	0%	0%	0%
17 (B5)	3	Off	Standard	Normal	0%	0%	0%
18	3	On	Standard	Normal	31%	21%	16%

† B denotes baseline. The baseline values for Site 1 are the average values of Tests 1 and 6. The baseline values for Site 2 are the average values of Tests 8 and 13.
B3 baseline with 3 bookcases
B5: baseline with 5 bookcases
*Air supply to Airjacket was on but air supply hose was kinked.
** Three bookcases sprayed.

Figures 3-5 show the breathing zone concentrations of Compounds 111-76-2 and 107-98-2 for all tests at each site. From the plots, two significant inferences concerning the results of tests of the Airjacket can be made. First, the plots show that the measured concentrations of Compounds 111-76-2 and 107-98-2 were highly correlated ($r^2 > 0.87$). Second, the plots show no significant change in measured concentrations at different configurations tested. In many cases, the variability in concentrations at identical configurations is greater than the variability in concentrations between different configurations.

Figure 6 shows the orientation of the bookcases at each site. At Site 1, the spray worker oriented the bookcases along one side wall of the spray booth. This forced the spray worker to often point the spray nozzle perpendicular to the flow in the spray booth while spraying. At Site 2, the spray worker oriented the bookcases side by side across the inlet to the spray booth. Thus the spray worker usually had his back to the flow of the spray booth while spraying. At Site 3 for the first two tests, the bookcases were oriented sideways across the inlet to the spray booth. With this orientation, the spray worker had to turn sideways to the flow of the spray booth to spray the front of the bookcases.

Each spray worker moved around the bookcases to spray both sides, top and bottom of the bookcases. This forced the spray workers to sometimes not be facing downstream while spraying. Based upon preliminary results from Site 1, for the second set of tests at Sites 2 and 3, the spray workers were asked to spray facing strictly downstream and not move around the bookcases. With this request, the Site 2 spray

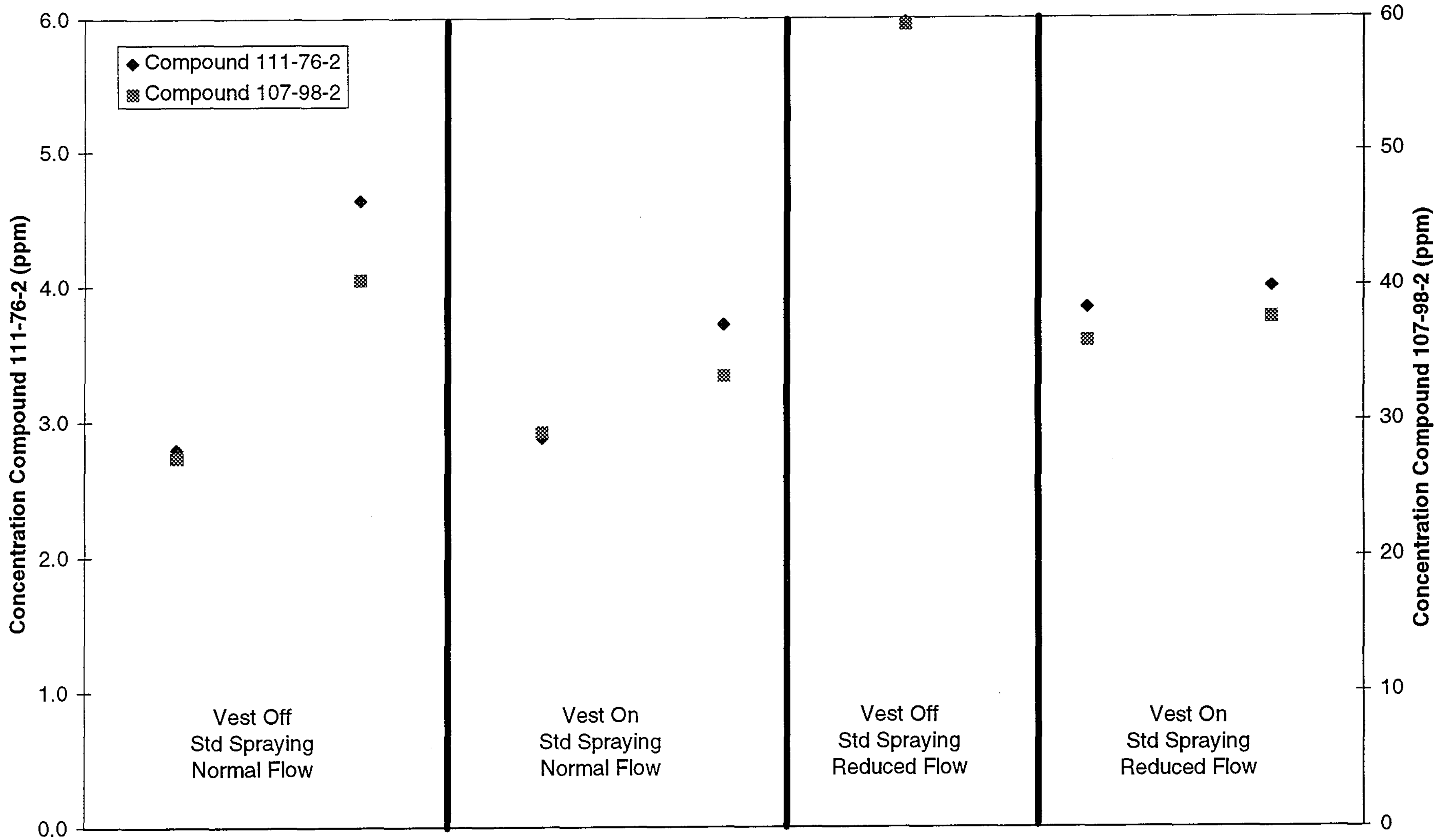

Figure 3. Breathing zone concentrations of Compounds 111-76-2 and 107-98-2 at Site 1.

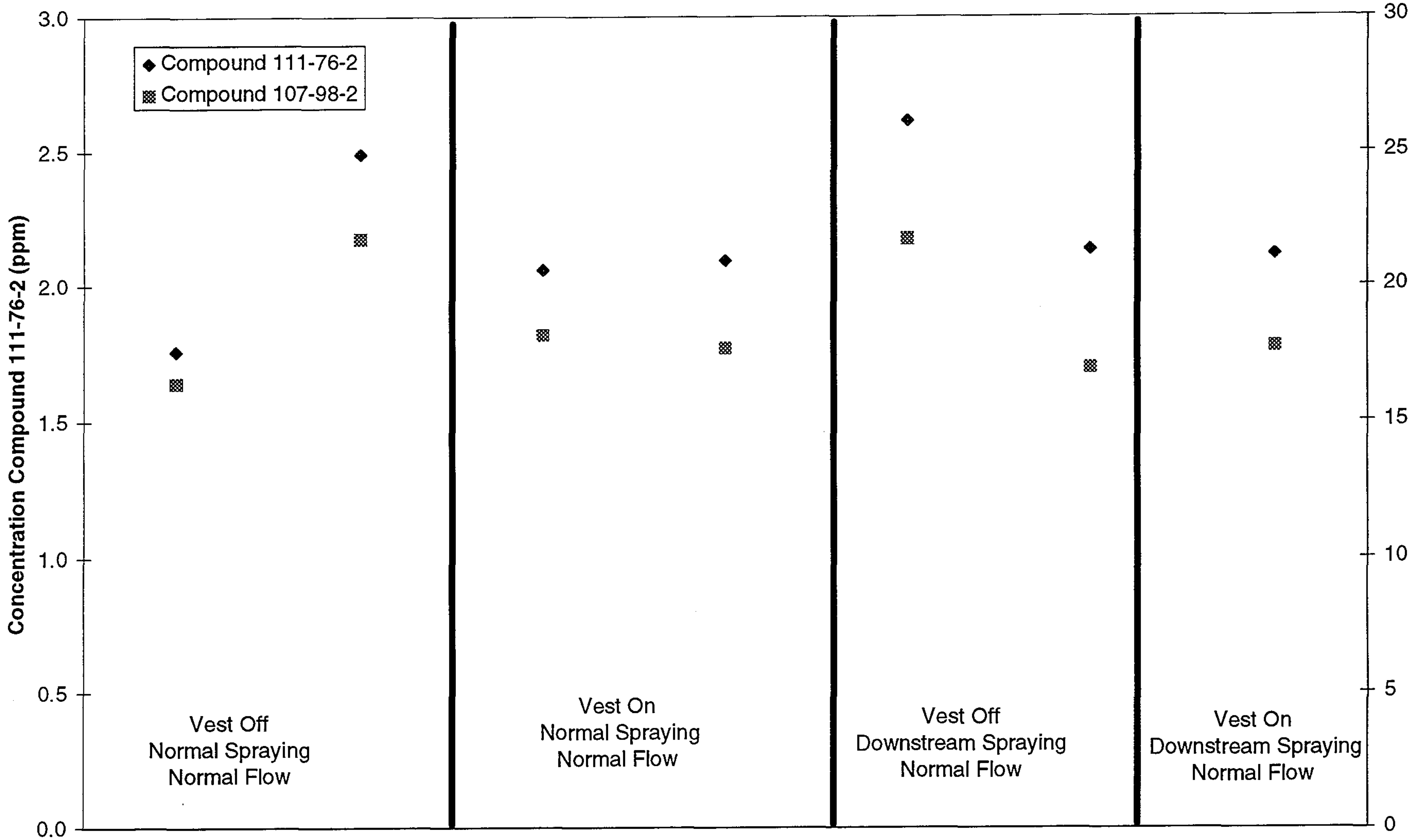

Figure 4. Breathing zone concentrations of Compounds 111-76-2 and 107-98-2 at Site 2.

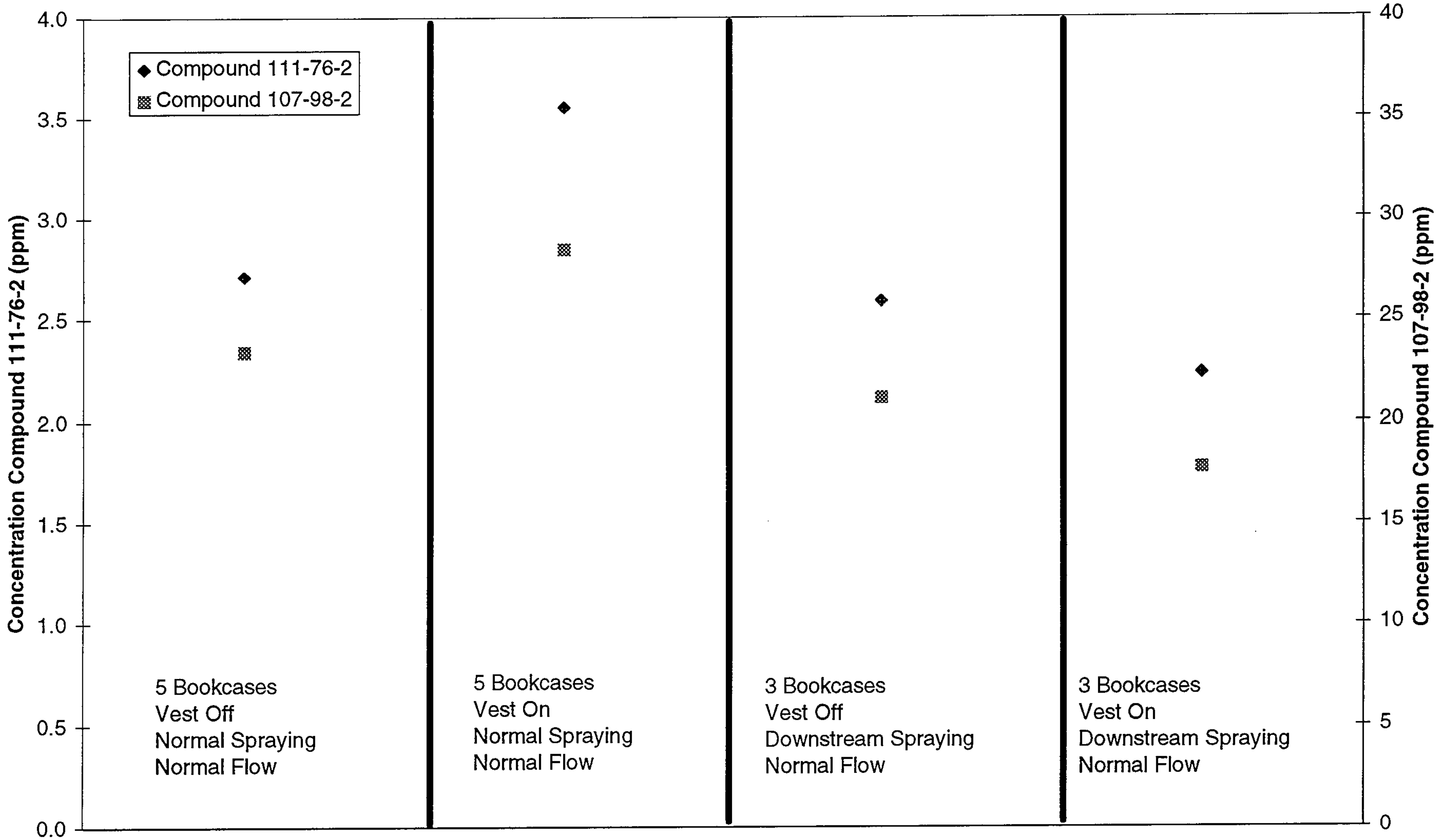

Figure 5. Breathing zone concentrations of Compounds 111-76-2 and 107-98-2 at Site 3.

