NIOSH Mining Program Report of Investigations RI 9701

Dust Control Handbook for Industrial Minerals Mining and Processing

Second Edition

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

IMA-NA®
Industrial Minerals Association North America

Report of Investigations 9701

DUST CONTROL HANDBOOK FOR INDUSTRIAL MINERALS MINING AND PROCESSING

Second edition

Andrew B. Cecala, Andrew D. O'Brien, Joseph Schall, Jay F. Colinet,
Robert J. Franta, Mark J. Schultz, Emily J. Haas, Jamie E. Robinson, Justin Patts,
Brian M. Holen, Robert Stein, Jake Weber, Mark Strebel, Lindsie Wilson, and
Mark Ellis

DEPARTMENT OF HEALTH AND HUMAN SERVICES
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Office of Mine Safety and Health Research
Pittsburgh, PA • Spokane, WA

March 2019

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NIOSH [2019]. Dust control handbook for industrial minerals mining and processing. Second edition. By Cecala AB, O'Brien AD, Schall J, Colinet JF, Franta RJ, Schultz MJ, Haas EJ, Robinson J, Patts J, Holen BM, Stein R, Weber J, Strebel M, Wilson L, and Ellis M. Pittsburgh PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2019–124, RI 9701. https://doi.org/10.26616/NIOSHPUB2019124

DOI: https://doi.org/10.26616/NIOSHPUB2019124

DHHS (NIOSH) Publication No. 2019–124

March 2019

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Chapter Contents

ABOUT THIS HANDBOOK

The second edition of this handbook represents a successful collaborative effort by government and industry toward protecting the health of U.S. mine workers. The two principal stakeholder partnerships active in creating this handbook were between the NIOSH Mining Program of the National Institute for Occupational Safety and Health (NIOSH) and the Industrial Minerals Association–North America (IMA-NA). The mission of the NIOSH Mining Program is to eliminate mining fatalities, injuries, and illnesses through research and prevention, while the IMA-NA is the representative voice of companies that extract and process raw materials known as industrial minerals.

This handbook was written by a task force of safety and health specialists, industrial hygienists, and engineers to provide information on proven and effective control technologies that lower workers' dust exposures during all stages of mineral processing. The handbook describes both dust-generating processes and the control strategies necessary to enable mine operators to reduce worker dust exposure. Implementation of the engineering controls discussed can assist operators, health specialists, and workers in reaching the ultimate goal of eliminating pneumoconiosis and other occupational diseases caused by dust exposure in the mining industry.

Designed primarily for use by industrial minerals producers, this handbook contains detailed information on control technologies to address all stages of the minerals handling process, including drilling, crushing, screening, conveyance, bagging, loadout, and transport. The handbook's aim is to empower minerals industry personnel to apply state-of-the-art dust control technology to help reduce or eliminate mine and mill worker exposure to hazardous dust concentrations—a critical component in ensuring the health of our nation's mine workers.

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Andrew B. Cecala, MBA, Principal Supervisory Mining Engineer, Dust, Ventilation, and Toxic Substances Branch, NIOSH

Andrew D. O'Brien, MS, CIH, CSP, Vice President of Safety & Health, Covia Corporation

TASK FORCE COMMITTEE MEMBERS, SECOND EDITION

Robert Brown, Senior Manufacturing Technology Specialist, 3M Industrial Mineral Products Division

Brandon Christ, Industrial Engineer, Pittsburgh Safety and Health Technology Center (PS&HTC), Dust Division, Mine Safety and Health Administration (MSHA)

Jay F. Colinet, MS, PE, Principal Mining Engineer, Dust, Ventilation, and Toxic Substances Branch, NIOSH

Robert J. Franta, Quotation Engineer, Spraying Systems Co.

Emily J. Haas, PhD, Senior Scientist, Human Factors Branch, NIOSH

Brian M. Holen, CSP, CIH, Industrial Hygienist-Product Steward, 3M Industrial Minerals Products Division

Justin Patts, BS, Lead Mechanical Engineer, Dust, Ventilation, and Toxic Substances Branch, NIOSH

Jamie E. Robinson, MS, CIH, CSP, General Manager/Industrial Hygiene, Covia Corporation

Joseph Schall, MA, Health Communications Specialist, Health Communications, Surveillance, and Research Support Branch, NIOSH

Mark J. Schultz, PE, Senior Mining Engineer, Pittsburgh Safety and Health Technology Center (PS&HTC), Dust Division, Mine Safety and Health Administration (MSHA)

Robert Stein, PE, General Engineer, Conformity Verification and Standards Development Branch, National Personal Protective Technology Laboratory (NPPTL), NIOSH

Mark Strebel, Division Manager—Dust, Martin Engineering

Jake Weber, General Manager, Distribution & Service, ASGCO Manufacturing, Inc.

Lindsie Wilson, MS, CIH, Industrial Hygienist, Covia Corporation

TASK FORCE CONTRIBUTORS, SECOND EDITION

The following individuals are acknowledged for their content contributions to specific chapters of the second edition of this handbook.

Steven E. Mischler, PhD, Senior Mining Engineer,
Dust, Ventilation, and Toxic Substances Branch, NIOSH

Chapter 1: Overview of Dust Exposure Assessment and Control

David Gilroy, Sales Manager, Dust Solutions, Inc.

