HealthHazard® Evaluation Program

Evaluation of Volatile Organic Compound Exposures at a Tire Manufacturing Facility

HHE Report No. 2023-0062-3404

November 2024

Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

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Keywords: North American Industry Classification System (NAICS) 326211 (Tire Manufacturing [except Retreading]), Tennessee, Tires, Rubber, Carbon Disulfide, Ventilation

Disclaimer

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Availability of Report

Recommended Citation

NIOSH [2024]. Evaluation of volatile organic compound exposures at a tire manufacturing facility. By Beaucham C, Tomasi S. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Health Hazard Evaluation Report 2023-0062-3404, https://www.cdc.gov/niosh/hhe/reports/pdfs/2023-0062-3404.pdf.

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Introduction

Request

Union representatives requested a health hazard evaluation to evaluate fume exposures in the 4-roll section of a rubber tire manufacturing facility. Representatives were concerned about employees in the 4-roll area who reported eye, nose, throat, and sinus irritation caused by fumes from rubber processing.

Workplace

This large tire manufacturer processed raw materials into rubber that was then used to produce bus and truck tires. Many components of these raw materials are potentially released into the air during rubber processing. In the 4-roll area of the facility, processed rubber was passed through a series of mills that heated and pressed the rubber multiple times. After the final mill, the rubber was fed into the top and bottom of a calender machine. Thin wires were fed into the calender and pressed between the top and bottom rubber pieces. Employees in the 4-roll area collected quality control samples, ensured the mills and calender were operating correctly, changed the type of wire and raw materials, and troubleshot machinery errors.

To learn more about the workplace, go to Section A in the Supporting Technical Information

Our Approach

We visited the facility in July 2023 to learn more about employee health concerns and to assess the air for volatile organic compounds. We conducted opening and closing meetings with employees, union representatives, and management. We discussed what NIOSH was, the purpose of our evaluation, and what to expect. We sent a letter after this evaluation with our initial findings and preliminary recommendations. We completed the following activities during our evaluation:

- Observed the work process and ventilation system including fume hood smoke capture surrounding the 4-roll mills.
- Reviewed documentation of previous exposure sampling for volatile organic compounds given off by processed rubber and for carbon disulfide in personal air samples.
- Assessed emissions and collected samples of volatile organic compounds to understand what type of chemicals were being emitted in the 4-roll area.
- Conducted employee interviews about their work, symptoms, and health concerns.

To learn more about our methods, go to Section B in the Supporting Technical Information

Our Key Findings

The local exhaust ventilation system at the 4-roll area did not contain all the emissions.

- Air sampling results showed several chemicals in the air that could irritate eyes, nose, throat, and sinuses.
- Visualization of smoke capture showed that the local exhaust ventilation system did not trap all the fumes in the 4-roll area fume hoods, especially at the final mill.

All employees reported eye, nose, or sinus symptoms.

- Employees working in the 4-roll area reported eye symptoms (burning, watery, or itchy eyes) that improved when away from work.
- Employees in the 4-roll area also reported nose or sinus symptoms that improved when away from work.

Management took action to address exposure concerns.

- Following our visit, management followed our initial recommendations. They redesigned the local exhaust ventilation system to reduce employee exposure to volatile organic compounds. However, at the time of the writing of this report, the redesigned ventilation system has yet to be installed.

To learn more about our results, go to Section B in the Supporting Technical Information

Our Recommendations

The Occupational Safety and Health Act requires employers to provide a safe workplace.

Potential Benefits of Improving Workplace Health and Safety:

↑ Improved worker health and well-being	↑ Enhanced image and reputation
↑ Better workplace morale	↑ Superior products, processes, and services
↑ Easier employee recruiting and retention	↑ May increase overall cost savings

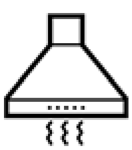
The recommendations below are based on the findings of our evaluation. For each recommendation, we list a series of actions you can take to address the issue at your workplace. The actions at the beginning of each list are preferable to the ones listed later. The list order is based on a well-accepted approach called the "hierarchy of controls." The hierarchy of controls groups actions by their likely effectiveness in reducing or removing hazards. In most cases, the preferred approach is to eliminate hazardous materials or processes and install engineering controls to reduce exposure or shield employees. Until such controls are in place, or if they are not effective or practical, administrative measures and personal protective equipment might be needed. Read more about the hierarchy of controls at https://www.cdc.gov/niosh/hierarchy-of-controls/about/index.html.

We encourage the company to use a health and safety committee to discuss our recommendations and develop an action plan. Both employee representatives and management representatives should be included on the committee. Helpful guidance can be found in *Recommended Practices for Safety and Health Programs* at https://www.osha.gov/shpguidelines/index.html.

Recommendation 1: Reduce exposure to rubber fumes and volatile organic compounds

Why? Volatile organic compounds are chemicals containing a carbon that can readily evaporate into the air at room temperature. Volatile compounds include a variety of different chemicals, some of which may have short- and long-term adverse health effects. Volatile organic compounds can cause eye, nose, throat, and sinus irritation, even at exposure levels not known to cause chronic health effects. We found that the local exhaust ventilation system enclosing the 4-roll area was inefficient at containing the fumes generated by the 4-roll process.

How? At your workplace, we recommend these specific actions:



Redesign the local exhaust ventilation system.