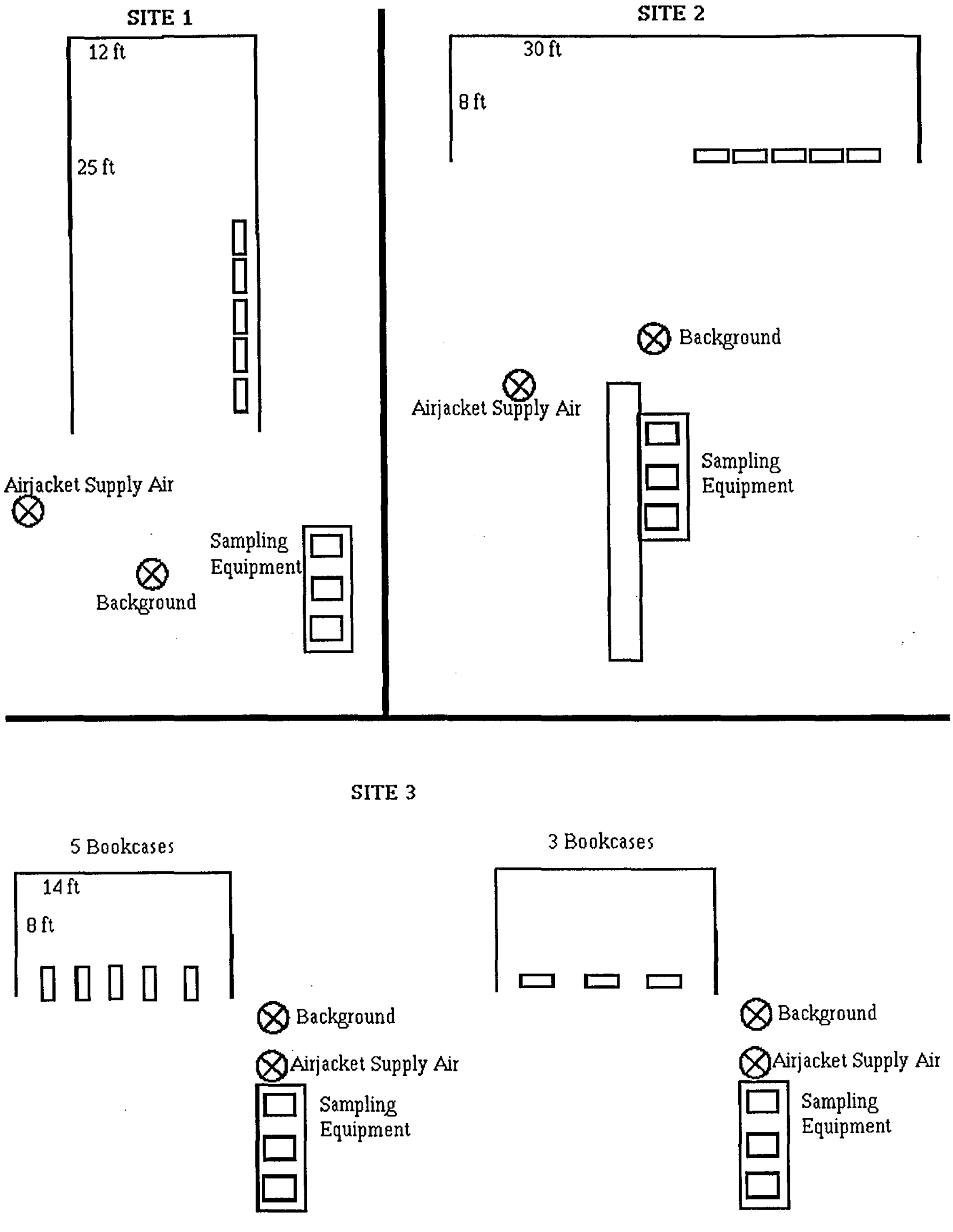

Figure. H Field site spray booth dimensions and location of bookcases, sample points and Airjacket supply air.

worker placed the bookcases on dollies with wheels, so the bookcases could be rotated during spraying. At Site 3, two bookcases were taken out of the spray booth and the remaining three were oriented side by side in the spray booth inlet.

Table 4 below lists spray booth inlet velocities and dimensions for each site. The velocities at Site 3 are about half of the velocities at Sites 1 and 2. The flow rate at Site 1 was reduced by about one-half for the second half of tests. The booth at Site 3 was not wide enough to allow the spray worker to easily spray all five bookcases oriented side by side. About half of the width of the booth at Site 2 was used for spraying all five bookcases.

Table 4. Spray booth dimensions, inlet velocities and flow rates.

Site	W x H x D (ft)	Average Velocity(fpm)	Flow rate (cfm)
1	12 x 7.7 x 25	91	8,408
1 Reduced	12 x 7.7 x 25	51	4,712
2	30 x 10 x 8	95	28,500
3	14 x 7.5 x 8	59	6,195

During each test, the background concentrations of the air outside the spray booths were measured using the sorbent tubes. Except for Tests 17 and 18 all of these background concentrations were below the detection level of the GC used for analysis (detection level was about 0.5 ppm for all compounds). For Tests 17 and 18 the background concentration of Compound 111-76-2 was 0.6 ppm.

All of the concentration measurements for all compounds analyzed with the sorbent tubes were below the time weighted average (TWA) or short term exposure limit (STEL) threshold limit values (TLV), found on MSDS, see Table 5 (in Appendix). The greatest measured concentration of the three compounds, 60 ppm for Compound 107-98-2, was at Site 1 during reduced spray booth flow and supply air to the Airjacket off.

The first and foremost question to be answered from the measurement results is whether operating the Airjacket substantially decreased exposures of the spray worker to paint fumes during any of the different configurations tested. The results indicate that the operating Airjacket had little or no effect on exposures to the spray worker. In general, the range in measured concentration values, with the sorbent tubes, at identical operating conditions is comparable to the range in concentrations values at different operating conditions (e.g., Airjacket on versus Airjacket off). Also, the real-time plots of measurements at each site are similar and seem to be unaffected by Airjacket operation, see Figures 7 and 8.

We assess below the effectiveness of the Airjacket in three different modes of use. First, while the spray workers used their standard spraying methods with the spray booth airflow normal; second while the spray workers used their standard spraying methods with the spray booth airflow reduced; and third while the spray workers modified their technique to spray only downstream and the spray booth airflow normal.

For the first mode with the spray worker using their standard techniques and the spray booth airflow at the normal setting, at Site 1 and 2, there was about a ± 25% difference in time-integrated concentration values whether the supply air to the Airjacket was off or on. At Site 3, the time-integrated concentrations with the supply air to the Airjacket on, were about 20 - 30% higher than with the Airjacket supply air off. Plots of real time measurements from the breathing zone, appeared to be nearly the same whether the supply air to the Airjacket was on or off.

We studied the second mode, (the airflow in the booth was reduced by about half the normal) only at Site1. In this configuration, the Airjacket with supply air on, time-integrated concentrations were lower by 50 - 60% than with the Airjacket supply air off, but the time-integrated concentration measurements were greater than the baseline (standard spraying technique, normal spray booth airflow and Airjacket supply air off). So the Airjacket may have reduced exposures with the hood flow reduced, but the

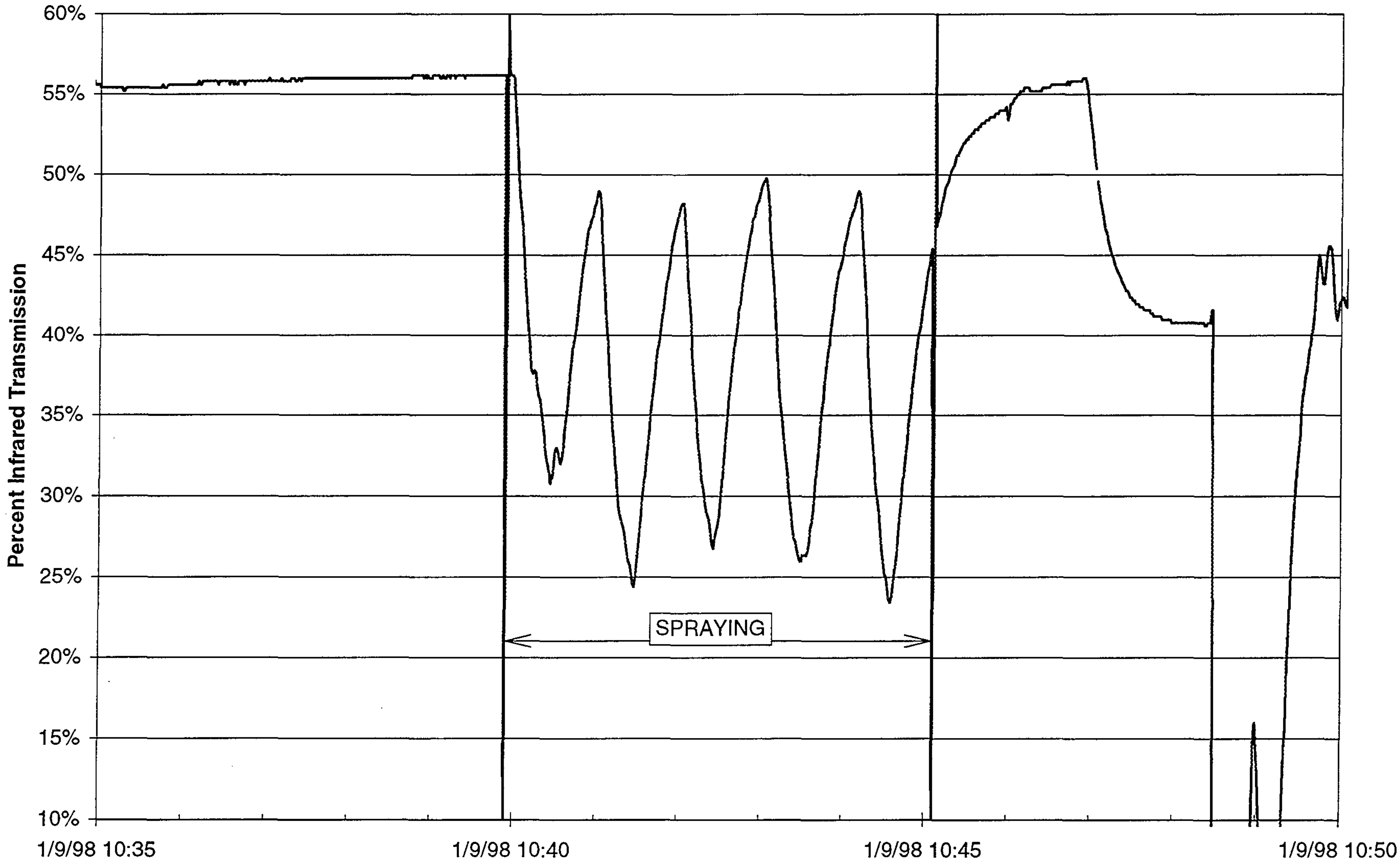

Figure 7. Measured infrared transmission at 3.45 micrometers at Site 2, while Airjacket supply air was Off, Downstream spraying technique and Normal spray booth flow rate, Test 14.

