

ENGINEERING CONTROL GUIDELINES FOR HOT MIX ASPHALT PAVERS



PART 1 New Highway-Class Pavers



U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health



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Foreword

The Occupational Safety and Health Act of 1970 (Public Law 91-596) assures so far as possible every working man and woman in the Nation safe and healthful working conditions. The act charges the National Institute for Occupational Safety and Health (NIOSH) with recommending occupational safety and health standards and describing exposures that are safe for various periods of employment, including but not limited to the exposures at which no worker will suffer diminished health, functional capacity, or life expectancy as a result of his or her work experience.

This document represents the collaborative efforts of industry, labor, and government to protect the health of workers exposed to asphalt fumes during paving operations. Guidelines are presented for implementing engineering controls that reduce highway asphalt fumes at the source. Such primary prevention methods are the cornerstone of public and occupational health.

The guidelines presented here result from preliminary NIOSH research and a public meeting convened on July 8 and 9, 1996, in Cincinnati, Ohio. Participants discussed ongoing efforts to design and test engineering control systems for asphalt pavers, and they developed draft guidelines that could be used by contractors and manufacturers of large hot-mix asphalt (HMA) pavers. Although the health risks from asphalt exposure are not yet fully defined, all partners agreed that prudent action was needed to reduce worker exposures. The willingness of all partners to find a workable approach should serve as a model for others who are developing occupational safety and health recommendations. Development of these guidelines and this document was truly a joint effort. I would like to thank the National Asphalt Pavement Association, the Asphalt Institute, the Laborers' Health and Safety Fund of North America, and the International Union of Operating Engineers for their cooperation and hard work. This collaboration should serve as a model for others who are developing occupational safety and health recommendations.

These guidelines (which address large paver equipment weighing 16,000 pounds or more) are only the beginning of a process to develop controls for all types of paver equipment—old, new, large, and small. NIOSH will continue to build on this effort with industry and labor. These guidelines are a useful first step in this process.



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Part I

New Highway-Class Pavers

Introduction

These guidelines originate from a collaborative effort by industry, government, and labor to develop and implement engineering controls for the asphalt paving industry. Initiated by the National Asphalt Pavement Association (NAPA), this effort involved five asphalt paver manufacturers who represented more than 80% of the highway-class* paver market. These five manufacturers began independently designing engineering controls for their respective pavers. Through an agreement with the Department of Transportation (DOT), NAPA requested that the National Institute for Occupational Safety and Health (NIOSH) assist the manufacturers with their prototype designs and independently evaluate the performance of each prototype. To facilitate the development of engineering controls, NIOSH engineers designed a protocol for performing the evaluation of prototype engineering controls using

*Self-propelled hot mix asphalt (HMA) pavers weighing 16,000 pounds or more.

qualitative smoke and quantitative tracer gas methods. Sulfur hexafluoride (SF₆) was released as a tracer gas to quantify the capture efficiency and exhaust volume of each engineering control within a test environment. Using this information, NIOSH researchers recommended modifications designed to improve the performance of engineering controls during actual paving operations. Field testing of the improved prototype controls has been a long, difficult process; but preliminary results indicate that these engineering controls can reduce worker exposures to asphalt fumes and excessive temperatures.

In July 1996, NIOSH convened a public meeting in Cincinnati, Ohio, to discuss the use of engineering controls for reducing worker exposures to asphalt fumes during paving operations. On the basis of promising preliminary research, representatives of industry and labor wanted to move forward with the field implementation of the engineering controls. This meeting resulted in a draft document entitled *Engineering Control Guidelines for Hot Mix Asphalt Pavers*, which NIOSH published for public comment in October

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1996 [61 Fed. Reg. 51708 (Oct. 3, 1996)]. The draft document applied recommendations for engineering controls to a wide spectrum of new and existing paving equipment. On the basis of the comments from the public, NIOSH modified the approach and divided the effort between new and existing highway- and nonhighway-class pavers. The first priority was to create an engineering control document for new highway-class pavers. As a result, NIOSH created this revised document (Part I). NIOSH intends to address at a later date the application of engineering controls for nonhighway-class pavers and for the retrofit of all existing pavers (Part II).

Paver Size Classifications

This document does not deal with non-highway-class pavers because all the research on engineering controls for asphalt paving is based on prototype controls applied to highway-class pavers. Although the same basic engineering control principles apply to various sizes of pavers, the industry segment that operates nonhighway-class pavers may be better served by its own research initiative. Such an effort is currently being initiated, and the resulting guidelines and recommendations will be published in a future NIOSH document.

Existing HMA Pavers

Public comments offered two general reasons for excluding the retrofit of existing highway- and nonhighway-class

hot mix asphalt (HMA) pavers from the current guidelines:

- ✦ Current research applies only to new equipment that has the engineering control designs integrated into the basic paver design. Retrofit applications pose real challenges to manufacturers, who must develop kits for reducing worker exposures without creating tripping hazards from duct work, increased noise exposure from externally mounted exhaust fans, or undue burdens on paver hydraulic or electrical systems.
- ✦ Concerns that retrofitting could become a costly mandate for small business operators.