- Make sure each mill is completely enclosed, where possible, and fumes generated inside the mill hoods do not escape to the 4-roll area. Focus on the final mill first.
- Stop using personal cooling fans directed at the mills that may create wind disturbances (sometimes called eddies). The fans may also reduce the local exhaust system's ability to completely capture the volatile organic compounds.
- Replace the temporary flexible ductwork to the calender with hard, smooth bore ductwork. Ductwork with smooth bore construction allows for air to move more efficiently through the system.
- Consider adding a separate exhaust system specifically for the calender process. This would keep the exhaust from the mills separate from the calender exhaust.

Improve general ventilation.

- Make sure the general ventilation system works together with the local exhaust ventilation system to sufficiently dilute the air in the 4-roll area.
- Check that the general ventilation system provides enough cooling for employees so personal cooling fans are not needed.
- Refer to the American National Standards Institute ASHRAE Standard 55-2023, "Thermal Environmental Conditions for Human Occupancy," which reports on human comfort to temperature and humidity levels. The standard also establishes a range of temperatures and humidity levels that 80% or more of employees consider comfortable.
    - Assuming slow air movement (around 20 feet per minute) and 50% indoor relative humidity, the operative temperatures recommended by ASHRAE are around 64.5°F to 74°F in the winter, and from 69.5°F to 77°F in the summer.
    - ASHRAE recommends relative humidity kept at or below 65% in all seasons.
- Reevaluate employees who reported symptoms after these changes have been made to the ventilation systems.

Recommendation 2: Encourage employees to report work-related symptoms

Why? Recognizing work-related symptoms early can help identify potential job-related exposures and risk factors for work-related disease. This can help prioritize actions to prevent work-related illnesses in employees. Work-related symptoms are symptoms that typically improve on days away from work or on vacation. Identifying symptoms early can reduce severity and lead to treatment, if needed.

How? At your workplace, we recommend these specific actions:

Encourage employees to report work-related health symptoms to their healthcare provider and, as instructed by their employer, to a designated individual at their workplace.

- Keep a record of what was happening in the workplace when the symptoms occurred.
- Identify and put into place measures, if needed, to reduce potential exposures related to the reported symptoms.
- Document any corrective or follow-up actions taken to address the issue(s).

Employees should seek care for work-related medical concerns from healthcare providers knowledgeable in occupational medicine.

- Encourage employees with work-related health concerns to report their potential exposure to volatile organic compounds to their healthcare provider and to share a copy of this report with the healthcare provider.
- The American College of Occupational and Environmental Medicine (https://acoem.org/Find-a-Provider) and the Association of Occupational and Environmental Clinics (http://www.aoec.org/index.htm) maintains databases of healthcare providers trained in occupational medicine.

Supporting Technical Information

Evaluation of Volatile Organic Compound Exposures at a Tire Manufacturing Facility

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Section A: Workplace Information

Employee and Background Information

Number of employees at time of evaluation: 49 in the 4-roll area

Length of shift: 12 hours

Number of employees onsite at time of evaluation: 8

Mean tenure at company: 22 years (range: 10–32 years)

Mean tenure in 4-roll area: 12 years (range: 0.3–32 years)

Mean hours per week: 44 hours (range: 40–54 hours)

Mean days per week: 4 days (range: 3.5–5 days)

This large facility, constructed in 1990, processed raw materials into rubber. The processed rubber was then turned into bus and truck tires. Many components of these raw materials are potentially released into the air during rubber processing. One portion of the manufacturing facility was called the 4-roll area (Figure A1). In this area, the raw material (processed rubber) was passed through a series of mills to heat, compress, and cool the rubber. Starting with one of two breakdown mills (Figure A2), flexible rubber was fed into the back of a silver cylinder creating a ridged black product. At one end, a thin strip of rubber was cut off and fed onto a conveyor to the surge mill. In the surge mill (Figure A3), smooth black rubber was fed into the back of a silver cylinder, creating a thick smooth black piece of rubber that was cut and fed onto a conveyor and then fed into the final mill. In the final mill (Figure A4), smooth rubber was fed into the back of a silver cylinder and cut into two sets of three thicknesses of rubber. This was then fed into two different conveyors and fed to the calender machine.

Employees in the creel room fed metal wires into a calender machine (Figure A5). The processed rubber from the final mill was fed into the top bite and the bottom bite of the calender where the rubbers were pressed together with the metal wires in between. Excess rubber was removed from the sides and recycled. The rubber with metal wires was rolled for further processing.

The 4-roll area was in operation 24-hours a day, 7-days a week. Seven to eight employees per crew worked 12-hour shifts from 7:00 a.m. to 7:30 p.m. (or 7:00 p.m. to 7:30 a.m.). Workers alternated in A and B teams (day shift) and C and D teams (night shift) with rotating schedules of 2 days on, 2 days off, 3 days on, and then 2 days off. Employees in the 4-roll area reported experiencing eye and skin irritation for at least 10 years. Employees reported symptoms were intermittent, although typically worse in the warmer months.