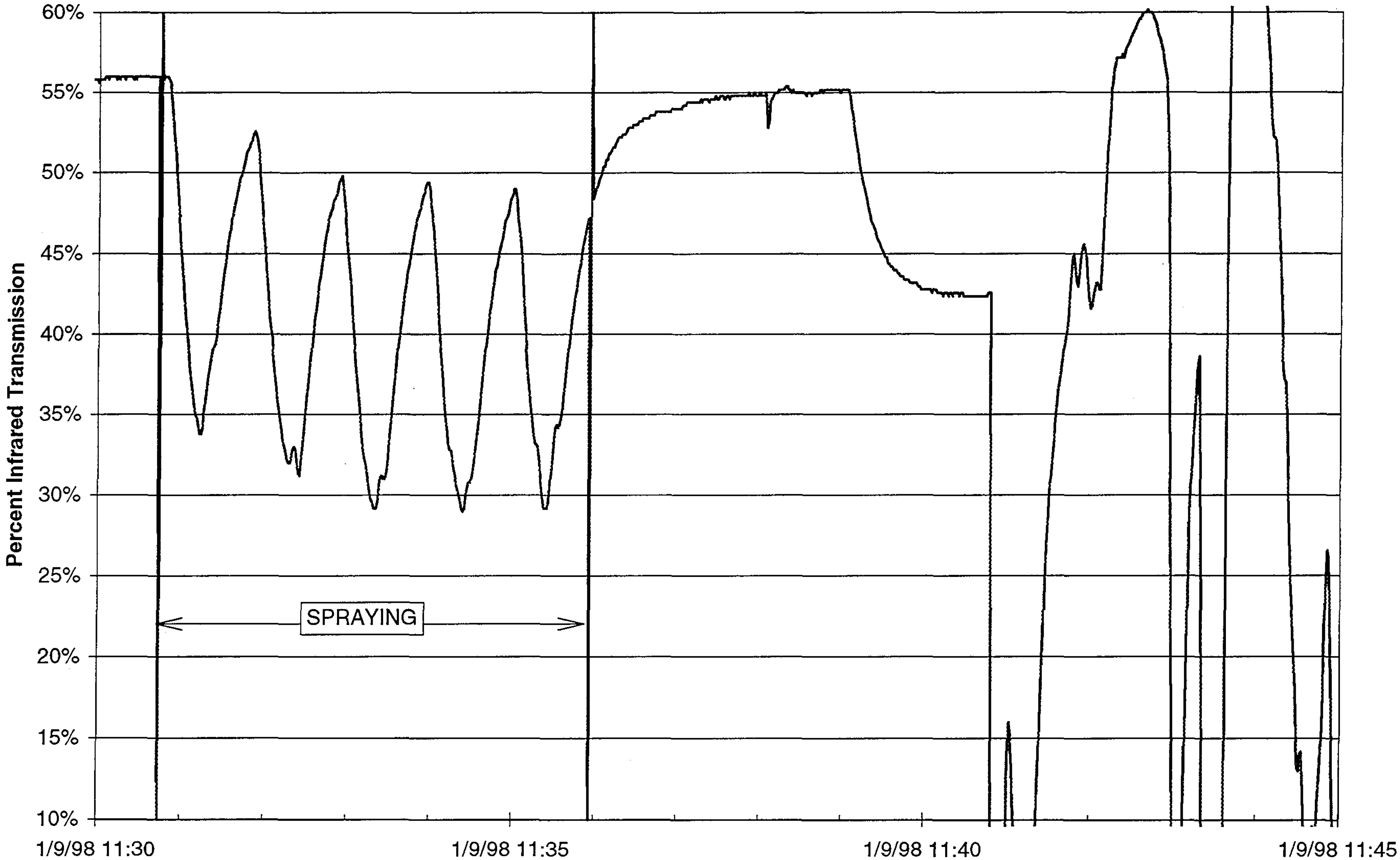

Figure 8. Measured infrared transmission at 3.45 micrometers at Site 2, while Airjacket supply air was On, Downstream spraying technique and Normal spray booth flow rate, Test 11.

reduction was not a large enough to overcome the increase in exposure caused by the reduced flow rate in the spray booth.

Based upon preliminary results from Site 1, the spray workers at Sites 2 and 3 were asked to modify their spraying technique during the second set of tests and to not move around the bookcases while spraying, but to keep the spray nozzle pointed downstream, this is mode 3. At both sites, the decrease in breathing zone time-integrated concentrations with the supply air to the Airjacket on versus off was from 14 - 19%.

As stated above, the real-time IR measurements were gathered to obtain information on the time history of paint fume exposures and not quantify the concentrations in the breathing zone. The real-time IR measurements indicated the exposure to the three compounds at the breathing zone was very periodic/episodic, see Figures 7 and 8. The periodic exposure was evident with and without the Airjacket operating. From plots of real-time measurements it is clear that the exposure to the spray worker is very dependent upon the spraying process. In many of the plots there are distinct peaks corresponding to each of the 5 bookcases sprayed.

To judge measurement uncertainty, four measures were examined. The first is the analysis of blank sorbent tubes. Blank sorbent tubes were always reported as having below the detection limit (the detection limit is about 0.5 ppm for all three compounds measured). The second uncertainty measure is the analysis of the spiked tubes. The spiked tubes were -10% to +20% different from predicted for Compounds 111-76-2 and 111-90-0. For Compound 107-98-2 the measured values were about -9% to 30% different than the predicted. The third determination of measurement uncertainty is to look at repeat measurements. For tests at Sites 2 and 3, the repeat measurements of the sorbent tube concentrations were within ± 10% for all compounds. For tests at Site 1, the repeat measurements were ± 40% due to a pump with unsteady sample flow rates, thus the values from this pump were not included in Tables 3 and 5. The correlation between time averaged concentration values from the sorbent tubes and the time-average output signal from the real-time IR measurements was good ($r^2 > 0.8$). Overall, we estimate that the concentration values reported in Table 5 (in the Appendix) are accurate within about ± 20%.

6. Discussion

Real time and time integrated measurements, indicate the Airjacket does not significantly reduce exposures to spray paint workers while using HVLP spray guns. The variability in repeat measurements at identical operating conditions was comparable to the variability at different conditions, thus, no effect of Airjacket operation is clearly evident. Based on the repeatability of data, we conclude that the Airjacket changes paint fume concentrations in the breathing zone of the spray workers by approximately 25% or less.

The difference between the large reductions in exposures in the breathing zone while using the Airjacket during the proof of concept studies and slight to no reductions in the field studies was most likely due to the behavior of the spray worker. In the proof of concept experiments a mannequin was used that did not move. There were no bookshelves or other objects located close to the mannequin. In the field studies, the spray workers moved around the bookcases sometimes spraying perpendicular to the air flow or even upstream. The movement of the spray workers caused the eddy, that the Airjacket was to eliminate, to not always be in front of the spray worker. Also, the spray workers in the field stood close to the bookcases and held the spray guns about 1 foot from the bookcases. The bounce-back of lacquer spray resulted in a cloud of lacquer aerosols and VOCs which frequently completely enveloped the spray worker. A recommended practice by a large HVLP spray equipment manufacturer is to keep the spray gun at a constant 6" - 8" away from the object, so the spray workers in this study were using recommended spraying techniques. Reviewing standards concerning spray painting in spray paint booths, we found no guidelines concerning the movement of sprayers around an object while spraying.

The real-time data indicated that exposures were very episodic and was dependent upon the position of the spray worker relative to the bookcases. In general, the spray workers at all sites, started at the top of the bookcases and worked downward. From the time history measurements, it seems that the highest exposures were while the spray worker was working near the bottom of the bookcases.

We believe that the Airjacket did not significantly lower exposures while using HVLP techniques because of bounce-back and overspray. The Airjacket may work better with powder coating since there is negligible bounce-back due to low velocity of the ejected powder. Also the Airjacket may work better if the spray worker stood back from the object so that bounce-back and overspray would be reduced, but again this is not recommended practice for HVLP spraying. Also, the Airjacket might be effective where workers wash parts in solvent baths since in there is no bounce-back or overspray.

Since the Airjacket did not significantly reduce exposures, the Airjacket is not a potential source of energy savings. Also, the Airjacket technology does not make it possible to reduce spray booth flow rates (which could lower the cost of associated air pollution control equipment.) At present, there is no evidence that the Airjacket technology has a significant market potential.

The cost of mass production of the Airjacket was not investigated. The Airjacket that was fabricated for this project, cost $70 for parts and, once the design was established, required 8 hours to assemble. The regenerative blower that supplied air to the Airjacket has a retail price of approximately $500.

We found no evidence of excessive long or short term exposures to the spray workers, as compared to published exposure limits. At Site 3, the spray booth flow rate was about half that of Sites 1 and 2, but the concentrations of the three marker compounds were in the same range at all three sites and below published exposure limits.

7. Conclusions

Our experimental findings indicate that the Airjacket does not significantly reduce the exposure of spray workers to paint fumes during HVLP spraying. The difference between ideal and actual spray paint procedures influence the mechanisms driving spray workers exposures to paint fumes and influence the viability of the Airjacket technology. In the ideal procedure, for which the Airjacket was conceived, the spray worker's exposure to paint fumes is due largely to the formation of a recirculating eddy between the spray worker and the object painted. The Airjacket ejects air to diminish and ventilate this eddy. In actual practice, exposures may result largely from directing paint upstream and from the bounce-back of the air/paint jet of the object being painted. The Airjacket, would not be expected to dramatically reduce exposures to paint fumes when the paint is not directed downstream or when the bounce-back of paint on the object creates a cloud of paint aerosols around the spray worker.

8. Acknowledgments

We would like to thank Alfred Hodgson for advice concerning the measurement of VOCs in paints.

This research was supported by the South Coast Air Quality Management District and the California Institute for Energy Efficiency (CIEE).

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Appendix 1. Human subjects protocol

The Lawrence Berkeley National Laboratory requires that a human subjects protocol be prepared and approved when research involves human subjects. "Human subjects mean a living person about whom a researcher obtains data through interventions ...... or interaction (for example, interviews) with the person........" Based on our prior research experience, we anticipated only a modest effort to develop an approved human subject protocol, or a waiver from the requirement to develop a protocol, since the planned research did not include collection of data about persons. Unfortunately, the start of this project coincided with a time period in which prior potentially unethical human subject experiments supported by the US government became a national issue, repeatedly discussed in the newspapers and on television news. Obtaining waivers or approved protocols became, in our experience, much more difficult. The UC Berkeley Committee for Protection of Human Subjects denied our request for a waiver, even for pilot studies that measured the concentrations of paint fumes in front of a fully protected spray worker. Therefore, after research plans were established adequately, a full protocol and consent form was prepared and submitted in May of 1996. After several rounds of minor modifications to the protocol, we finally received notice that our protocol was approved in November 1996.

Appendix 2. Measured concentrations of marker compounds and threshold limit values.

Table 5. Time averaged concentrations of three compounds from sorbent tube analysis. Tests at each site are sorted by concentration.

					Concentration in ppm		
Test	**Site**	**Airjacket Flow**	**Spray Technique**	**Booth Flow**	**Compound 111-76-2†**	**Compound 107-98-2†**	**Compound 111-90-0†**
1	1	Off	Standard	Normal	2.8	27.3	0.8
2	1	On	Standard	Normal	2.9	29.2	0.6
3	1	On	Standard	Normal	3.7	33.4	1.3
4	1	On	Standard	Reduced	3.8	35.9	1.6
5	1	On	Standard	Reduced	4.0	37.6	1.5
6	1	Off	Standard	Normal	4.6	40.5	1.8
7	1	Off	Standard	Reduced	6.0	59.5	1.9
8	2	Off	Standard	Normal	1.8	16.4	0.4
9	2	On	Standard	Normal	2.1	18.2	0.5
10	2	On	Standard	Normal	2.1	17.7	1.0
11	2	On	Downstream	Normal	2.1	17.7	1.1
12	2	Off*	Downstream	Normal	2.1	16.9	1.3
13	2	Off	Standard	Normal	2.5	21.8	1.2
14	2	Off	Downstream	Normal	2.6	21.8	1.5
15	3	On	Downstream**	Normal	2.2	17.7	1.0
16	3	Off	Downstream**	Normal	2.6	21.2	1.1
17	3	Off	Standard	Normal	2.7	23.4	1.3
18	3	On	Standard	Normal	3.6	28.5	1.5

†Exposure Limits

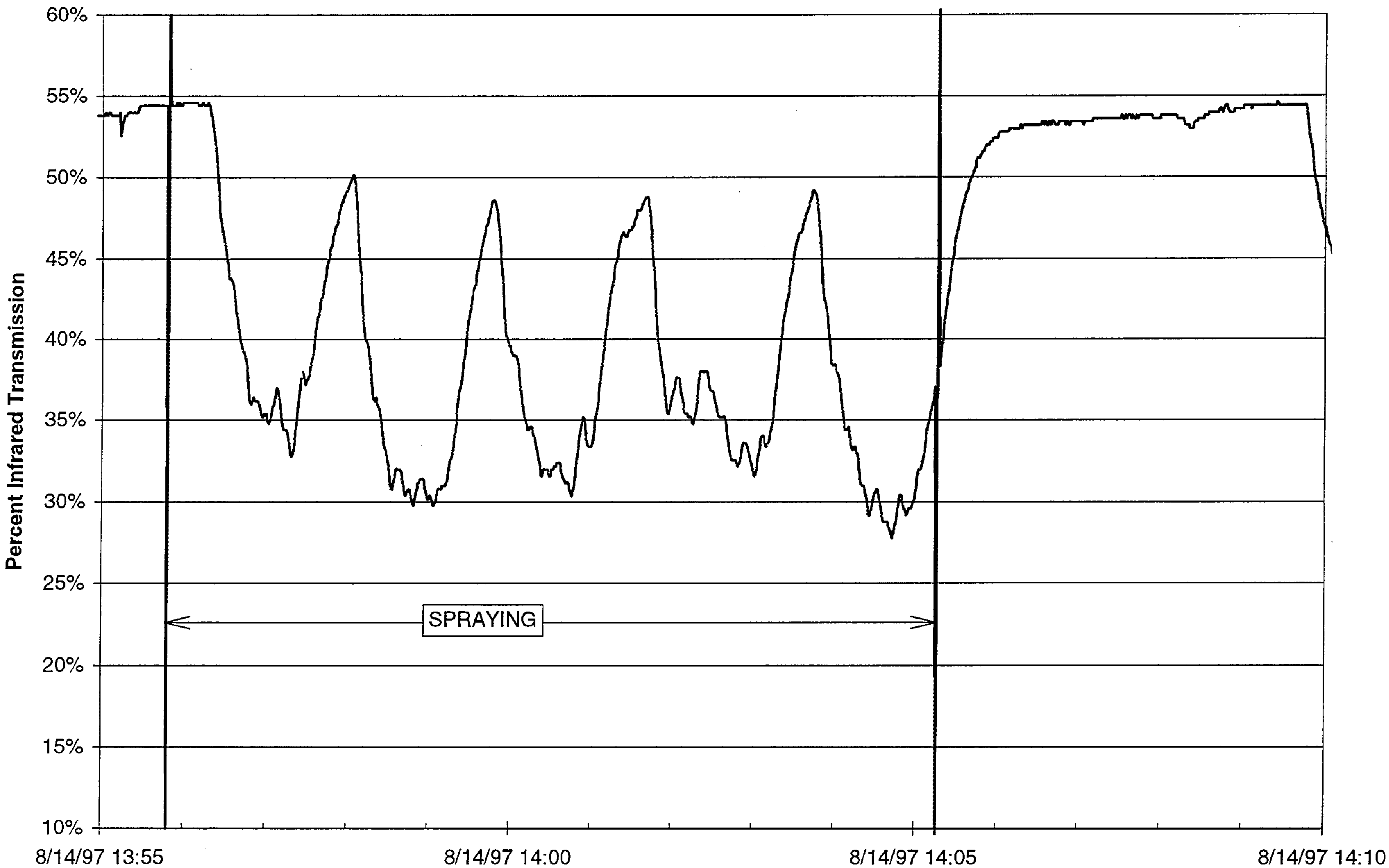
Compound 111-76-2 OSHA PEL-TWA: 50 PPM (SKIN)
ACGIH TLV-TWA: 25 PPM (SKIN)