NIOSH strongly believes that paving contractors and workers should be able to improve their occupational environment without purchasing a completely new paving machine. NIOSH intends to address this issue in a future document as research develops. In the interim, NIOSH encourages paver manufacturers to develop generic retrofit kits that reduce worker exposure to asphalt fumes.

Performance Testing and Criteria

No field data exist to compare with laboratory data collected according to the specifications contained in the Appendix. Thus the 80% indoor tracer gas criterion identified in this document

may not translate to an 80% reduction in worker exposures. However, the indoor testing does provide manufacturers with an index of engineering control performance. The relationship between this index and worker exposures during paving will be a focus of further NIOSH research. To provide some current protection to workers, NIOSH and its partners have agreed on an 80% indoor tracer gas collection efficiency as a minimum performance index. All the involved parties understand that as the research on engineering controls progresses, these guidelines and recommendations will change or expand to accommodate the knowledge gained.

Enclosure

When designing a ventilation control system, the designer should consider three factors: the level of enclosure, the hood design, and the airflow capacity. The ideal approach is to maximize the level of enclosure to isolate and contain the emissions. However, worker access or other process requirements often limit the amount of enclosure permitted. Since indoor tracer gas testing may not adequately reflect performance reductions in field operations caused by poor enclosure, equipment manufacturers are strongly encouraged to identify and incorporate the maximum feasible level of enclosure in their engineering control designs.

Guidelines

These guidelines for highway-class HMA pavers result from an unprecedented cooperative research effort by industry, labor, and Federal representatives to improve working conditions during HMA paving operations. The participating construction equipment manufacturers entered into the collaborative research effort with NIOSH in order to reduce worker exposure to paving asphalt fumes. The following recommendations are an effort to achieve this laudable goal.

① *Engineering Controls —Ventilation Systems*

Each paver manufacturer should develop and install exhaust ventilation systems with a minimum controlled indoor capture efficiency of 80% (as determined by the tracer gas method described in the Appendix) on all new self-propelled HMA pavers weighing 16,000 pounds or more and manufactured after July 1, 1997. Each paver manufacturer should test the exhaust ventilation system for each model of paver and should certify that each model year meets the minimum indoor capture efficiency specified above. Each manufacturer should install an indicating device on each paver so that the system flow rate can be determined. The indicating device should incorporate a means

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for visually determining whether the exhaust ventilation system is operating within the designed operating range.

Each manufacturer should develop and implement a quality control plan designed to ensure that exhaust ventilation systems on each paver will

comply with the minimum indoor capture efficiency specified above.

Each manufacturer should attach a plate to the paver showing a simple schematic of the exhaust ventilation system and a list of field-maintenance procedures. An example of this schematic is shown in **Figure 1**.

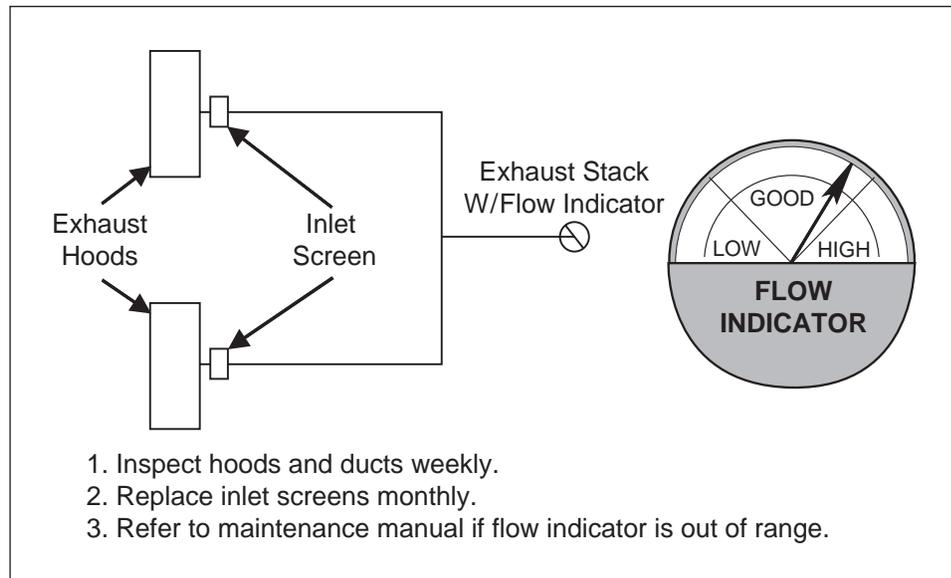


Figure 1. Example of a 3- by 5-inch information plate.

② **Certification**

Manufacturers of highway-class HMA pavers should certify the following to purchasers of new pavers:

—[**Manufacturing company**] hereby certifies that (1) the paver (**model number**) being purchased has been tested on (**Date**) in accordance with the Appendix of the *Engineering Control Guidelines for Hot Mix Asphalt Pavers: Part I*, published by the National Institute for Occupational Safety and Health (NIOSH) and, (2) the paver model has been found to achieve at least an 80% indoor capture efficiency (standard tests provide 95% confidence that indoor capture efficiency is **T%** or better). [**T% is the T-statistic calculated in accordance with the Appendix to these Guidelines.**]

The manufacturer should keep a copy of all such certifications and their supporting test data for at least 3 years.