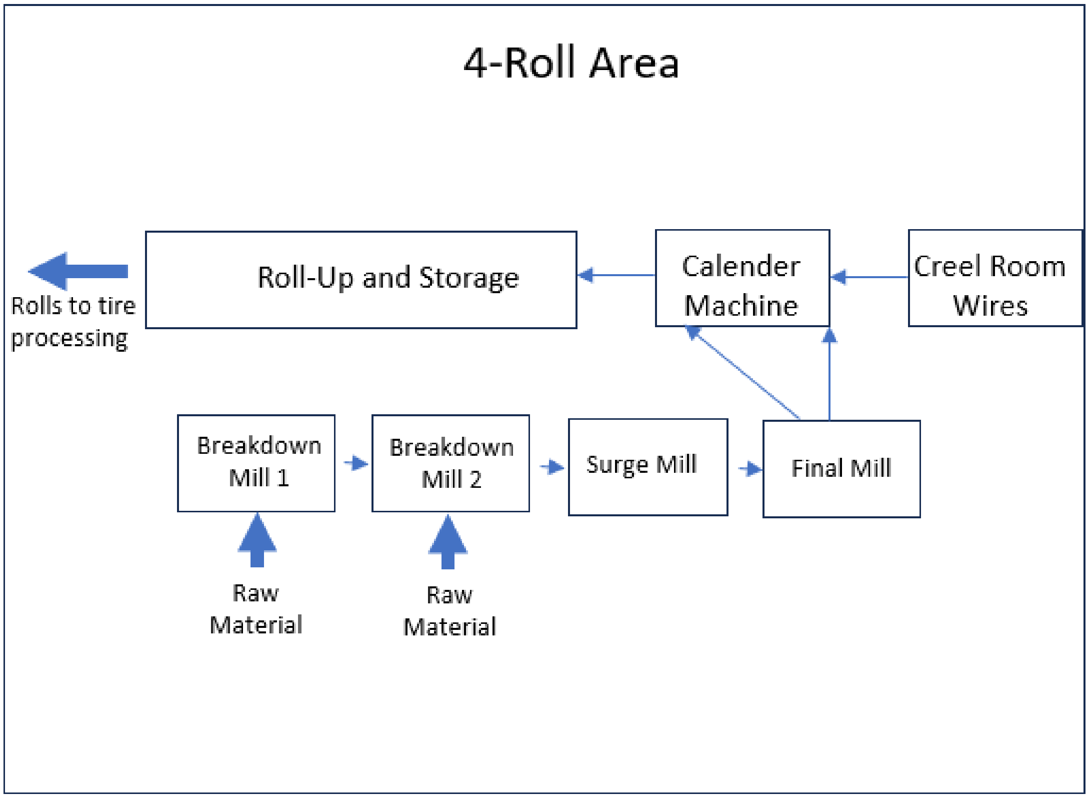

Figure A1. Layout of the 4-roll area showing process flow.

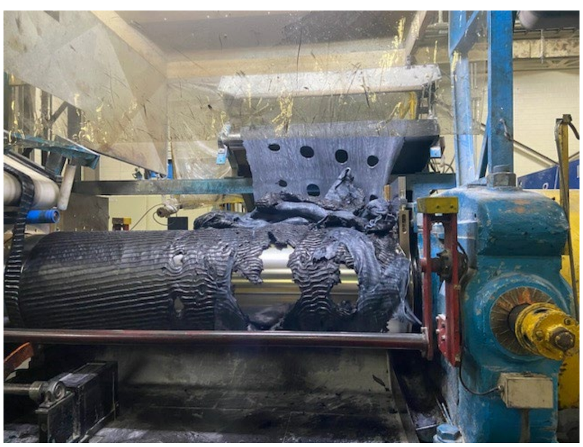

Figure A2. Breakdown mill number 1. Photo by NIOSH.

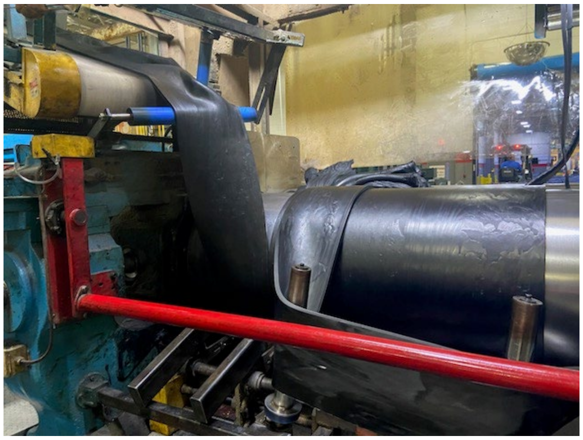

Figure A3. Surge mill. Photo by NIOSH.

Figure A4. Final mill. Photo by NIOSH.

Figure A5. Calender machine bottom bite. Photo by NIOSH.

Section B: Methods, Results, and Discussion

Methods: Workplace Observations: Employee and Local Exhaust Ventilation System

We observed work processes in the 4-roll area, including employee tasks, activities, and personal protective equipment (PPE) use. We used smoke tubes to visually evaluate the capture of the fume hoods enclosing the 4-roll mills. We generated smoke at the edges of the plastic curtains by each of the mills (where an employee might stand) to determine if the draw from the hood exhaust was strong enough to pull the smoke into the exhaust or if it created turbulent flow or escaped capture. We also generated smoke inside of the enclosure to visualize turbulence and to see if fumes could evade capture once inside the hood and escape the enclosure.

Results: Workplace Observations: Employee and Local Exhaust Ventilation System

Employee Observations

The employees in the area ensured that the raw material was fed into the breakdown mill properly, took quality control samples throughout the process, ensured the wires were fed into the calender properly, and performed troubleshooting of the operation as needed. The required PPE for the 4-roll area included safety glasses, steel-toed boots, long pants, and ear plugs. All 4-roll employees were observed properly wearing the required PPE.

Local Exhaust Ventilation System Observations

Above each of the four mills was an exhaust hood that connected to one smokestack located on the roof of the building (Figure B1). Mill exhaust was unfiltered. All ductwork entered at a proper angle and duct diameter increased with each new addition. We did not hear any abnormal sounds from the fan. The air handling units (also located on the roof) were sufficiently spaced to prevent reintroduction of air into the building from the 4-roll exhaust.

Figure B1. Exhaust stack for the 4-roll local exhaust ventilation system. Photo by NIOSH.