Compound 107-98-2 ACGIH TLV-STEL: 150 PPM
ACGIH TLV-TWA: 100 PPM

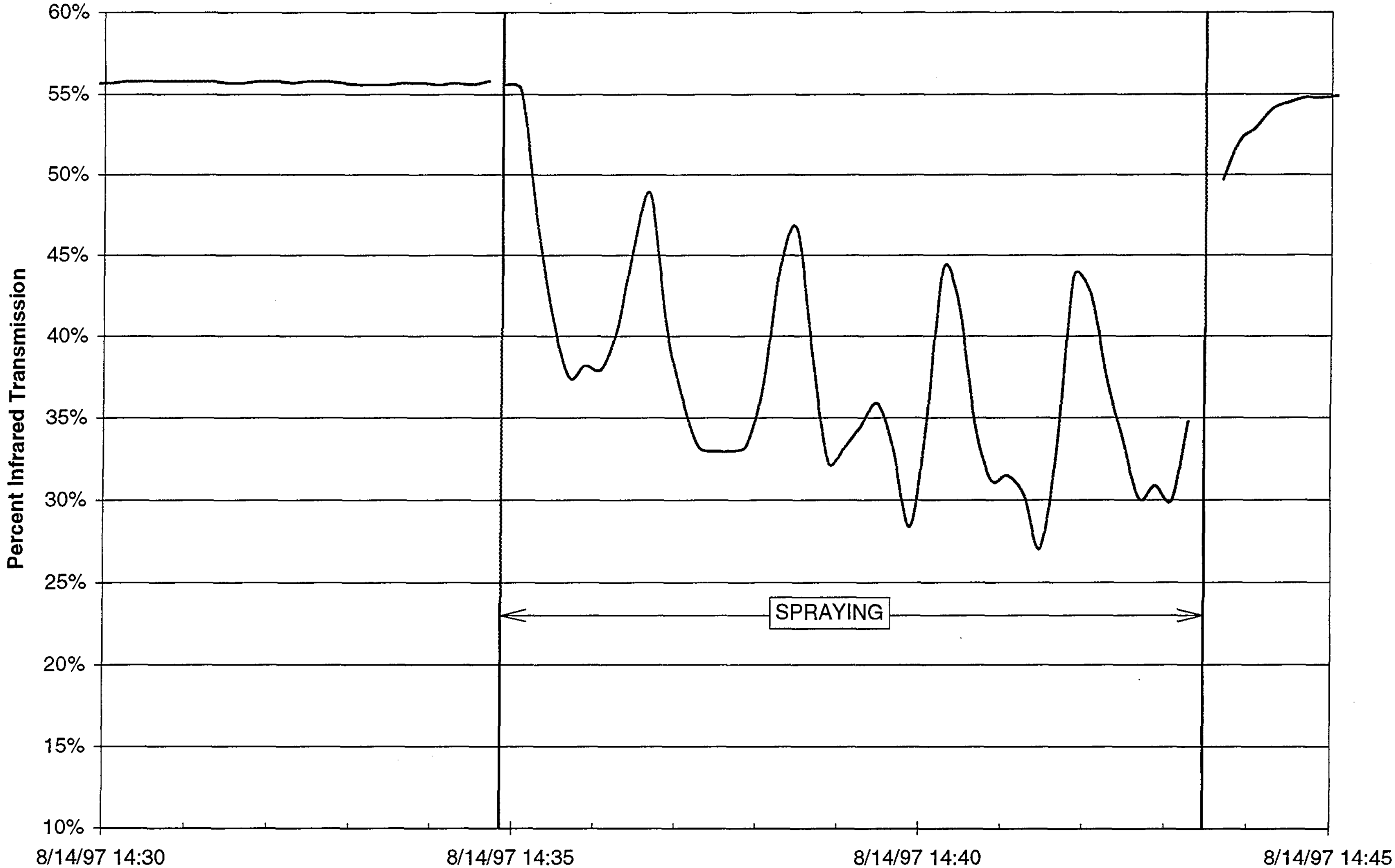
Compound111-90-0 AIHA TWA: 25PM

*Air supply to Airjacket was on but air supply hose was kinked.

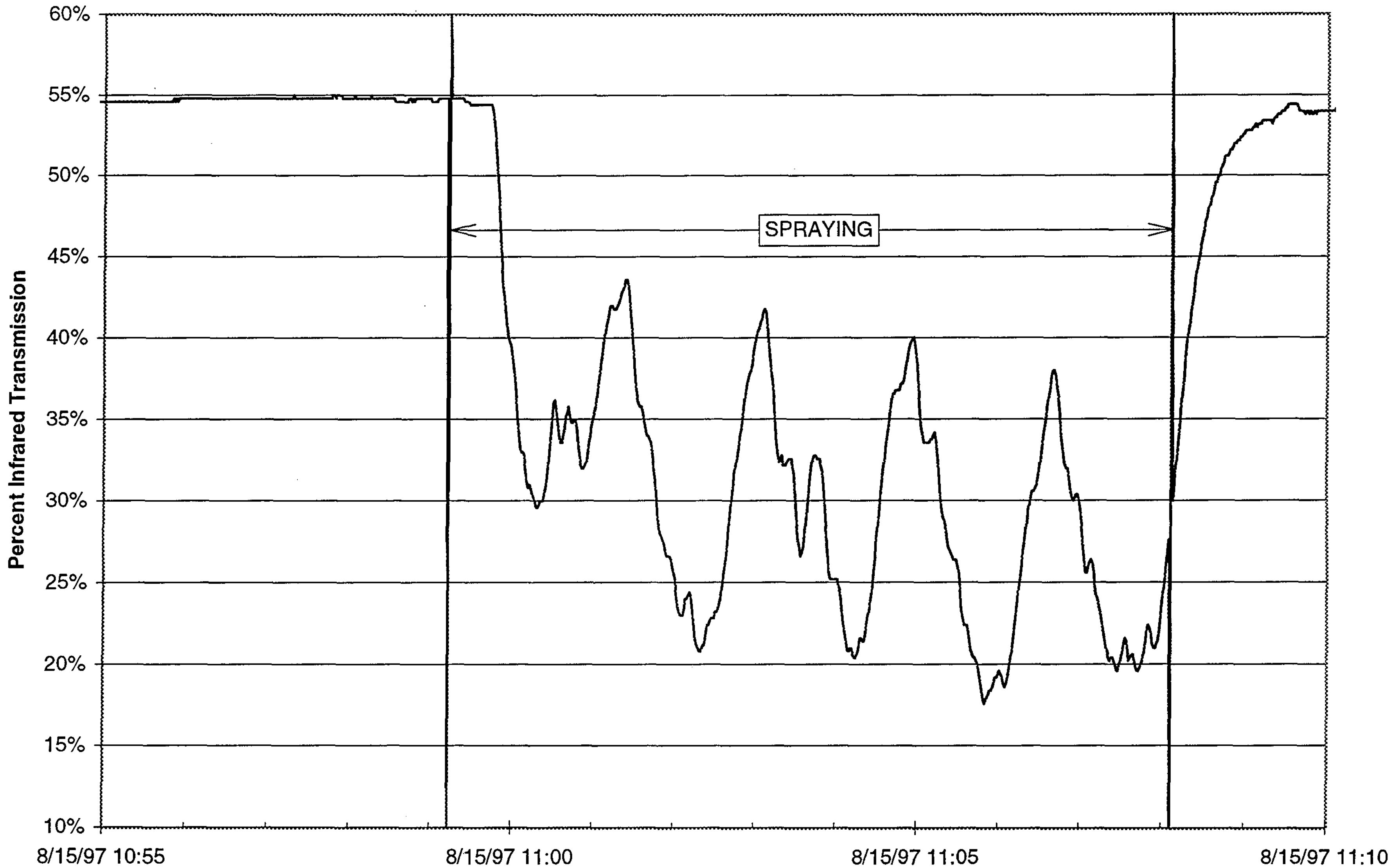
** Three bookcases sprayed.



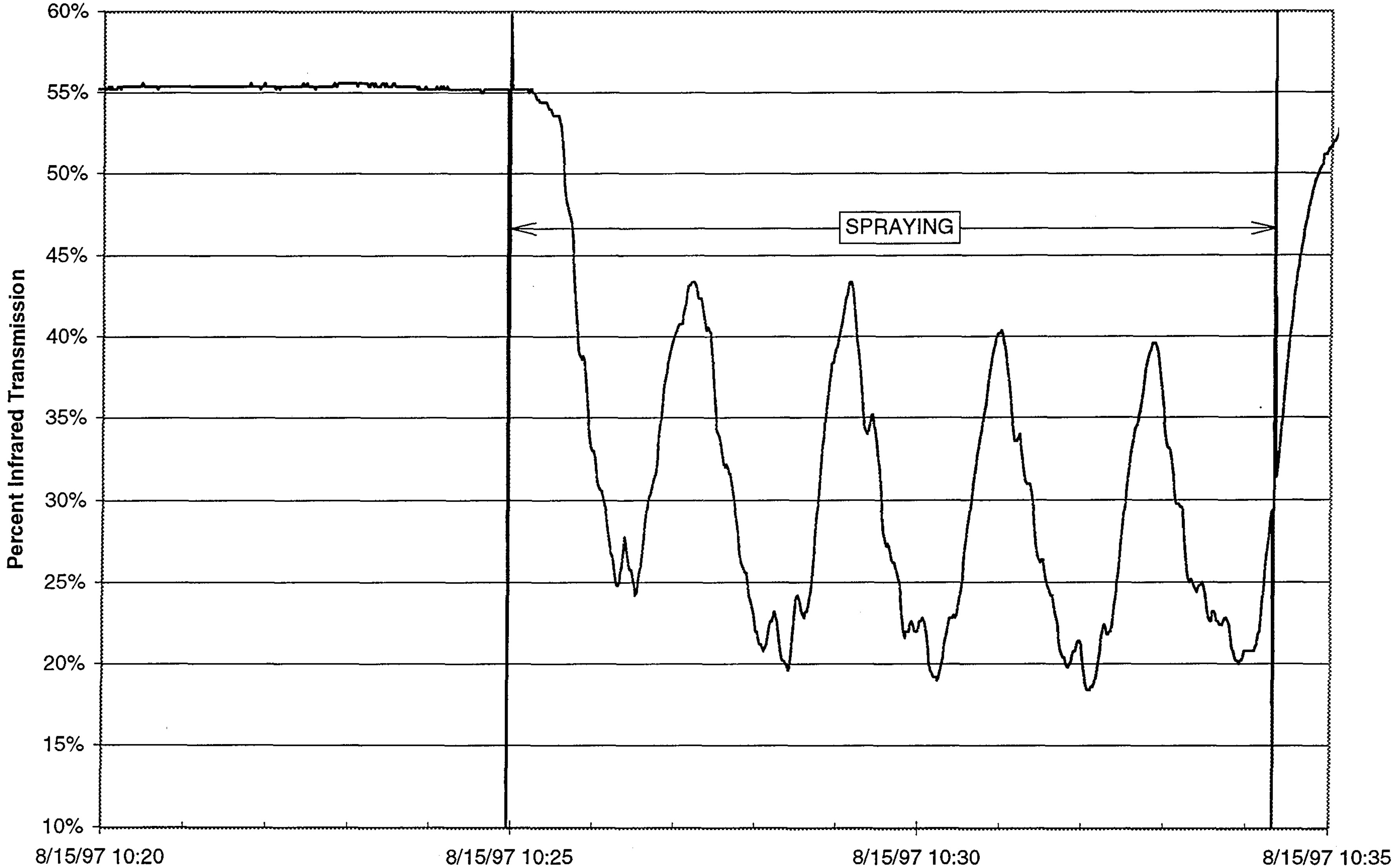
Test 1. Measured infrared transmission at 3.45 micrometers at Site 1, while Airjacket supply air was Off, Standard spraying technique and Normal spray booth flow rate.