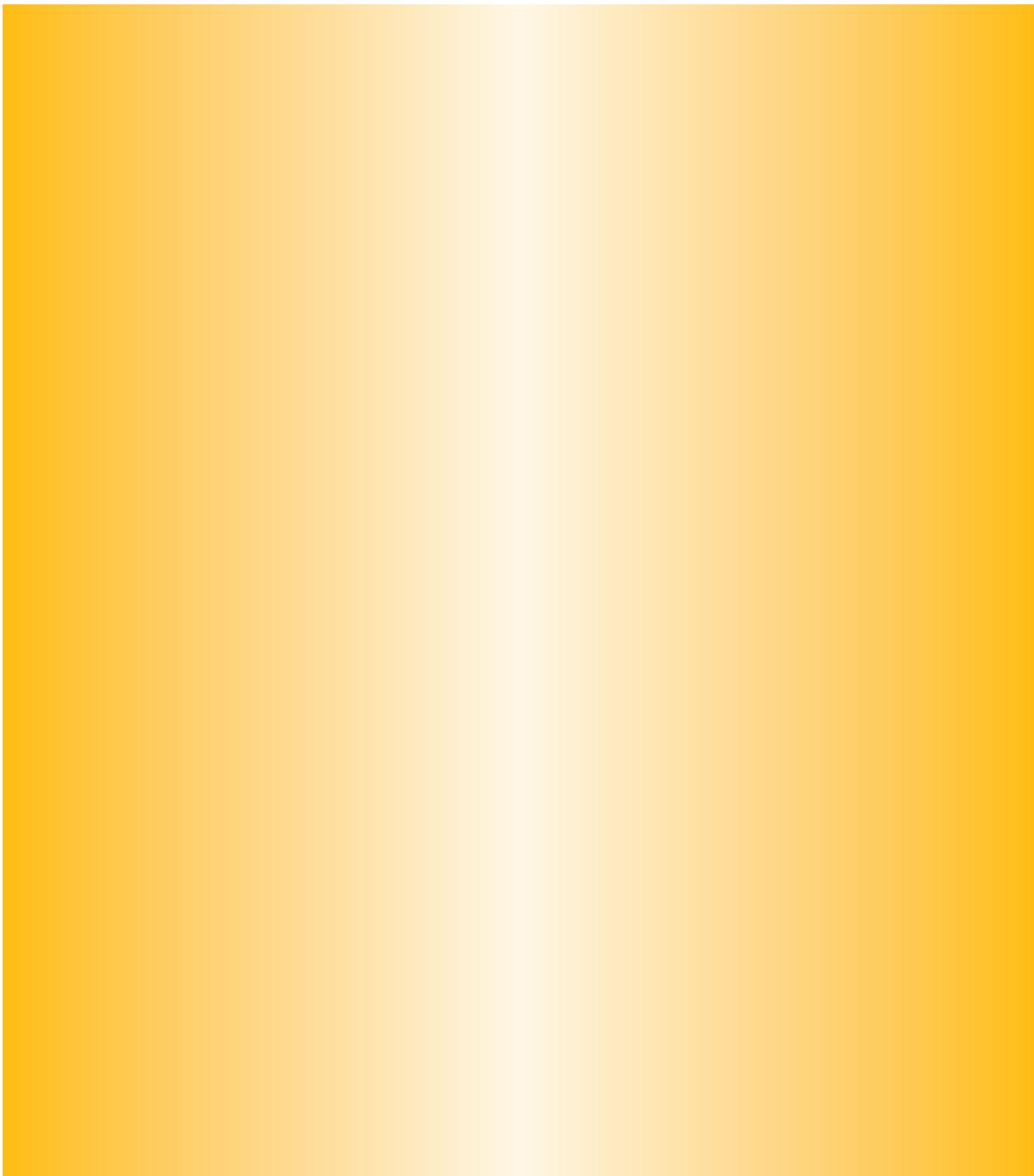
③ **Operation and Maintenance**

For each exhaust ventilation system, HMA paver manufacturers should

provide an operator's manual that contains a maintenance schedule. Each operator's manual should also include detailed sketches and performance criteria for equipment owners to use in their annual assessment of the exhaust ventilation systems; troubleshooting instructions should also be included for low or high exhaust flows. Owners of HMA pavers with exhaust ventilation systems are advised to inspect and maintain the systems according to the manufacturer's recommendations and to record the dates of annual performance inspections within the operator's manual.

④ **Training**

Equipment mechanics trained in the maintenance and repair of asphalt paving equipment may require additional training to perform these services on exhaust ventilation systems. Equipment manufacturers should create or identify training manuals and instructions designed to train equipment owners in the operation, maintenance, and repair of exhaust ventilation systems for HMA pavers.



Appendix

Laboratory/Factory Test Procedure for HMA Pavers

Purpose

To evaluate the efficiency of exhaust ventilation systems used on highway-class HMA pavers in an indoor stationary environment.