Smoke capture at breakdown mills 1 and 2 was efficient; however, when a personal cooling fan was blowing towards the mills, the air flow from the fan defeated the smoke capture of the exhaust system. Airflow inside the breakdown mills was not turbulent and flowed directly from the point of smoke generation to the exhaust without escaping the enclosure.

Airflow inside the surge mill was turbulent and caused a buildup of smoke to the left side of the hood (near the conveyor belt). Particulate (likely from cooled rubber fumes) could also be seen building up in this location of the mill. Although most of the generated smoke was drawn into the exhaust hood, some smoke escaped to the 4-roll environment around the rubber conveyor.

Smoke generation around the final mill showed very little smoke capture by the exhaust and a substantial amount of escaping smoke at the front top right, front top left, and at the face of the hood by the rubber conveyors. Inside the hood the airflow was turbulent.

Smoke capture at the calender, both top and bottom bites, appeared sufficient. However, the ductwork to the calender was corrugated flexible ductwork (Figure B2). Compared with hard metal ductwork, flexible ductwork is less durable and more susceptible to tearing, twisting, kinking, and other issues. These include turbulent airflow inside the ductwork and material buildup along the ridges of the duct.

Figure B2. Gray, metallic ductwork connecting one of the four mills and a black flexible duct from the calender. Photo by NIOSH.

Methods: Document Review

We reviewed the results of an assessment conducted by the facility in November 2020. At that time, three samples of the rubber product were sent to the company headquarters to be tested by gas chromatograph mass spectrometry for compounds that could potentially cause irritation. As stated in the report, the three samples included one "irritant sample" (the rubber mixture that was suspected of causing the majority of employee symptoms), one "sample in question," and one "control sample." The company's internal laboratory identified carbon disulfide in the samples as a compound that could cause eye irritation. They recommended that the company conduct personal air sampling for carbon disulfide on the calender mill operators. We reviewed that report and a log of duct velocity taken at various points of the local exhaust ventilation (LEV) system serving the 4-roll area starting in 2011 and ending in 2022.

Results: Document Review

The documentation of this assessment showed that carbon disulfide was detected with a similar concentration in all samples. The laboratory's recommendations included (1) conducting personal sampling for carbon disulfide, (2) continuing to ensure ventilation hoods are pulling effectively, (3) possibly increasing fan speed in the 4-roll area, (4) modifying and improving the capture velocity at the mill hoods, and (5) continuing to collect rubber samples when irritation is noted. The facility conducted personal exposure monitoring for carbon disulfide (described below), installed new LEV at the calender machine, and then tested the air velocity of the LEV system.

We reviewed personal air samples for eight calender machine operators for carbon disulfide collected in February and March 2021. All carbon disulfide samples were found to be below the analytical limit of detection (< 0.7 parts per million [ppm]). They were also below the established occupational exposure limits (OELs) of 20 ppm for the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL), 1 ppm for the American Conference of Governmental Industrial Hygienists (ACGIH®) Threshold Limit Value (TLV®), and the NIOSH recommended exposure limit (REL).

We reviewed air velocity measurements on the LEV system collected by the health and safety department at the facility. These measurements were collected at least once a year and at times quarterly. The exhaust at the calender ranged 2,700–4,000 feet per minute (fpm) but was typically 4,000 fpm. We suspected 4,000 fpm to be the maximum range for the instrument used to take the measurement. The breakdown mill exhaust ranged 0–3,449 fpm but was typically above the manufacturer minimum recommended velocity of 1,000 fpm. These readings suggested that the ventilation system was operating as designed. The system was not in use when the measurements read 0 fpm.

Methods: Confidential Employee Interviews

We gathered information about employee health through employee interviews that included questions about work and health history.

We asked about job tasks, chemicals used, previous jobs at the facility, PPE use, and health symptoms. We defined a work-related symptom as a symptom experienced at work that improved when away from work.

Results: Confidential Employee Interviews

The eight employees working in the 4-roll area during the site visit participated in the confidential interviews. Employees reported eye symptoms (burning, watery, or itchy eyes) that improved when away from work or on vacation. When asked which tasks or products caused the eye symptoms, some employees reported experiencing heat in the 4-roll area, operating the calender, working in the calender room, or running the mills. More than half of the employees interviewed reported work-related nose or sinus symptoms. When asked which tasks or products they associated with nose symptoms, a couple of employees reported working in the creel room.

Methods: Area Air Sampling

We collected task-based area samples for qualitative identification of volatile organic compounds (VOCs) on stainless steel thermal desorption tubes containing three beds of sorbent material. We collected eight task-based area air samples for 45–64 minutes. Two samples were collected in the bottom bite of the calender, two in the top bite, two in the final mill, one in breakdown mill number 2, and one in the surge mill areas. Samples were collected at 50 cubic centimeters per minute, ran for 45–64 minutes, and then analyzed by a modified NIOSH Method 2549 [NIOSH 2024]. We focused the analysis on VOCs that were identified in the sample at relatively higher levels (above 5,000,000 abundance) compared with other VOCs at lower levels.

Results: Area Air Sampling

The eight task-based sample results identified about 90 different VOCs (Table C1). VOCs with peaks above 5,000,000 abundances are listed in Table C2. The area that had the greatest number of different chemicals was the final mill for both sampling sessions. Breakdown mill 2 and the bottom bite of the calender operator area samples had the next highest number of different chemicals during the second sampling session. The most abundant chemicals were methyl isobutyl ketone, methyl styrene, decane, dodecane, undecane, diphenyl ether, butylated hydroxytoluene, and diphenyl propane.