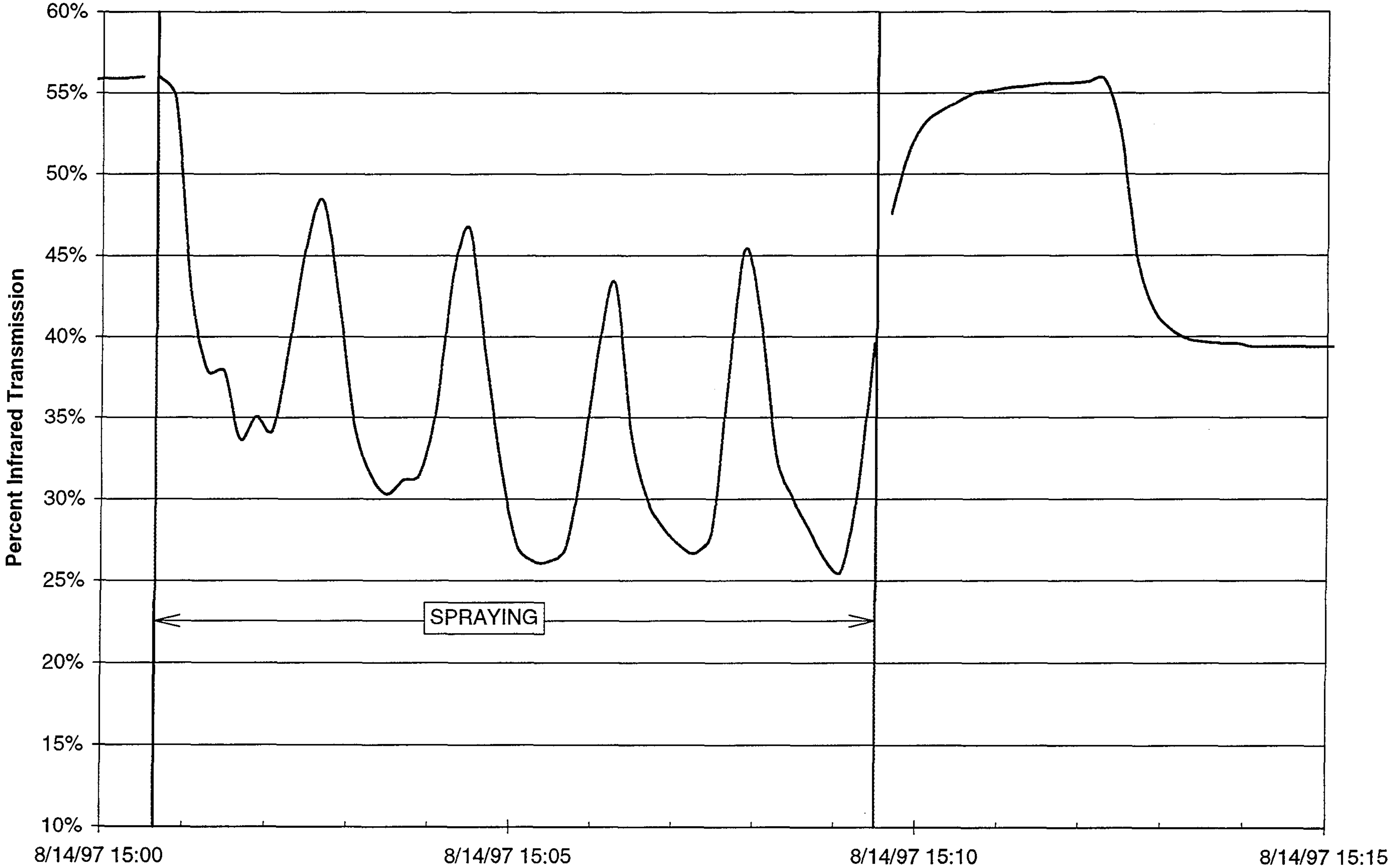
Test 3. Measured infrared transmission at 3.45 micrometers at Site 1, while Airjacket supply air was On, Standard spraying technique and Normal spray booth flow rate.



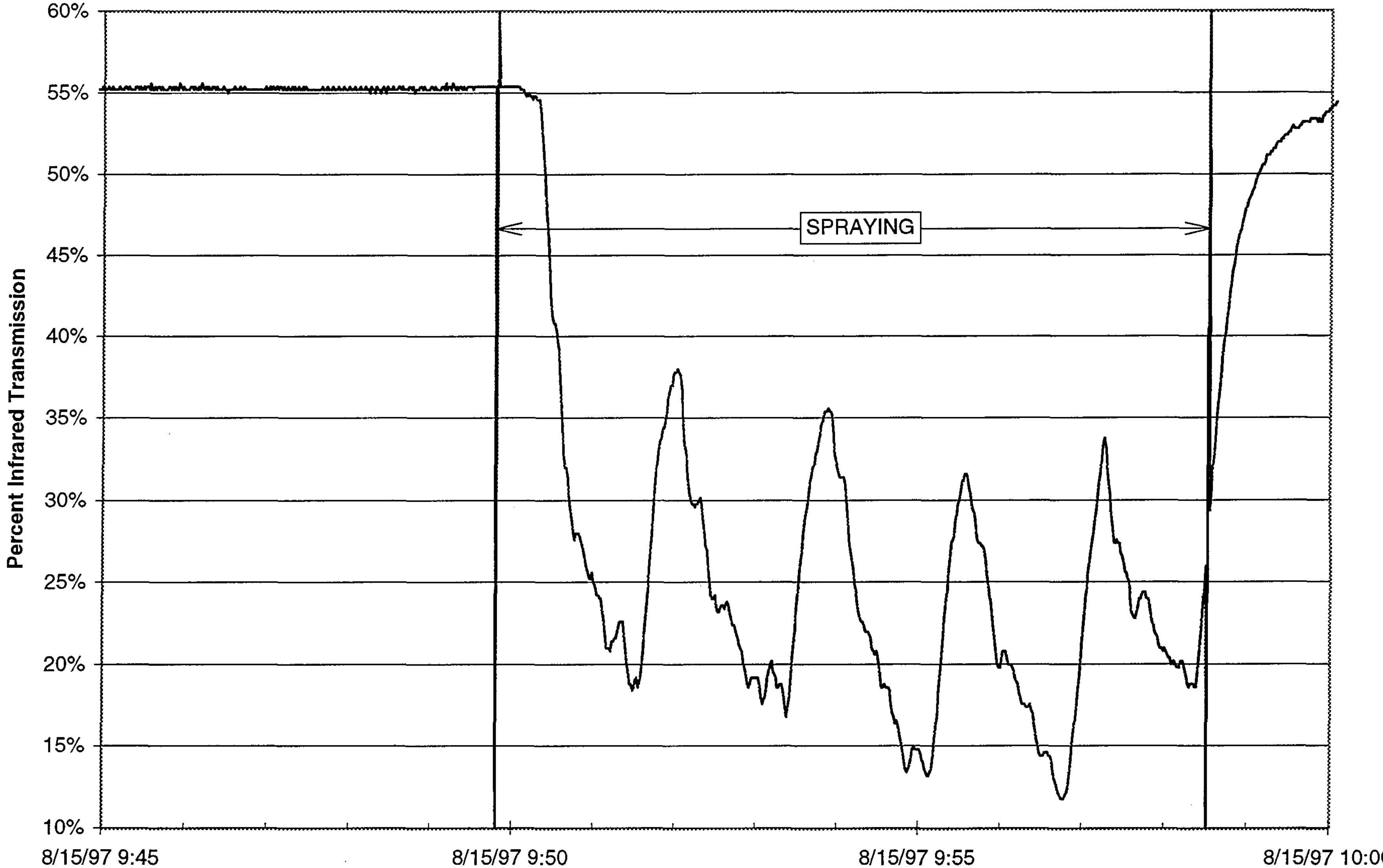
Test 4. Measured infrared transmission at 3.45 micrometers at Site 1, while Airjacket supply air was On, Standard spraying technique and Reduced spray booth flow rate.



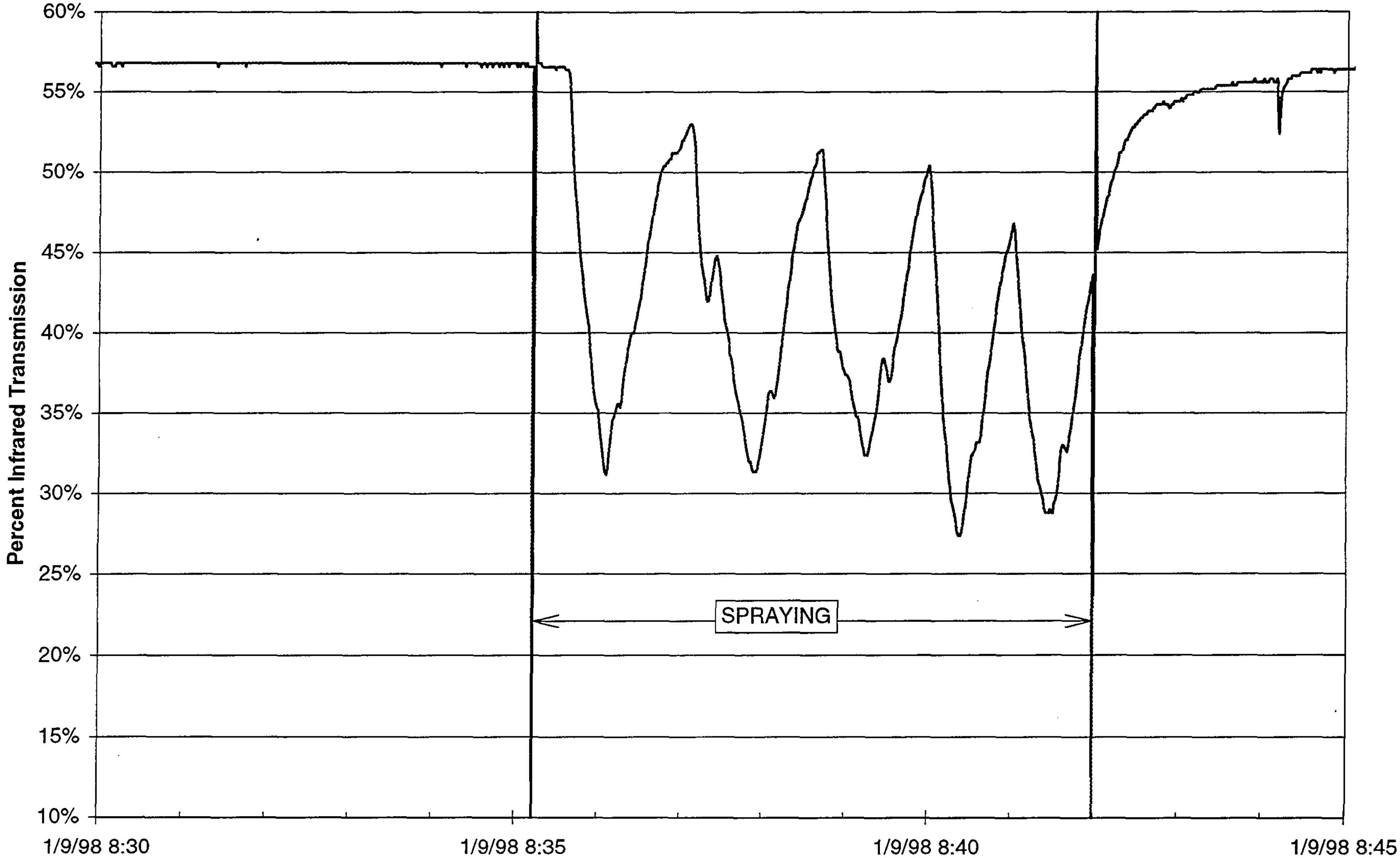
Test 5. Measured infrared transmission at 3.45 micrometers at Site 1, while Airjacket supply air was On, Standard spraying technique and Reduced spray booth flow rate.