Scope of Use

This test procedure was developed to help the HMA industry develop and evaluate prototype exhaust ventilation systems with an ultimate goal of reducing worker exposures to asphalt fumes. This test procedure is a first step in evaluating the capture efficiency of paver exhaust ventilation systems and is conducted in a controlled environment. The test is not meant to simulate actual paving conditions. The data generated using this test procedure have not been correlated with exposure reductions during actual paving operations.

Materials

- HMA paver fitted with an exhaust ventilation system
- Building with large opening (overhead door) to the outdoors
- Materials to construct a barrier—such as cardboard, plastic sheeting or tarpaulins, 2 × 4 and 4 × 4 lumber of varying length, and duct tape
- Smoke generator
- PVC pipe: 2-inch inside diameter, 10 feet long, capped on one end, 1/4-inch-diameter holes drilled in a line every 6 inches on center
- Video camera (optional)
- Tracer gas cylinder: SF₆ CP-grade, 99.8% pure, with pressure regulator
- Detector tracer gas calibration cylinder: 12 ppm SF₆ (analyzed to 0.1 ppm or lower)
- Air or nitrogen cylinder: 0 ppm SF₆
- Two 12-liter gas-sampling bags
- An SF₆ detector with detection limit as low as 0.01 ppm and calibration curve as high as 15 ppm SF₆ with an accuracy of at least ± 0.01 ppm
- Teflon tubing: 1/8-inch outside diameter, 13 feet long
- Copper pipe: 1/2-inch inside diameter, the same length as the fixed screed or

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- tractor width, 1/32-inch-diameter holes drilled in a line every 12 inches on center
- Polyethylene (PE) tubing: 1/4-inch outside diameter, 100 feet long
 - Two mass flow controllers with shut-off valves and a range of at least 200 to 1,000 cc/minute of SF₆
 - Bubble meter: 0.5-liter graduated cylinder, soap solution, and stop watch to calibrate gas flow rates; or a calibrated electronic bubble flow meter
 - Stainless steel tubing: 1/4-inch outside diameter, 12 inches long (sampling probe), sealed at one end, 1/16-inch diameter holes drilled in a line every 1 inch on center starting 1 inch in from the sealed end (the number of holes depends on the diameter of the ventilation exhaust duct: an 8-inch exhaust duct would require the use of a sampling probe with seven 1/16-inch holes)

Background

Engineering controls (i.e., exhaust ventilation systems) for HMA pavers will be evaluated in a laboratory setting (i.e., shop or warehouse) in which exhaust ventilation efficiency will be measured using smoke and tracer gas tests. The

smoke test will be used as a qualitative test to visualize air-flow patterns around the paver and auger area and to assist in setting up for the tracer gas tests. The tracer gas test will be used as a quantitative measure of the air-flow rate and capture efficiency of the ventilation system.

Asphalt is a complex mixture consisting of paraffinic and aromatic hydrocarbons and heterocyclic compounds containing sulfur, nitrogen, and oxygen. Emissions from heated asphalt are also complex mixtures that include both vapors and fumes. Fumes are small particles created by condensation from the gaseous state after volatilization. Fumes are typically in the size range of 1 micrometer (μm) or less in diameter (Stanford Research Institute [1961]. Characteristics of particles and particle dispersions. Stanford Research Institute Journal, 3rd Quarter). This test will use smoke aerosol and SF₆ gas as surrogates for asphalt emissions.

To control small particle motion, one must control the motion of the air in which the small particles are suspended (W.C.L. Hemeon [1962]. Plant and process ventilation. 2nd edition. Industrial Press Inc., p. 26). Vapors, gases, and asphalt fumes can be controlled by ventilation described in these guidelines.

Safety

The following safety precautions must be taken for each test:

- ✓ Handle smoke-generating equipment with appropriate caution: it can be **HOT!**
- ✓ Make sure that the smoke generator does not set off fire sprinklers or create a false alarm.
- ✓ Avoid direct inhalation of smoke from the smoke generator. The smoke may act as an irritant in the upper respiratory tract.
- ✓ Transport, handle, and store all compressed gas cylinders according to the safety recommendations of the Compressed Gas Association.
- ✓ During testing, locate the compressed cylinder outdoors or in a well-ventilated area. The temperature should not exceed 125°F in the storage location.
- ✓ Avoid breathing the gas if a gas cylinder regulator malfunctions or some other major accidental release occurs. A major release of gas could displace the ambient air and reduce the oxygen level in the environment. Stand back, clear the immediate area, and let the tank pressure reach equilibrium with the ambient environ-

Procedures

General

To test the exhaust ventilation system, locate the paver in a bay area of a building or garage so that the paver can be parked with the screed and rear half of the tractor positioned in the bay area (referred to as the testing area) and the front half of the tractor and exhaust ducts positioned outside the building (see Figures A-1 and A-2). An overhead garage door or other barrier should separate the two areas. Lower the overhead door or barrier to rest on top of the tractor and seal the remaining door openings around and under the tractor with cardboard, plastic, or other suitable materials to isolate the paver's front and rear halves. Position the screed on the ground with the screed end plate extended 1 foot on each side of the screed. Position auger to a height typically used during paving. Close the conveyor flow gates at the back of the hopper as far as possible and close the remaining tunnel opening to simulate the limited air flow in the tunnel during actual paving. During the performance evaluations, set the engine speed for the paver (which can affect the exhaust rate of the ventilation system) to the typical revolutions per minute (rpm) that are maintained during normal paving operations.