Although carbon disulfide (one of the VOCs) was detected in six of the samples, it was only seen above 5,000,000 abundances from the calender bottom bite sample. There was an error in collection of the second sample from the top bite, and therefore we did not analyze that tube or receive those sampling results.

Discussion

Rubber products such as truck tires are produced by combining numerous synthetic and natural chemicals that are subjected to a series of reactions using heat, pressure, and catalysts in the manufacturing process [Governa et al. 1987; Gupta et al. 1993]. During the mixing, milling, extruding, and vulcanizing that occurs in the rubber manufacturing process, dusts, gases, vapors, fumes, and chemical byproducts, collectively referred to as rubber manufacturing emissions, are produced and released into the work environment [Jonsson et al. 2008; McMichael et al. 1976]. Occupational exposure to rubber manufacturing emissions occurs through inhalation or skin contact during the manufacturing process [Attarchi et al. 2013; McMichael et al. 1976; Zuskin et al. 1996]. Because rubber manufacturing emissions are complex and vary by the ingredients, processing methods, and final products, studies have indicated a good ventilation system is the most effective method for reducing exposures among rubber manufacturing employees [Bascom et al. 1990].

During this evaluation, we detected the presence of multiple VOCs that could be associated with reported symptoms. No specific chemical or group of chemicals emerged as the cause for the employees' reported symptoms. The ventilation assessment indicated that improving the ventilation system will likely reduce employee exposures to all VOCs. Instead, the VOC levels supported the need for strengthening engineering controls to reduce exposure. The reported health symptoms are most likely coming from a combination of the VOCs and not just carbon disulfide. Although not reported during this evaluation, breathing chronic low levels of carbon disulfide can cause headaches, tiredness, trouble sleeping, and vision changes [Khalid et al. 2024]. Strengthening the ventilation system would also reduce exposure to carbon disulfide. Instead of focusing on one specific chemical as the cause of symptoms, it is most likely coming for a combination of the VOCs.

VOCs are a large class of chemicals that contain carbon and have a sufficiently high vapor pressure to allow some of the compound to exist as a gas at room temperature. Both natural and synthetic rubbers are commonly used in the manufacture of tires. During the rubber manufacturing process, numerous VOCs are released. In one study conducted by Huang et al. [2022], alkanes were the dominant categories of VOCs emitted from rubber tire manufacturing. Lee et al. [2012] examined personal hydrocarbon exposures in the calendering process at two tire manufacturing facilities and identified methylcyclohexane (0.015–1.733 ppm), heptane isomers (0.004–0.933 ppm), and hexane isomers (not detectable to 0.134 ppm) as the hydrocarbons with the three highest concentrations. Our sampling identified a complex mixture of VOCs at relatively low levels that may have acted together to cause irritant symptoms among employees.

Two important routes of VOC exposure are by inhalation and skin (dermal) [Cone 1986]. Most VOCs can cause skin irritation, and many may cause minimal to mild irritation of the respiratory tract [Rosenberg et al. 1997]. Furthermore, some VOCs are classified as either known or suspected carcinogens. For example, benzene (not present in this facility) is a known carcinogen and ethyl benzene, methyl styrene, and naphthalene are suspected carcinogens. Therefore, controlling VOC exposure is essential. Occupational exposure criteria exist for some individual VOCs, but do not exist for VOCs as a group [NIOSH 2020].

Thermal desorption tube samples cannot be directly compared with OELs because they are not personal air samples, nor do they result in a specific concentration of the compound. However, they can be used to highlight areas with a higher risk of exposure and identify potential chemicals of concern. Many of the chemicals seen in the spectra cause eye, skin, nose, and throat irritation. In addition, the self-reported nature of the information collected through interviews may have been affected by participants ability to recall and report information accurately.

Limitations

This evaluation was conducted at a single point in time and therefore may not be reflective of all possible exposure scenarios. Exposures may be different on different days due to changes in the environment, temperature, and workplace conditions. This cross-sectional study design may not accurately capture changes in exposures or reported health symptoms over time. Although using thermal desorption tubes allowed us to identify VOCs in the part per billion range, the results are not directly quantifiable; therefore, we do not know the precise levels at which these VOCs were present.

Section C: Tables

Table C1. Thermal desorption tube peak identification indicating the volatile organic compounds present in the 4-roll area samples