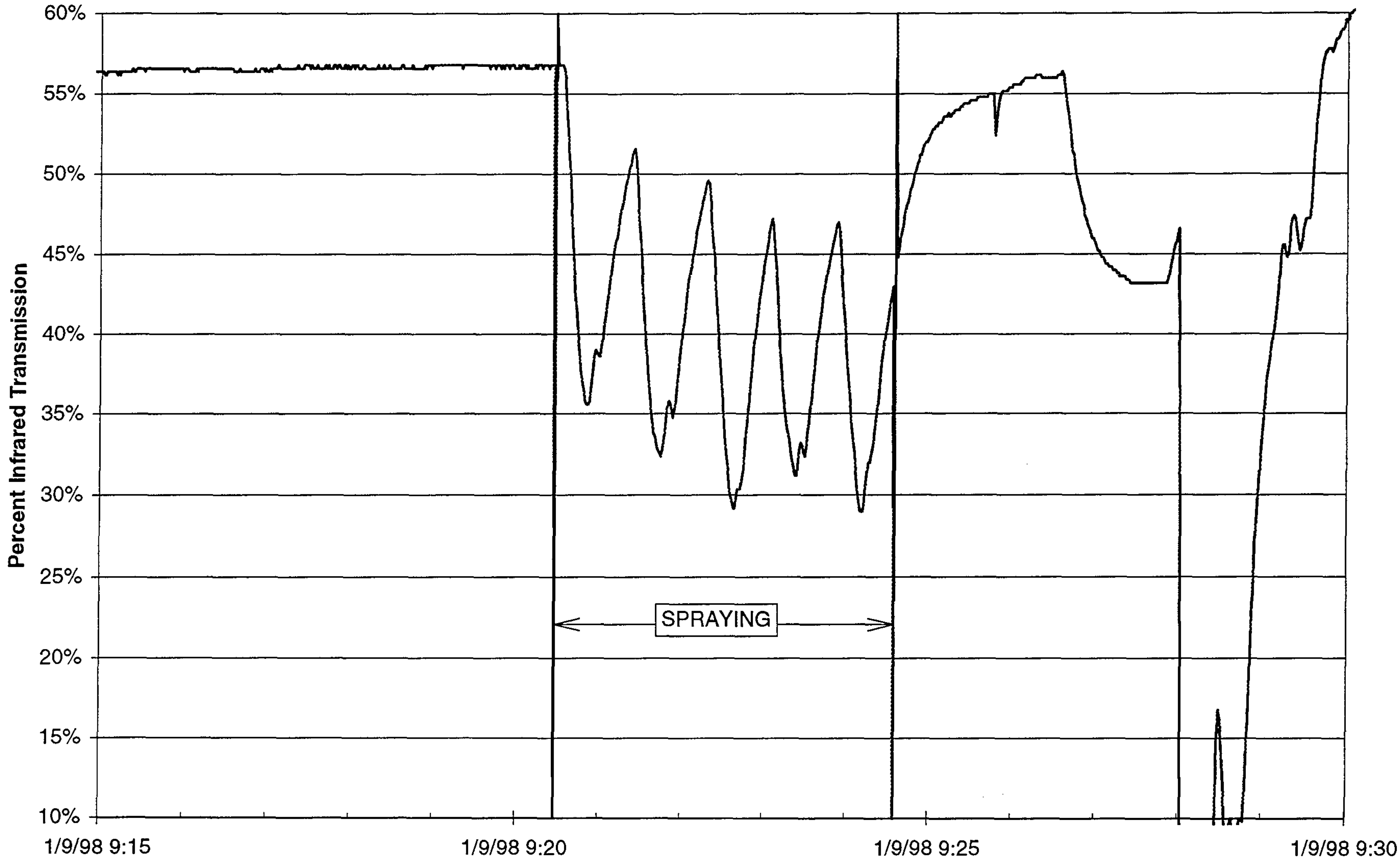
Test 6. Measured infrared transmission at 3.45 micrometers at Site 1, while Airjacket supply air was Off, Standard spraying technique and Normal spray booth flow rate.



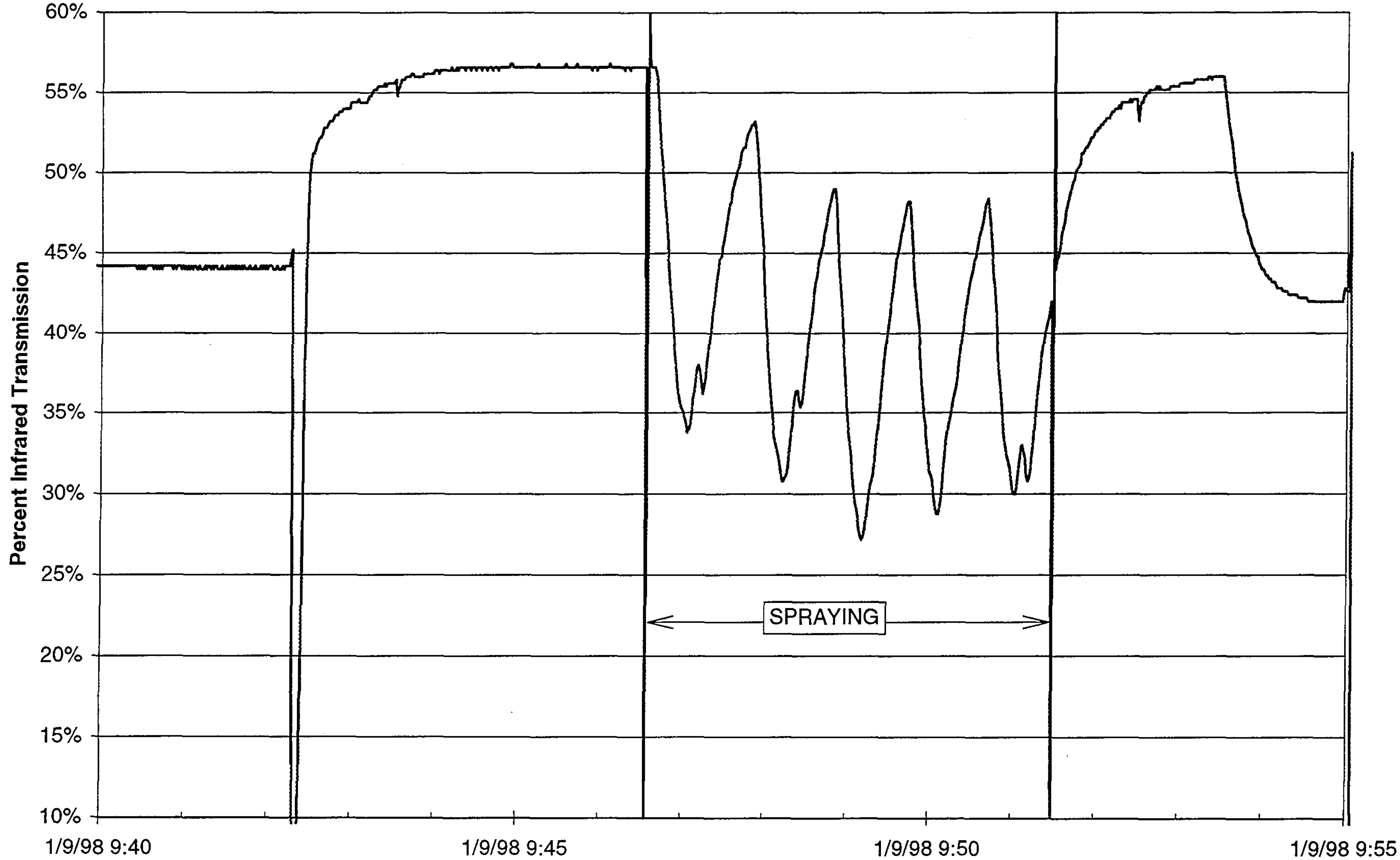
Test 7. Measured infrared transmission at 3.45 micrometers at Site 1, while Airjacket supply air was Off, Standard spraying technique and Reduced spray booth flow rate.



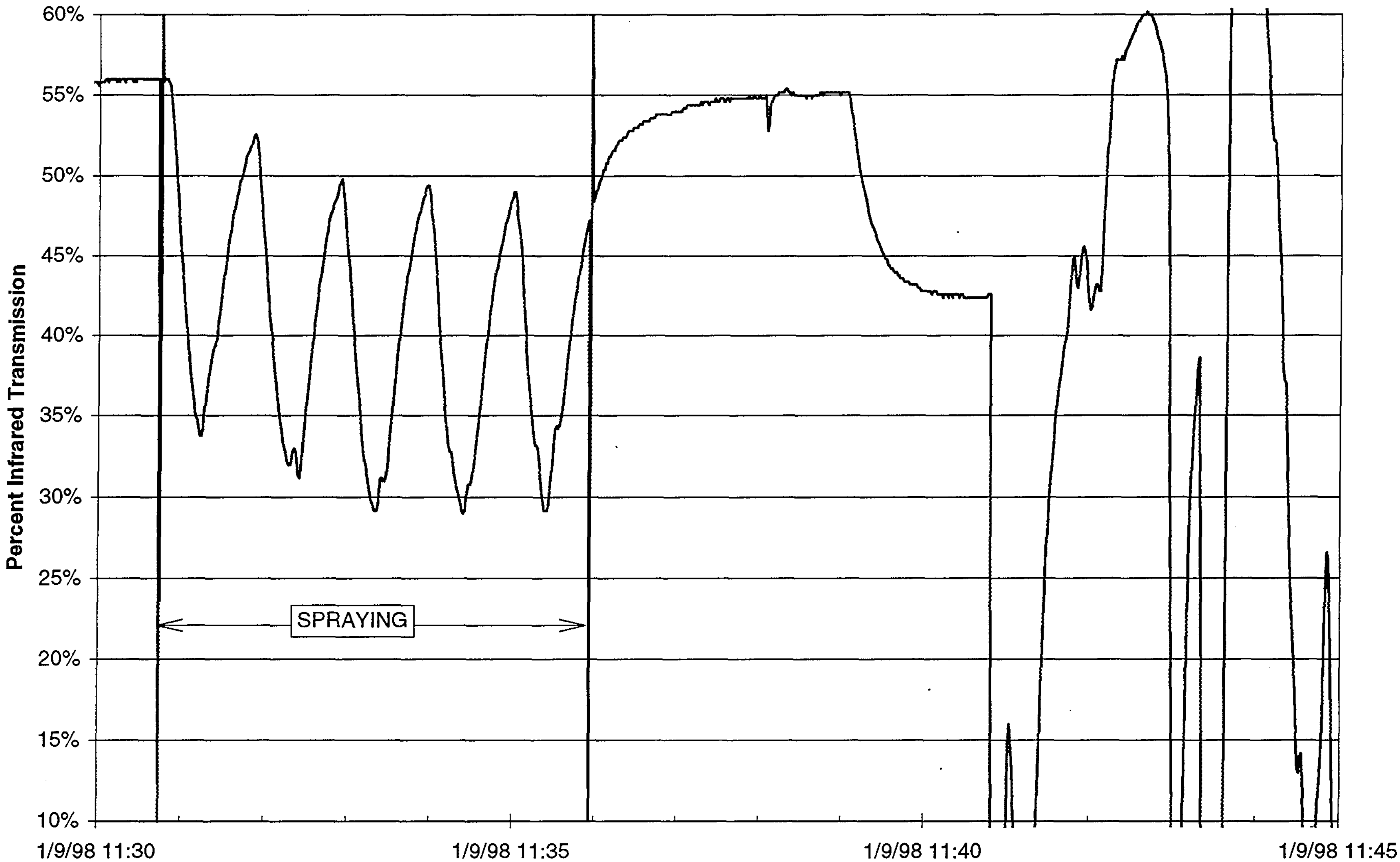
Test 8. Measured infrared transmission at 3.45 micrometers at Site 2, while Airjacket supply air was Off, Standard spraying technique and Normal spray booth flow rate.



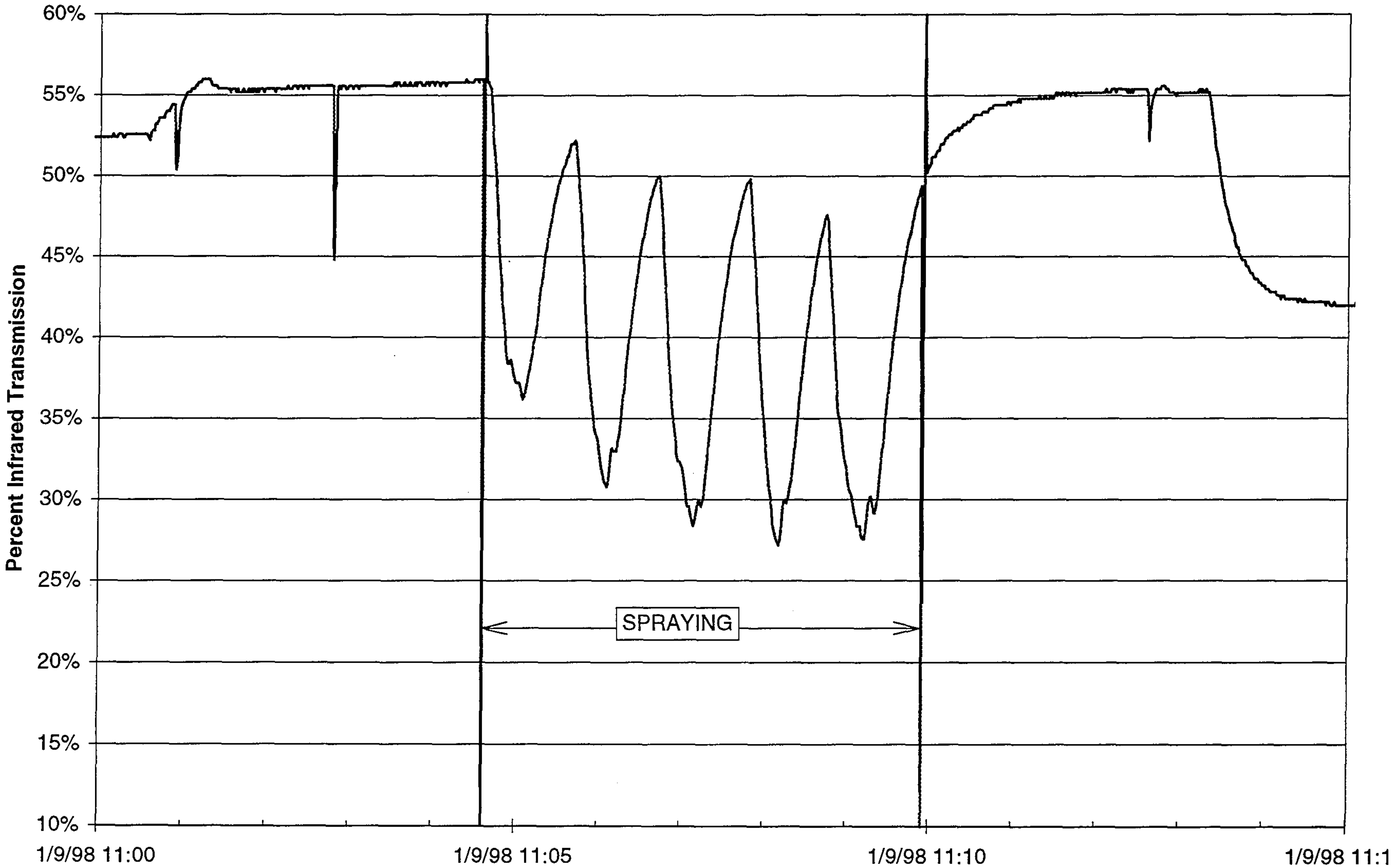
Test 9. Measured infrared transmission at 3.45 micrometers at Site 2, while Airjacket supply air was On, Standard spraying technique and Normal spray booth flow rate.