Smoke Test

The smoke generator test is designed to ensure that the barrier is adequate for the quantitative tracer gas test and to visualize airflow patterns around the paver and auger areas. Support the 2-inch diameter distribution pipe above the ground under the auger so that the holes are oriented upward on center with the auger and the pipe rests in a horizontal position within 1 inch of the bottom of the auger. With the ventilation system on, release smoke within the auger area and observe for leaks in the barrier. Seal any identified leaks. Release smoke again to verify the integrity of the barrier system, to identify

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Figure A-1. Test area rear half of paver isolated from front half of paver.



Figure A-2. Front half of paver isolated from test area.

airflow patterns within the test area, and to observe the exhaust ventilation system's performance visually. A video camera (optional) can be used during this test to document the test setup and air-flow patterns made visible by the smoke release.

The sequence of a typical smoke test is outlined below:

- Verify that the smoke test will not set off a fire alarm or fire-suppression system.
- Position paving equipment within the door opening and lower the overhead door or other barrier so that all the paver exhaust ducts are outside the building and the auger area is inside the building.
- Seal the remaining opening around and under the tractor to isolate all paver exhaust from the auger area.
- Place the 2-inch-diameter smoke distribution pipe directly beneath the augers and secure in a horizontal position.
- Connect the smoke generator to the distribution pipe.
- Clear the auger area of any extraneous materials.
- Activate the video camera if a record is desired.
- Activate the exhaust ventilation system and the smoke generator.

- Inspect the separating barrier for integrity failures and correct them as required.
- Inspect the exhaust ventilation system for unintended leaks at all fittings.
- Deactivate the exhaust ventilation system for a short time to simulate a no-control condition for comparison purposes.
- Deactivate the smoke generator and wait for smoke levels to subside. You may want to turn on additional exhaust ventilation to clear the room more quickly.
- Disassemble the test equipment (the smoke generator may be HOT).
- Move the smoke generator outside and introduce smoke into the engine cooling air intake. Observe the auger area for signs of smoke leaking from the engine area into the auger area. If smoke is observed in the auger area, corrections to the equipment design may be needed. Engine-cooling air that is blowing into the auger area will make the ventilation system less effective in capturing asphalt fumes.

Tracer Gas Test

The tracer gas test is designed to (1) calculate the total exhaust flow rate of the paver exhaust ventilation system and (2)

evaluate the system's effectiveness in capturing and controlling a surrogate contaminant under controlled indoor conditions. SF₆ should be used as the surrogate contaminant.

Calibrate the SF₆ detector and the mass-flow controllers before testing begins. If the manufacturer of the detector can provide a calibration curve for the SF₆ concentration range of interest, a two-point calibration check may be sufficient. The two-point calibration consists of a 0-ppm SF₆ point and a 12-ppm SF₆ point. Gas cylinders for each calibration point can be purchased. Fill industrial hygiene sampling bags from each cylinder and hook each bag to the detector; then record the response of the detector for each concentration. Clearly mark each sample bag with the concentration of SF₆ it contains. Bags can be reused; however, they should be emptied before reuse, and they should be filled with approximately the same concentration of SF₆. For example, a bag used to hold 12 ppm SF₆ in a previous test should not be used to hold the 0-ppm SF₆ air sample in the next test, since residual gas may cause an incorrect calibration point. If the detector response to the 0-ppm SF₆ air sample is less than 3 times the lower limit of detection, and if the detector response to the 12 ppm SF₆ is within 7% of the detector calibration curve at that point, proceed with the testing. If the calibration checks are not within these specifications, determine the source of the errors and correct them before proceeding.

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Calibrate the mass-flow controllers with a bubble meter and a timer. Allow the CP-grade SF₆ to flow through the pressure regulator to the mass-flow controllers, which can regulate the flowrate as determined from Table 1. Direct the flow through the wet bubble meter to determine the actual SF₆ flow rate (NIOSH [1973]. The Industrial Environment — Its Evaluation and Control. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, p. 105).

The 100% Capture Test

The 100% capture test is achieved by releasing a known rate of CP-grade SF₆ into the ventilation system, mixing the

air to obtain a uniform concentration, and sampling the concentration of SF₆ in the exhaust of the ventilation system. The accuracy with which the SF₆ flow controllers are calibrated directly affects the accuracy of the test. All the SF₆ must be released into the ventilation system and be thoroughly mixed before reaching the detector sampling point. Releasing the SF₆ at two points just inside the exhaust hood on each side of the paver exhaust ventilation system will give the best chance for complete mixing. Connect the supply tank of CP-grade SF₆ to the two release points via a pressure regulator, two mass-flow controllers, and as much 1/4-inch-tubing as needed.