1)	CO_2*	47)	Benzaldehyde
2)	Sulfur dioxide (SO_2)	48)	C_9H_{12} aromatic hydrocarbons
3)	Acetaldehyde	49)	Methylstyrene
4)	Methanol	50)	Octamethylcyclotetrasiloxane
5)	C_4H_8	51)	Decane
6)	Trimethylamine	52)	Ethylhexanol?
7)	Ethanol	53)	Dihydromethylvinylfurnanone
8)	Acetone	54)	$C_{10}H_{14}$ aromatic hydrocarbons
9)	Methyl butane (C_5 hydrocarbon)	54A)	C_{10} hydrocarbons
10)	Isopropanol	55)	$C_{10}H_{16}$
11)	Trichlorofluoromethane	55A)	3-Carene
12)	Pentane	56)	Acetophenone
13)	C_5H_8 isomer	57)	Methoxyphenol?
14)	Carbon disulfide	58)	Menthol?
15)	Methacrolein	59)	Decahydronaphthalene?
16)	Methyl vinyl ketone (MVK)	60)	Undecane
17)	Butanal	61)	C_{11} & C_{12} hydrocarbons
18)	Methyl ethyl ketone (MEK)	62)	Decamethylcyclopentasiloxane
19)	Acetic acid	63)	Naphthalene
20)	Methylfuran	64)	Dodecane
21)	Tetrahydrofuran (THF)	65)	C_9 & C_{10}*
22)	Isovaleraldehyde	66)	Benzothiazole
23)	Methylbutanal	66A)	Tetrahydromethylnaphthalene?
24)	Benzene	67)	Methylnaphthalenes
25)	Butanol	68)	Tridecane
26)	Cyclohexane	69)	$C_{13}H_{28}$
27)	C_7 hydrocarbons	70)	tert-Butyl cresol?
28)	Propanoic acid	71)	$C_{15}H_{22}$
29)	Heptane	72)	$C_{15}H_{24}$
30)	Dimethylfuran	73)	$C_{11}H_{16}O$?
31)	Methyl isobutyl ketone (MIBK)	74)	MW 147, $C_8H_5NO_2$?
31A)	Methylcyclohexane	75)	Diphenyl ether
32)	MW 110?	76)	Tetradecane
33)	Toluene	77)	Phthalamide?
34)	Hexanal	78)	Acenaphthylene
35)	C_8H_{18} & C_8H_{16} hydrocarbons	79)	$C_{18}H_{30}$?
36)	Octene (or cyclooctane, C_8H_{16})	80)	Pentadecane
37)	Octane	81)	Butylated hydroxytoluene
38)	Hexamethylcyclotrisiloxane	82)	$C_{15}H_{16}$, diphenyl propane
39)	Ethyl cyclohexane	83)	Diethyl phthalate
40)	Ethylbenzene/xylene isomers	84)	Hexadecane
41)	C_9H_{20} & C_9H_{18} hydrocarbons	85)	$C_{18}H_{20}$ & $C_{18}H_{22}$
42)	MW 114 ketones (such as methyl amyl ketone)	86)	Diisopropyl biphenyl isomers
43)	MW 124 ketone	87)	Ditertbutylhydroxybenzaldehyde
44)	Butyl propanoate	88)	Hexadecanoic acid?
45)	Nonane	89)	MW 250, isocyanate containing compound?
46)	Butanediol	90)	Unknown hydrocarbons

Abbreviations: MW = molecular weight
* The group of peaks identified as #65 could not satisfactorily be identified because of the lack of peak resolution, elevated chromatographic baseline, and inability to identify a molecular ion. Based on some of the ions in the mass spectra, it is suspected that these compounds could be esters.
? Indicates some doubt in the precise identification of the chemical compound.

Table C2. Identified volatile organic compounds detected in the 4-roll area with an abundance over 5,000,000		
Location	Substance	Health effects [IARC 2024; NIOSH 2020]
Calender Operator area	Sulfur dioxide	Irritation to the nose, eyes, throat, and lungs; sore throat, runny nose, burning eyes, cough
	Methyl styrene	Irritation to eyes, skin, nose, throat; drowsiness, dermatitis, suspected carcinogen*
	Methyl isobutyl ketone (MIBK)	Headaches, dizziness, narcosis, irritates eyes, nose, and throat
Final mill	Butanol	Irritation eyes, nose, throat, headache; dizziness, drowsiness, corneal inflammation, blurred vision, lacrimation, photophobia, dermatitis, possible auditory nerve damage, hearing loss, central nervous system depression
	Heptane	Irritation of eyes, nose, throat; headache, dizziness, nausea, dermatitis
	Methyl isobutyl ketone (MIBK)	Headaches, dizziness, narcosis, irritates eyes, nose, and throat
	Octane	Irritation of nose, throat, lungs, eyes, skin; headache, dizziness, lightheadedness
	Ethylbenzene	Eye and throat irritation, respiratory effects, dizziness, vertigo, suspected carcinogen
	MW 124 Ketone	Not specified
	Nonane	Irritation of skin, eyes, nose, throat, lungs; shortness of breath
	C_9H_{12} aromatic hydrocarbons	Not specified
	Methyl styrene	Irritation to eyes, skin, nose, throat; drowsiness, dermatitis
	Decane	Not specified
	Acetophenone	Not specified
	Undecane	Not specified
	Dodecane	Not specified
	Tridecane	Not specified
	Tert-butyl cresol	Eye/skin irritation
	$C_{15}H_{22}$	Not specified
	$C_{15}H_{23}$	Not specified
	Diphenyl ether	Eye irritation
	Butylated hydroxytoluene	Low acute toxicity
	Diphenyl propane	Not specified

Table C2. Continued. Identified volatile organic compounds detected in the 4-roll area with an abundance over 5,000,000		
Location	Substance	Health effects
Breakdown mill 2	Butanol	Irritation eyes, nose, throat; headache, dizziness, drowsiness, corneal inflammation, blurred vision, lacrimation, photophobia, dermatitis, possible auditory nerve damage, hearing loss, central nervous system depression
	Heptane	Irritation of eyes, nose, throat; headache, dizziness, nausea, dermatitis
	Methyl isobutyl ketone (MIBK)	Headaches, dizziness, narcosis, irritates eyes, nose, and throat
	Octane	Irritation of nose, throat, lungs, eyes, skin; headache, dizziness, lightheadedness
	Ethylbenzene	Eye and throat irritation, respiratory effects, dizziness, vertigo, suspected carcinogen
	MW 124 ketone	Not specified
	Butyl propanoate	Irritating to the skin and eyes
	C9H12 aromatic hydrocarbons	Not specified
	Methyl styrene	Irritation to eyes, skin, nose, throat; drowsiness, dermatitis, suspected carcinogen
	Decane	Not specified
	Ethylhexanol	Irritation to eyes, skin, nose, throat
	Acetophenone	Not specified
	Undecane	Not specified
	Naphthalene	Headaches, nausea, dizziness, vomiting, suspected carcinogen
	Dodecane	Not specified
	Tert-butyl cresol	Eye/skin irritation
	$C_{15}H_{22}$	Not specified
	$C_{15}H_{24}$	Not specified
	Diphenyl ether	Not specified
	Tetradecane	Not specified
	Butylated hydroxytoluene	Low acute toxicity
	Diphenyl propane	Not specified