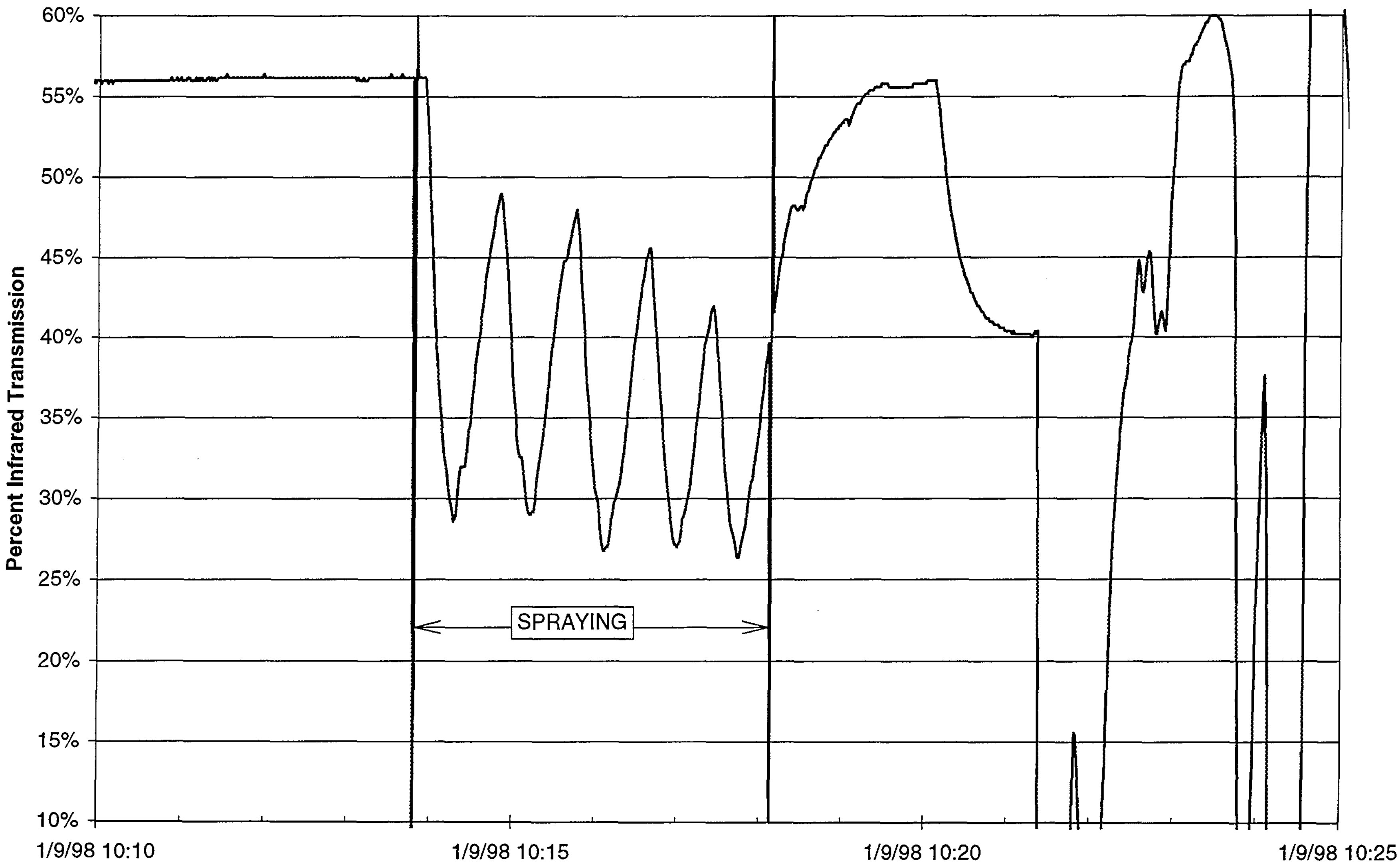
Test 10. Measured infrared transmission at 3.45 micrometers at Site 2, while Airjacket supply air was On, Standard spraying technique and Normal spray booth flow rate.



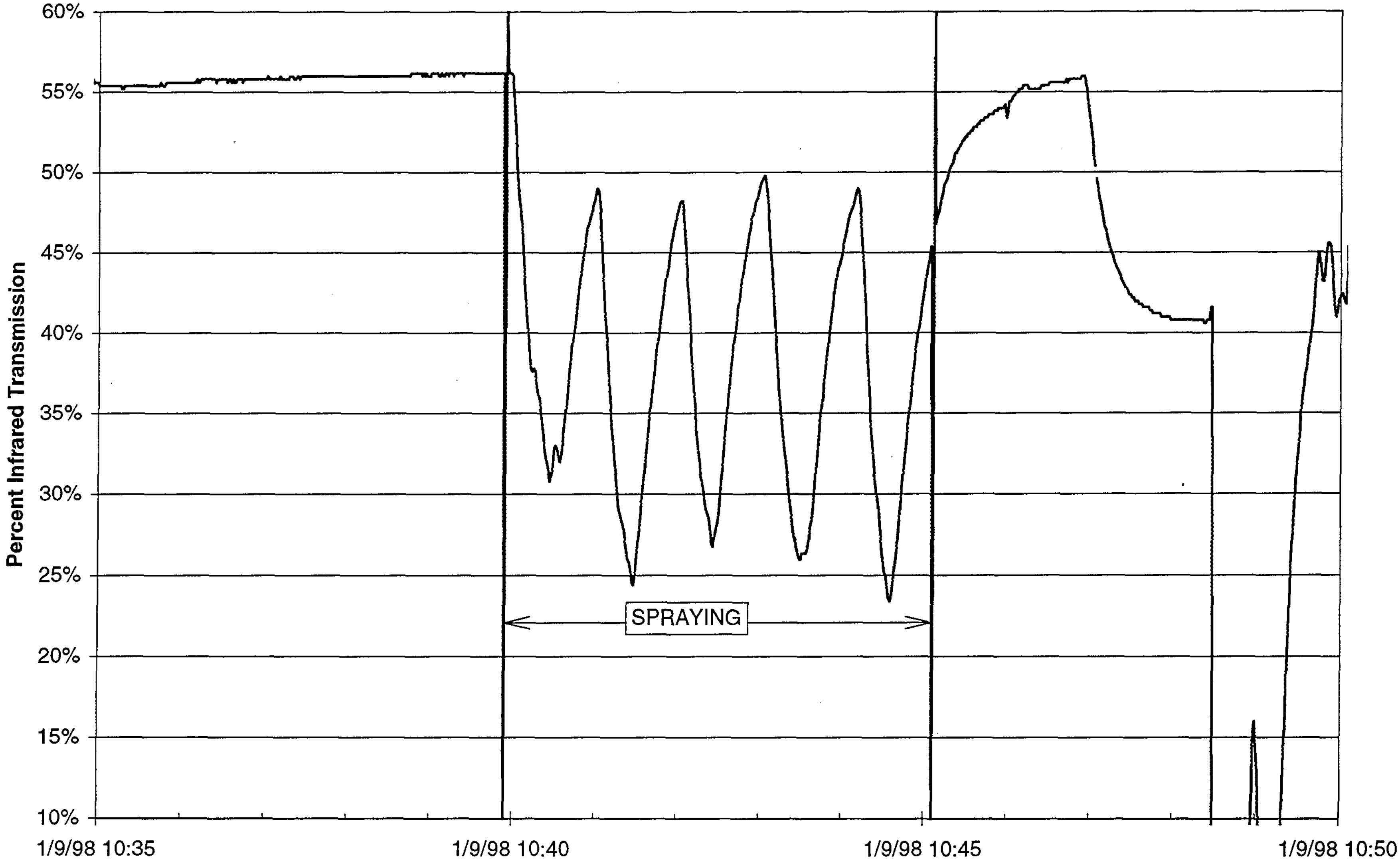
Test 11. Measured infrared transmission at 3.45 micrometers at Site 2, while Airjacket supply air was On, Downstream spraying technique and Normal spray booth flow rate.



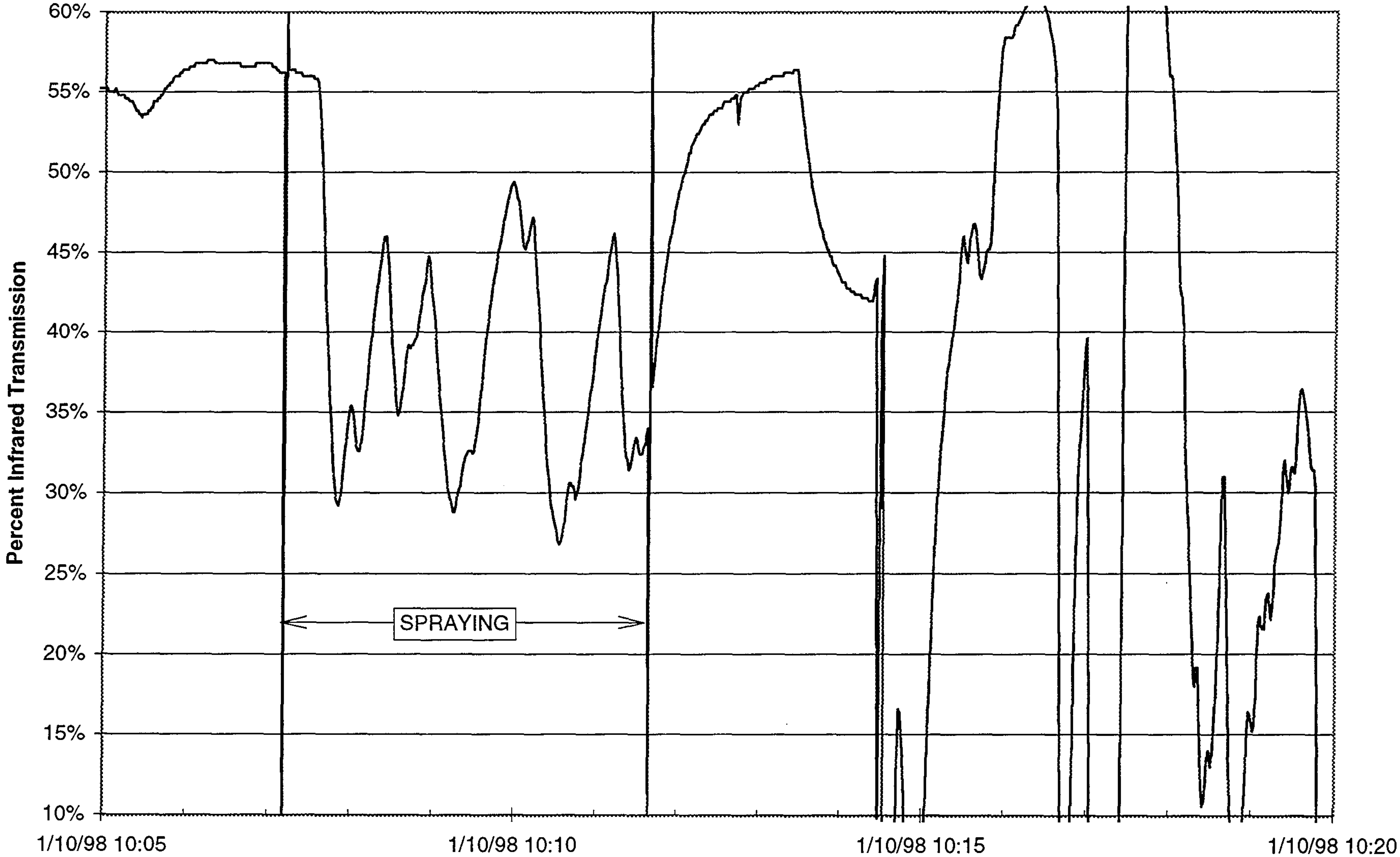
Test 12. Measured infrared transmission at 3.45 micrometers at Site 2, while Airjacket supply air was kinked, Downstream spraying technique and Normal spray booth flow rate.