Find a downstream sampling location in the exhaust ventilation system where the SF₆ gas has been thoroughly

Table 1. Flow Rate Determination

Total ventilation flow rate predicted from ventilation measurements (cubic feet/minute)	Total SF ₆ flow rate needed (liters/minute)	SF ₆ flow rate needed to each side of the paver (liters/minute)
1,500	0.51	0.25
2,000	0.68	0.34
2,500	0.85	0.42
3,000	1.02	0.51
3,500	1.19	0.59
4,000	1.36	0.68

mixed so that a sample from that point will be representative of all gas in the system. Thorough mixing can be achieved by the fan that moves the air; thus if the sample is taken downstream of the fan, it should be sufficiently mixed. However, if there are two fans and the air from each fan meets near the detector sampling point, the two streams of air may not be thoroughly mixed by the time the gas reaches the sampling point. If the gases are not thoroughly mixed, an extension on the exhaust duct may be needed.

If the air is thoroughly mixed, place a 1/4-inch-diameter sampling hole in the exhaust ventilation duct two-thirds of the way between the base of the exhaust duct at the paver deck and the top of the exhaust duct (closer to the top). Insert the sampling probe into the hole perpendicular to the exhaust air flow. Position the holes in the sampling probe inside the duct and perpendicular to the exhaust air flow. The 1/8-inch-diameter tubing should connect the sampling probe to the detector and should be airtight to ensure that the sample is pulled from within the exhaust duct and not from the surrounding area. Take at least five measurements during a 3-minute period and use the average concentration to calculate the exhaust volume with the following equation:

$$Q_{(exh)} = \frac{Q_{(SF_6)}}{C_{(SF_6)}^*} \times 10^6 \quad \text{Equation 1A}$$

where

$Q_{(exh)}$ is the flow rate of air exhausted through the ventilation system (liters/minute or cubic feet/minute) [to convert from liters/minute to cubic feet/minute, divide liters/minute by 28.3],

$Q_{(SF_6)}$ is the flow rate of SF_6 (liters/minute or cubic feet/minute) introduced into the system, and

$C_{(SF_6)}^*$ is the concentration of SF_6 (parts per million) detected in exhaust during the 100% SF_6 capture test.

Repeat the above procedure for each duct if there is more than one exhaust ventilation duct. Allow sufficient time between tests for the background readings to drop below 0.1 ppm SF_6 . Subtract background readings between sequential tests from the detector response before calculating the exhaust volume.

Quantitative Capture Efficiency

Position the 1/2-inch-diameter copper distribution plenum under the augers and orient the holes of the plenum upward on center with the augers. Connect the two 1/4-inch-diameter discharge tubes coming from the calibrated flow controllers to the distribution plenum with a tee connection. Release the SF_6 at the same predetermined flow rate used in the 100% capture test. The SF_6 distribution plenum is designed to release the SF_6 evenly

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throughout the length of the auger area. This test uses the sampling probe, sampling location, and SF₆ detector used in the 100% capture test (See Figure A-3).

Take at least five measurements during a 3-minute period and calculate an average value. Calculate the capture efficiency using the following equation:

$$\eta = \frac{C_{(SF_6)}}{C^*_{(SF_6)}} \times 100 \quad \text{Equation 2A}$$

where

η is the capture efficiency,

$C_{(SF_6)}$ is the concentration of SF₆ (parts per million) detected in exhaust, and

$C^*_{(SF_6)}$ is the concentration of SF₆ from the 100% capture test.

Perform a total of four pairs of the 100% capture tests and capture efficiency tests and determine the overall capture efficiency of the ventilation system from the average of all four trials.

Shut down the paver between each pair of tests (i.e., after one 100% capture test and one capture efficiency test) to signify the completion of the test. Monitor background SF₆ measurements to determine whether any SF₆ has accumulated in the test area. If more than 1.0 ppm SF₆ has accumulated, check the integrity of the barrier system and ventilate the test area well before proceeding. Allow sufficient time between tests for