Table C2. Continued. Identified volatile organic compounds detected in the 4-roll area with an abundance over 5,000,000		
Location	Substance	Health effects
Calender Operator area bottom bite	Carbon disulfide	Dizziness, headache, poor sleep, lassitude, anxiety, anorexia, weight loss, psychosis, polyneuropathy, Parkinson-like syndrome, ocular changes, coronary heart disease, gastritis, kidney, liver injury, eye, skin burns, dermatitis
	Tetrahydrofuran	Not specified
	Methyl isobutyl ketone (MIBK)	Headaches, dizziness, narcosis, irritates eyes, nose, and throat
	Octane	Irritation of nose, throat, lungs, eyes, skin; headache, dizziness, lightheadedness
	Ethylbenzene	Eye and throat irritation, respiratory effects, dizziness, vertigo, suspected carcinogen
	MW 124 ketone	Not specified
	Nonane	Irritation of skin, eyes, nose, throat, lungs; shortness of breath
	Butanediol	Not specified
	C_9H_{12} aromatic hydrocarbons	Not specified
	Methyl styrene	Irritation to eyes, skin, nose, throat; drowsiness, dermatitis, suspected carcinogen
	Decane	Not specified
	Acetophenone	Not specified
	Undecane	Not specified
	Dodecane	Not specified
	Naphthalene	Headaches, nausea, dizziness, vomiting, suspected carcinogen
	Methylnaphthalenes	Irritant of skin, eyes, mucous membranes, and upper respiratory
	Tridecane	Not specified
	Tert-butyl cresol	Eye/skin irritation
	Diphenyl ether	Not specified
	Butylated hydroxytoluene	Low acute toxicity
	Diphenyl propane	Not specified

Table C2. Continued. Identified volatile organic compounds detected in the 4-roll area with an abundance over 5,000,000		
Location	Substance	Health effects
Calender Operator area top bite	Methyl isobutyl ketone (MIBK)	Headaches, dizziness, narcosis, irritates eyes, nose, and throat
	Octene	Skin irritation
	Octane	Irritation of nose, throat, lungs, eyes, skin; headache, dizziness, lightheadedness
	Ethylbenzene	Eye and throat irritation, respiratory effects, dizziness, vertigo, suspected carcinogen
	Nonane	Irritation of skin, eyes, nose, throat, lungs; shortness of breath
	Aromatic hydrocarbons	Not specified
	Methyl styrene	Irritation to eyes, skin, nose, throat; drowsiness, dermatitis, suspected carcinogen
	Decane	Not specified
	Hydrocarbons	Not specified
	Acetophenone	Not specified
	Undecane	Not specified
	Dodecane	Not specified
	Benzothiazole	Not specified
	Methylnaphthalenes	Irritant of skin, eyes, mucous membranes, and upper respiratory
	Diphenyl ether	Not specified
	Butylated hydroxytoluene	Low acute toxicity
	Diphenyl propane	Not specified

Table C2. Continued. Identified volatile organic compounds detected in the 4-roll area with an abundance over 5,000,000

Location	Substance	Health effects
Final mill	Sulfur dioxide	Irritation to the nose, eyes, throat, and lungs; sore throat, runny nose, burning eyes, cough
	Isovaleraldehyde	Not specified
	Heptane	Irritation of eyes, nose, throat; headache, dizziness, nausea, dermatitis,
	Methyl isobutyl ketone (MIBK)	Headaches, dizziness, narcosis, irritates eyes, nose, and throat
	MW 110	Not specified
	Octene	Skin irritation
	Octane	Irritation of nose, throat, lungs, eyes, skin; headache, dizziness, lightheadedness
	Ethylbenzene	Eye and throat irritation, respiratory effects, dizziness, vertigo, suspected carcinogen
	MW 124 ketone	Not specified
	Benzaldehyde	Not specified
	Aromatic hydrocarbons	Not specified
	Methyl styrene	Irritation to eyes, skin, nose, throat; drowsiness, dermatitis
	Decane	Not specified
	Acetophenone	Not specified
	Undecane	Not specified
	Naphthalene	Headaches, nausea, dizziness, vomiting, suspected carcinogen
	Dodecane	Not specified
	Methylnaphthalenes	Irritant of skin, eyes, mucous membranes, and upper respiratory
	Tert-butyl cresol	Eye/skin irritation
	Diphenyl ether	Not specified
	Acenaphthylene	Not specified
	Butylated hydroxytoluene	Low acute toxicity
	Diphenyl propane	Not specified
	Diisopropyl biphenyl isomers	Not specified