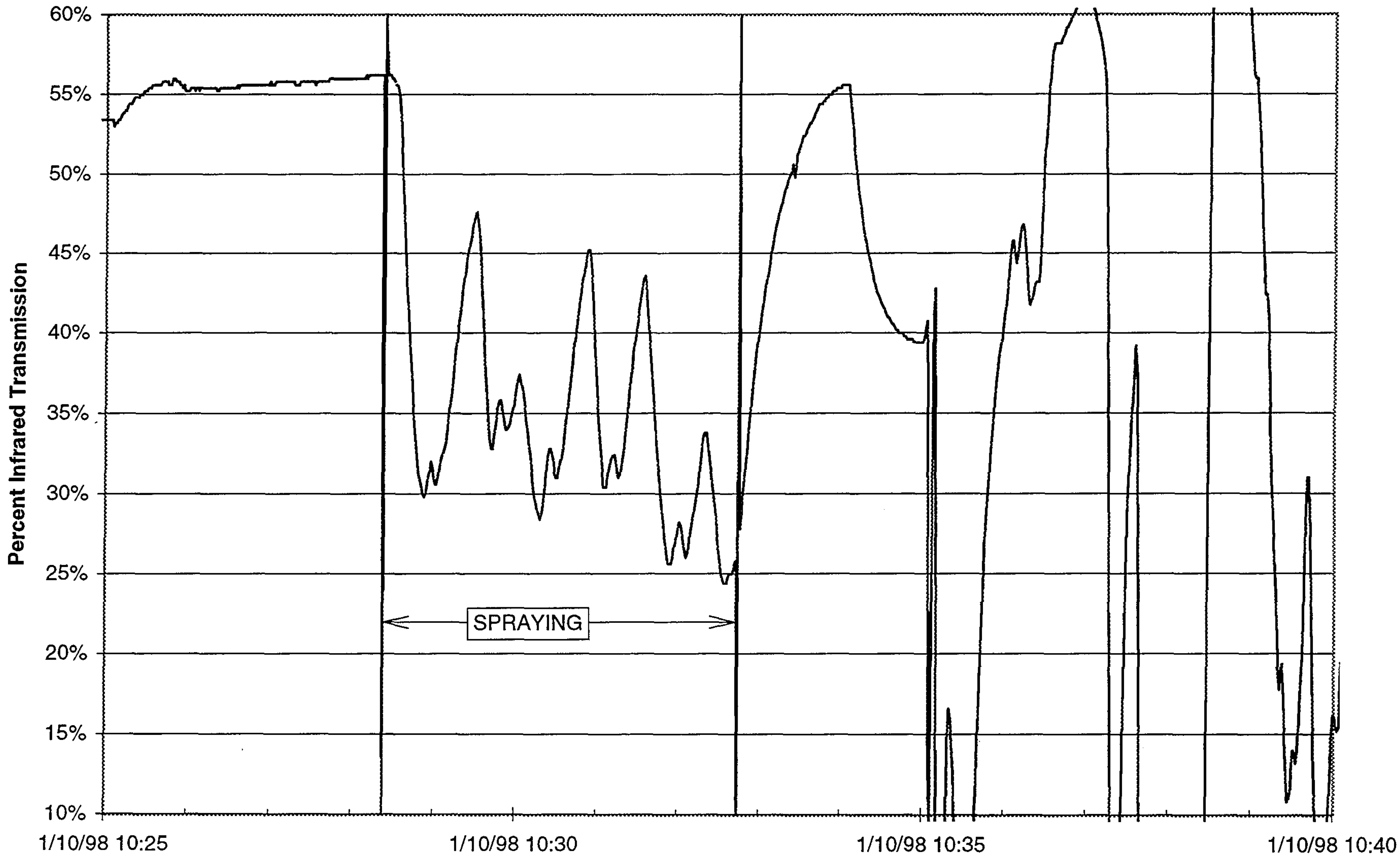
Test 13. Measured infrared transmission at 3.45 micrometers at Site 2, while Airjacket supply air was Off, Standard spraying technique and Normal spray booth flow rate.



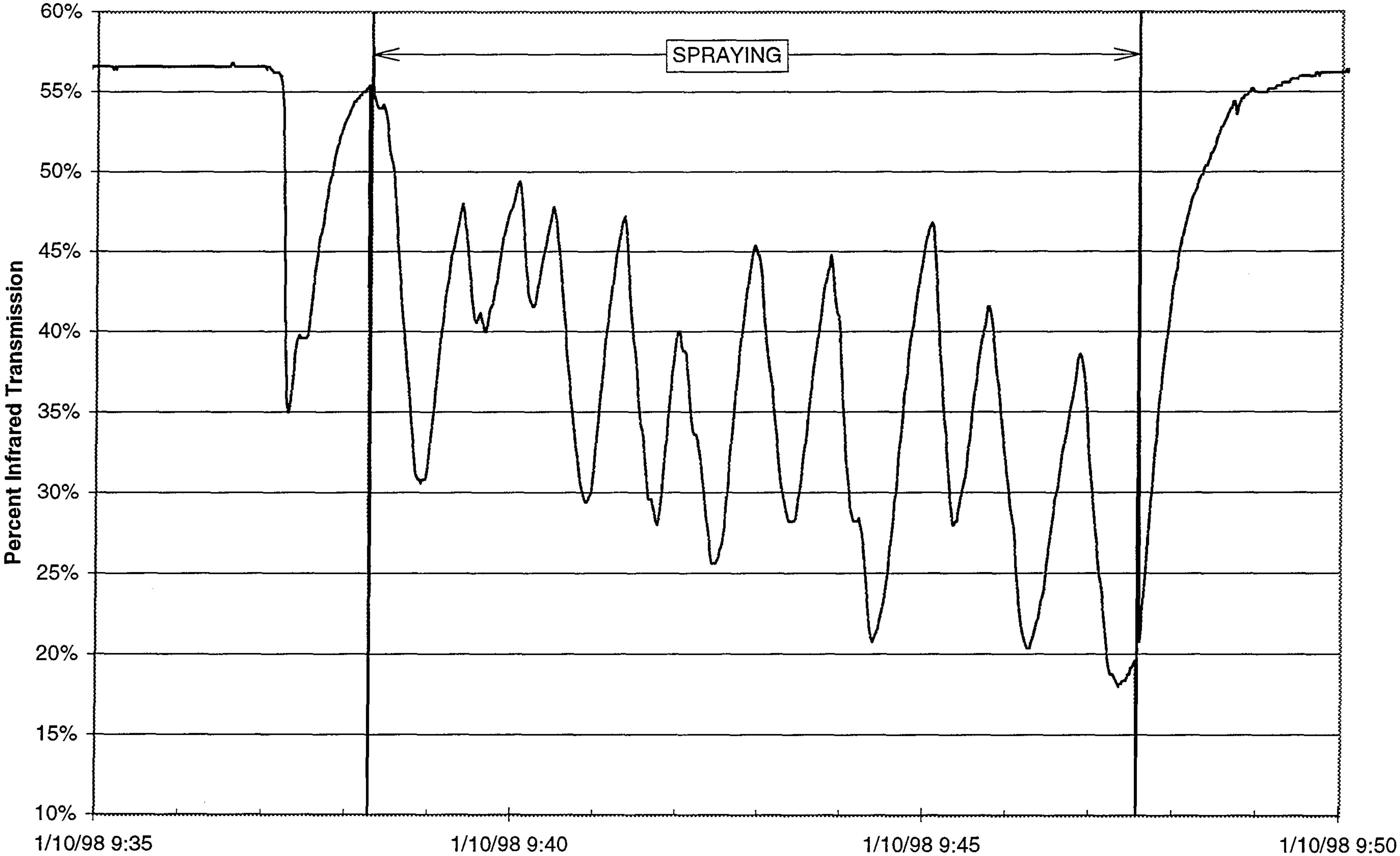
Test 14. Measured infrared transmission at 3.45 micrometers at Site 2, while Airjacket supply air was Off, Downstream spraying technique and Normal spray booth flow rate.



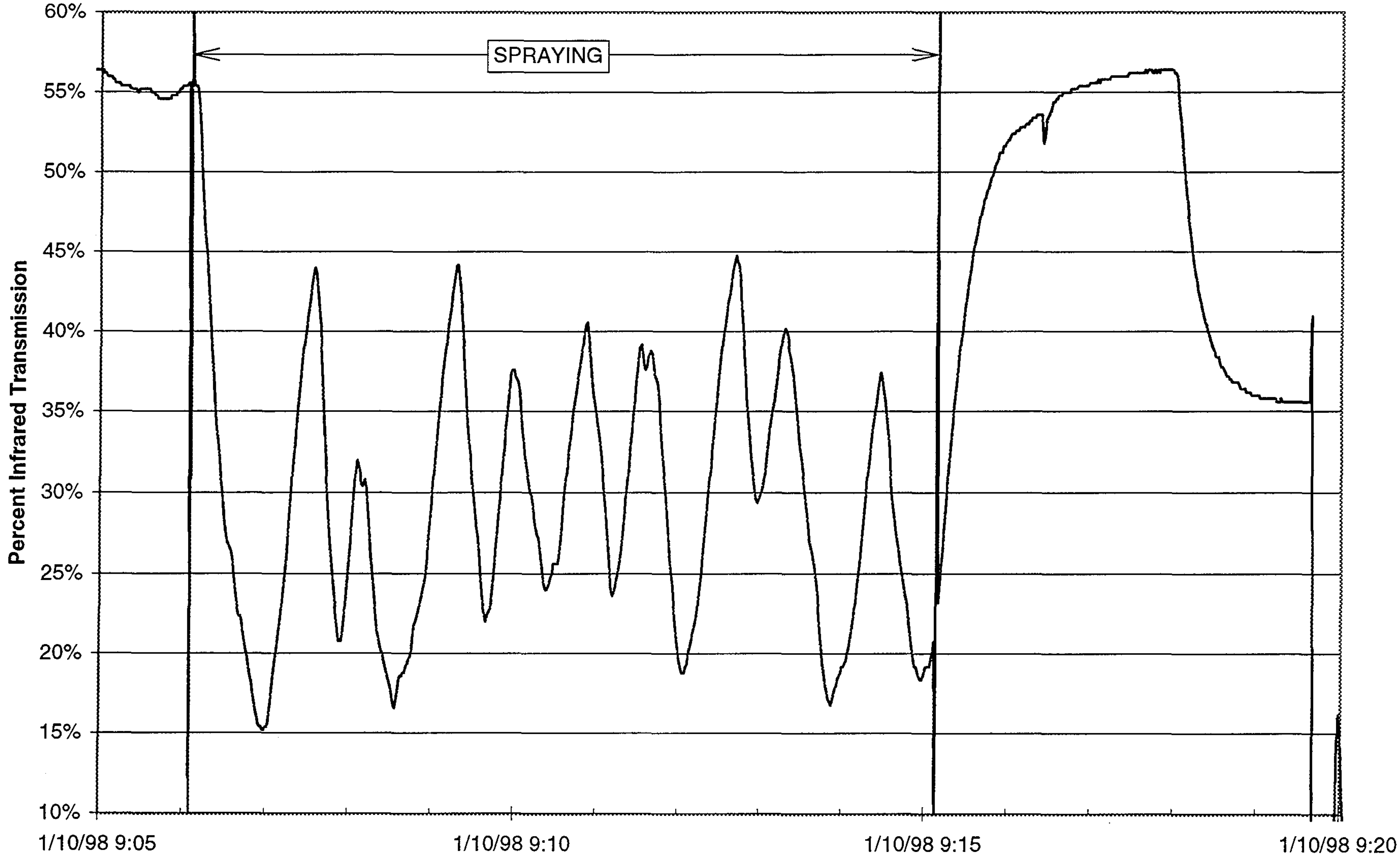
Test 15. Measured infrared transmission at 3.45 micrometers at Site 3, while Airjacket supply air was On, Downstream spraying technique of 3 bookcases and Normal spray booth flow rate.



Test 16. Measured infrared transmission at 3.45 micrometers at Site 3, while Airjacket supply air was Off, Downstream spraying technique of 3 bookcases and Normal spray booth flow rate.



Test 17. Measured infrared transmission at 3.45 micrometers at Site 3, while Airjacket supply air was Off, Standard spraying technique of 5 bookcases and Normal spray booth flow rate.



Test 18. Measured infrared transmission at 3.45 micrometers at Site 3, while Airjacket supply air was On, Standard spraying technique of 5 bookcases and Normal spray booth flow rate.