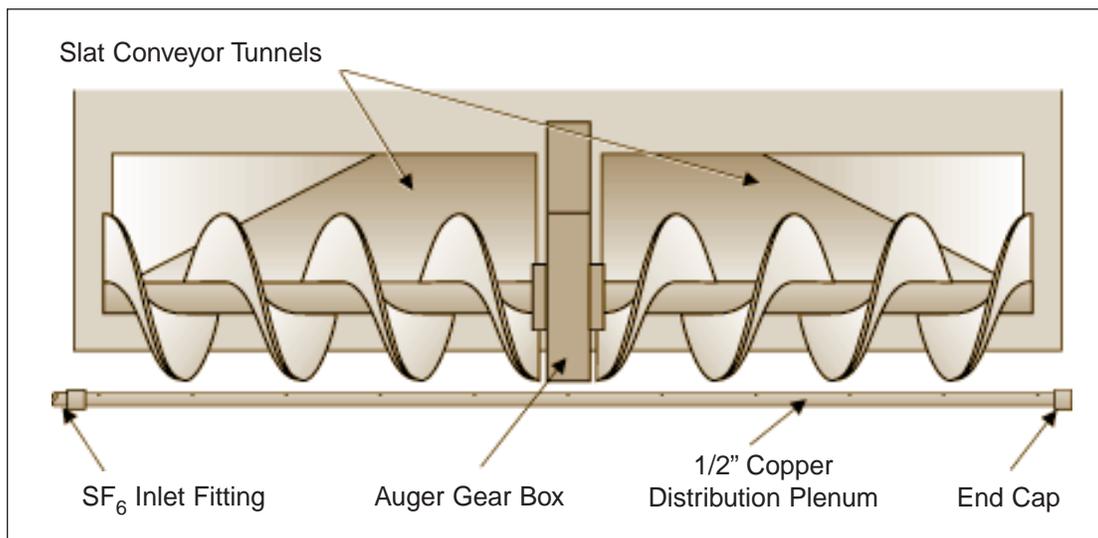


Figure A-3. Sample schematic for SF₆ release and capture at the paver auger.

the background readings to drop below 0.1 ppm of SF₆. Subtract background readings from the detector response before making calculations.

The sequence for a typical test run is outlined below:

- Position paving equipment and seal openings as outlined above. Perform the smoke test before conducting the tracer gas tests.
- Check the SF₆ detector calibration and record the two-point calibration check and the ambient temperature and pressure.
- Calibrate (exhaust to outdoors) the mass flow meters to levels dictated by Table 1 using SF₆.
- Drill an access hole in the exhaust ventilation duct and insert the detector's sampling probe. Determine whether the gas stream is thoroughly mixed.
- Start the paver engine and run at the rpm that will be used during normal paving operations. Start the exhaust ventilation system and begin monitoring for SF₆ to determine background levels.
- While maintaining the SF₆ tanks outdoors or in a well-ventilated area, run the discharge tubing from each mass flow meter to well within the exhaust

hood on each side of the paver exhaust ventilation system to create 100% capture conditions.

- Initiate the flow of SF₆ through the flow meter and allow it to reach steady-state (this step should take only a minute). Use a soapy water solution to check for SF₆ leaks throughout the SF₆ delivery system.
- Continue monitoring until five readings are recorded during at least 3 minutes.
- Deactivate the flow of SF₆.
- Remove quickly the discharge tubing to an outdoor location so that the SF₆ does not leak from the tubes and cause increased background levels of SF₆.
- End the 100% capture test (leave the tractor engine running).
- Initiate monitoring to establish background interference until SF₆ concentration drops below 0.1 ppm.
- Locate the copper distribution plenum under the auger area and connect the ends of both 1/4-inch discharge tubes from the mass flow meters to one end of the plenum with a tee connection.
- Check background concentration to ensure that it is less than 0.1 ppm SF₆.

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- Initiate the SF₆ flow through the mass flow meters and begin monitoring SF₆ concentrations (approximate steady-state conditions will be achieved in about 1 minute). Take at least five readings during a 3-minute period.
- Discontinue the SF₆ flow and remove the distribution plenum and discharge tubing from the auger area to an outside location. If the distribution plenum is left in place, there may be a longer delay before continuing to the next test.
- Continue monitoring to determine the concentration of SF₆ that escaped into the test area. Discontinue monitoring when the concentration of SF₆ is below 0.1 ppm.
- Turn off the ventilation system and paver engine; calculate the capture efficiency.
- Repeat both tracer tests four times.

Example Test Run and Calculations

The paver was positioned, the barrier was constructed, and smoke was used to visually test the system. Smoke was seen coming in the top of the overhead door. The opening in the overhead door was sealed, and the smoke test revealed no other leaks in the barrier or the exhaust ventilation system. No visible smoke was in the auger area when smoke was released into the engine cooling air intake.

For simplicity, the SF₆ detector was calibrated and adjusted to read SF₆ directly in ppm. The two SF₆ mass flow meters were set for an exhaust ventilation system that should deliver 2,600 cubic feet/minute. Using Table 1, the two mass flow meters were each adjusted to 0.45 liters per minute, for a total flow rate of 0.90 liters per minute shown below:

Trial number	Total SF ₆ flow rate (liters/minute) (half to each side of the paver)
1	0.903
2	0.908
3	0.899
4	0.900

The mean flow rate was $[(0.903 + 0.908 + 0.899 + 0.900)/4]$
= 0.903 liters/minute.

The sampling probe was placed in the exhaust ventilation duct, and background samples were registered by the detector. The 1/4-inch tubing (CP-grade SF₆ outlet)

from the two flow meters was placed through the hood and into the exhaust duct (upstream of the fan), one on each side of the paver. Readings were as follows:

Task	Reading number	Detector reading (ppm SF₆)
Background	1	0.0051
	2	0.0062
	3	0.0048
	4	0.0050
	5	0.0066
	6	0.0062
	7	0.0058
Start SF ₆	8	6.3
	9	14.0
	10	13.8
	11	13.9
	12	13.7
	13	13.8
End	14	13.9

Appendix

At least five consecutive measurements are needed; in this case, the last six data points were used (i.e., reading number 9-14). The eighth reading (6.3 ppm) does not reflect steady-state and was not used in determining the average. The mean concentration of SF₆ is 13.85 ppm (the average of those six

points). The mean background value is 0.0057 ppm. These values were used to calculate the volumetric flow rate (Q_{exh}) from Equation 1A. To change the SF₆ flow rate to cfm, divide by 28.3. To correct for background readings, subtract 0.0057 from the SF₆ average concentration.

$$Q_{(\text{exh})} = \frac{\left(\frac{0.903}{28.3}\right)}{13.85 - 0.0057} \times 10^6 = \frac{0.0319 \times 10^6}{13.84} = 2,305 \text{ cubic feet/minute}$$

In this case, the background value was negligible, and the calculated exhaust ventilation cfm was shown to be almost 300 cfm lower than the original estimate of 2,600 cfm.