Table C2. Continued. Identified volatile organic compounds detected in the 4-roll area with an abundance over 5,000,000		
Location	Substance	Health effects
Surge mill	Sulfur dioxide	Irritation to the nose, eyes, throat, and lungs; sore throat, runny nose, burning eyes, cough
	Methyl isobutyl ketone (MIBK)	Headaches, dizziness, narcosis, irritates eyes, nose, and throat
	Octane	Irritation of nose, throat, lungs, eyes, skin; headache, dizziness, lightheadedness
	Ethylbenzene	Eye and throat irritation, respiratory effects, dizziness, vertigo, suspected carcinogen
	MW 124 ketone	Not specified
	Nonane	Irritation of skin, eyes, nose, throat, lungs; shortness of breath
	Aromatic hydrocarbons	Not specified
	Methyl styrene	Irritation to eyes, skin, nose, throat; drowsiness, dermatitis, suspected carcinogen
	Decane	Not specified
	Acetophenone	Not specified
	Undecane	Not specified
	Naphthalene	Headaches, nausea, dizziness, vomiting, suspected carcinogen
	Dodecane	Not specified
	$C_{15}H_{22}$	Not specified
	$C_{15}H_{24}$	Not specified
	Diphenyl ether	Not specified
	Butylated hydroxytoluene	Low acute toxicity
	Diphenyl propane	Not specified

Abbreviations: MW = molecular weight

* Suspected carcinogens are noted by the International Agency for Research on Cancer to be possibly carcinogenic to humans (Group 2B)

Section D: Occupational Exposure Limits

NIOSH investigators refer to mandatory (legally enforceable) and recommended occupational exposure limits (OELs) for chemical, physical, and biological agents when evaluating workplace hazards. OELs have been developed by federal agencies and safety and health organizations to prevent adverse health effects from workplace exposures. Generally, OELs suggest levels of exposure that most employees may be exposed to for up to 10 hours per day, 40 hours per week, for a working lifetime, without experiencing adverse health effects.

However, not all employees will be protected if their exposures are maintained below these levels. Some may have adverse health effects because of individual susceptibility, a preexisting medical condition, or a hypersensitivity (allergy). In addition, some hazardous substances act in combination with other exposures, with the general environment, or with medications or personal habits of the employee to produce adverse health effects. Most OELs address airborne exposures, but some substances can be absorbed directly through the skin and mucous membranes.

Most OELs are expressed as a time-weighted average (TWA) exposure. A TWA refers to the average exposure during a normal 8- to 10-hour workday. Some chemical substances and physical agents have recommended short-term exposure limits (STEL) or ceiling values. Unless otherwise noted, the STEL is a 15-minute TWA exposure. It should not be exceeded at any time during a workday. The ceiling limit should not be exceeded at any time.

In the United States, OELs have been established by federal agencies, professional organizations, state and local governments, and other entities. Some OELs are legally enforceable limits; others are recommendations.

- OSHA, an agency of the U.S. Department of Labor, publishes permissible exposure limits [29 CFR 1910 for general industry; 29 CFR 1926 for construction industry; and 29 CFR 1917 for maritime industry] called PELs. These legal limits are enforceable in workplaces covered under the Occupational Safety and Health Act of 1970.

- NIOSH recommended exposure limits (RELs) are recommendations based on a critical review of the scientific and technical information and the adequacy of methods to identify and control the hazard. NIOSH RELs are published in the *NIOSH Pocket Guide to Chemical Hazards* [NIOSH 2020]. NIOSH also recommends risk management practices (e.g., engineering controls, safe work practices, employee education/training, PPE, and exposure and medical monitoring) to minimize the risk of exposure and adverse health effects.

- Another set of OELs commonly used and cited in the United States includes the threshold limit values or TLVs, which are recommended by the American Conference of Governmental Industrial Hygienists (ACGIH). The ACGIH TLVs are developed by committee members of this professional organization from a review of the published, peer-reviewed literature. TLVs are not consensus standards. They are considered voluntary exposure guidelines for use by industrial hygienists and others trained in this discipline "to assist in the control of health hazards" [ACGIH 2024].

Outside the United States, OELs have been established by various agencies and organizations and include legal and recommended limits. The Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (Institute for Occupational Safety and Health of the German Social Accident Insurance) maintains a database of international OELs from European Union member states, Canada (Québec), Japan, Switzerland, and the United States. The database, available at https://www.dguv.de/ifa/gestis/gestis-stoffdatenbank/index-2.jsp, contains international limits for more than 2,000 hazardous substances and is updated periodically.

OSHA (Public Law 91-596) requires an employer to furnish employees a place of employment free from recognized hazards that cause or are likely to cause death or serious physical harm. This is true in the absence of a specific OEL. It also is important to keep in mind that OELs may not reflect current health-based information.

When multiple OELs exist for a substance or agent, NIOSH investigators generally encourage employers to use the lowest OEL when making risk assessment and risk management decisions.

Carbon Disulfide

Carbon disulfide exposure can cause dizziness, poor sleep, headache, anxiety, anorexia, weight loss, and vision changes in humans [NIOSH 2019]. Chronic inhalation exposure may cause atherosclerosis, coronary heart disease, and neurobehavioral effects including psychomotor slowing, positional tremors, peripheral neuropathy, hearing loss, and Parkinsonism [ATSDR 2012]. OSHA has established a PEL of 20 ppm as an 8-hour TWA, 30 ppm as a ceiling limit, and 100 ppm as a 30-minute maximum peak [OSHA 2024]. NIOSH has established a REL of 1 ppm as an 8-hour TWA and a STEL of 10 ppm. NIOSH also designated carbon disulfide with a skin notation indicating that it can be absorbed through the skin [NIOSH 2019]. ACGIH has established a TLV of 1 ppm as an 8-hour TWA and a Biological Exposure Indices® (BEI) of 0.5 milligram urinary 2-thiothiazolidine-4-carboxylic acid (TTCA) per gram of creatinine, taken at the end of shift [ACGIH 2024].

Section E: References

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HHE Report No. 2023-0062-3404