The same mass flow meters and SF₆ flow rates were used for the capture efficiency test. The tubing was removed from the exhaust ventilation hood and connected to the 10-foot distribution plenum. Readings were as follows:

Task	Reading number	Detector reading (ppm SF₆)
Background	1	0.092
	2	0.084
	3	0.078
Start SF ₆	4	20.1
	5	11.8
	6	12.6
	7	12.7
	8	13.9
	9	10.3
	10	12.4
	11	11.9
	12	12.6

At least five consecutive measurements are needed; in this case, the last eight were used. The fourth reading (20.1 ppm) was high, which reflects the flow controller overshooting the set point during the startup of SF₆ flow; this point was not used in determining the average. The mean concentration of SF₆ was 12.28 ppm; the average background concentration was 0.0847 ppm.

From Equation 2A, the capture efficiency is calculated by dividing the aver-

age SF₆ concentration obtained during the efficiency test (minus the background) by the average SF₆ concentration obtained during the 100% capture test (minus the background). This is displayed as a percentage:

$$\frac{(12.28 - .0847)}{(13.85 - 0.0057)} \times 100 = 88.1\%$$

This procedure was done four times with the following results:

Trial number	100% capture (ppm SF₆)	Capture efficiency (ppm SF₆)	Capture efficiency (%)
1	13.84	12.20	88.1
2	13.67	12.95	94.7
3	13.74	11.90	86.6
4	13.93	12.11	86.9

Statistics

Calculate the capture efficiency average:

$$m = (88.1 + 94.7 + 86.6 + 86.9) / 4 = 89.1\%$$

Calculate the estimated standard deviation:

$$s = \{[(88.1 - 89.1)^2 + (94.7 - 89.1)^2 + (86.6 - 89.1)^2 + (86.9 - 89.1)^2] / (4-1)\}^{0.5}$$

$$= \{(1.0 + 31.4 + 6.3 + 4.8) / 3\}^{0.5} = 3.8$$

Appendix

If the number of trials, n , is different from 4, then $(n-1)$ is used in the denominator of this calculation and the numerator is the sum of all n -squared differences rather than just 4-squared differences. Choose the number t (from the Student's t -distribution table at the 95th percentile) from the following table based on the value of n :

t: 6.31 (n=2)	2.92 (n=3)	2.35 (n=4)
2.13 (n=5)	2.02 (n=6)	1.94 (n=7)
1.90 (n=8)	1.86 (n=9)	1.83 (n=10)

Calculate a test statistic (T):

$$T = m - \frac{(t \times s)}{n^{0.5}}$$

For this example, the average mean value is $m=89.1$; the t -distribution value is $t=2.35$; the standard deviation of the mean values is $s=3.8$; and the sample size is $n=4$:

$$T = 89.1 - \frac{(2.35 \times 3.8)}{4^{0.5}} = 89.1 - 4.5 = 84.6$$

If $T > 80.0$, it can be concluded with 95% confidence that the efficiency of the exhaust ventilation is greater than 80% as tested in the laboratory. In this example, we are 95% confident that the efficiency is greater than 84.6%.

If $T \leq 80.0$, the conclusion that the efficiency is greater than 80% cannot be made from these data.

Glossary of Terms

Asphalt paver: A self-propelled construction machine (either rubber-tired or crawler-mounted) designed to receive, convey, distribute, profile, and compact paving material by the free-floating screed method. There are two classes of paving equipment—highway-class pavers and nonhighway-class pavers.

Auger: A screw conveyor used to distribute paving material transversely ahead of the screed.

Conveyor: A device for transferring paving material from the hopper to the auger.

Conveyor flow gate: A device for regulating the height of paving

material being transferred by the conveyor.

Highway-class pavers: Self-propelled pavers weighing 16,000 pounds or more that are used principally to place hot mix asphalt on highways, roads, streets, and airports.

Hopper: The section of the paver that receives the paving material from an external source.

Nonhighway-class pavers: Pavers that weigh less than 16,000 pounds and are used principally to place hot mix asphalt on local streets, parking lots, driveways, and other small projects.

Operator: The person whose primary function is to control the

paver's speed and direction.

Screed: The device towed behind the tractor to strike off, compact, contour, and smooth the paving material.

Screed end plate: A vertically adjustable plate located at the outboard end of the screed to retain the paving material and form the edge of the mat.

Tractor: The portion of a paver that provides propulsion and may also receive, convey, and distribute paving material.

Tunnel: The passageway through which paving material moves from the hopper to the auger/screed.



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