Chapter 3: Wet Spray Systems
Chapter 11: Haul Roads, Stockpiles, and Open Areas

Kevin Peterson, Business Development Director, Titan Products,
Vortex Global Corporation

Chapter 8: Bulk Loading

John A. Organiscak, Senior Mining Engineer
Dust, Ventilation, and Toxic Substances Branch, NIOSH

Chapter 4: Drilling and Blasting
Chapter 10: Filtration and Pressurization Systems for Environmental Enclosures

Wm. Randolph (Randy) Reed, PhD, PE, Research Mining Engineer,
Dust, Ventilation, and Toxic Substances Branch, NIOSH

Chapter 4: Drilling and Blasting
Chapter 11: Haul Roads, Stockpiles, and Open Areas

EDITOR AND HANDBOOK LAYOUT COORDINATOR, SECOND EDITION

Joseph Schall, MA, Health Communications Specialist,
Health Communications, Surveillance, and Research Support Branch, NIOSH

IMA-NA COORDINATOR, SECOND EDITION

Mark G. Ellis, President, Industrial Minerals Association–North America

ACKNOWLEDGMENTS, SECOND EDITION

The handbook authors are indebted to the following individuals below, listed alphabetically, for their contributions as reviewers of the second edition of this handbook.

Dr.-Ing. Jürgen F. Brune, PE, Professor of Practice, Mining Engineering Department, Colorado School of Mines, Golden, CO

Joseph M. Denk, Staff Assistant, MSHA Metal and Nonmetal Mine Safety and Health, Northeastern District, Warrendale, PA

Christopher Findlay, CIH, MSHA Metal and Nonmetal Mine Safety and Health, Arlington, VA

Ali Ferguson, MA, Professional Wordsmith/Owner, Purple Ink Editing, Alameda, CA

William Francart, Director, MSHA Technical Support, Arlington, VA

Deborah Hirst, Acting Associate Director for Science,
Division of Applied Research and Technology, Cincinnati, OH

Kevin M. Jones, Manager Industrial Projects, IMERYS S.A., Atlanta, Georgia

Mike Pace, Chief Engineer, Covia Corporation, Saint Peter, MN

Chaolong Qi, PhD, PE, General Engineer, NIOSH, Cincinnati, OH

Emily A. Sarver, MS, PhD, Associate Professor,
Department of Mining and Minerals Engineering, Virginia Tech, Blacksburg, VA

Monique Spruill, Chief of Health, MSHA
Metal and Nonmetal Mine Safety and Health, Arlington, VA

David Weissman, Director, Respiratory Health Division, NIOSH, Morgantown, WV

Mike J. Wright, Director of Health, Safety and Environment,
United Steelworkers of America, Pittsburgh, PA

The authors also thank the below, listed alphabetically, for their work on graphics and equations.

Brittney Bragg, Web Designer, CACI/Attain

Rebecca Geromi, Graphics Specialist, Attain

Samantha Newman, Graphic Designer, CACI

John A. Organiscak, Senior Mining Engineer, NIOSH

Kenneth Strunk, Visual Information Specialist, NIOSH

TASK FORCE COMMITTEE CO-CHAIRS, FIRST EDITION

Andrew B. Cecala, MBA, Senior Research Engineer, Dust, Ventilation, and Toxic Substances Branch, NIOSH

Andrew D. O'Brien, CIH, CSP, General Manager/Safety & Health, Unimin Corporation

TASK FORCE COMMITTEE MEMBERS, FIRST EDITION

Jay F. Colinet, MS, PE, Senior Scientist, Dust, Ventilation, and Toxic Substances Branch, NIOSH

William R. Fox, Manager, Safety & Health, Unimin Corporation

Robert J. Franta, Quotation Engineer, Spraying Systems Co.

Jerry Joy, CIH, CSP, Research Scientist—Industrial Hygienist, Dust, Ventilation, and Toxic Substances Branch, NIOSH

Wm. Randolph (Randy) Reed, PhD, PE, Research Mining Engineer, Dust, Ventilation, and Toxic Substances Branch, NIOSH

Patrick W. Reeser, Engineering Manager, U.S. Silica Company

John R. Rounds, Director, Project Engineering, Unimin Corporation

Mark J. Schultz, PE, Senior Mining Engineer, Pittsburgh Safety and Health Technology Center (PS&HTC), Dust Division, Mine Safety and Health Administration (MSHA)

EDITOR, FIRST EDITION

Joseph Schall, MA, Health Communications Specialist, Health Communications, Surveillance, and Research Support Branch, NIOSH

HANDBOOK LAYOUT COORDINATOR, FIRST EDITION

Jeanne A. Zimmer, Physical Science Technician, Dust, Ventilation, and Toxic Substances Branch, NIOSH

IMA-NA COORDINATOR, FIRST EDITION

Mark G. Ellis, President, Industrial Minerals Association–North America

ACKNOWLEDGMENTS, FIRST EDITION

The following individuals, listed alphabetically, are acknowledged for their review and valuable contributions to the first edition of this handbook.

Roger Bresee, Vice President, Technical Services, Unimin Corporation, Peterborough, Ontario, Canada.

Chris Bryan (retired), CMSP, Occupational Health & Safety Manager, U.S. Silica Company, Berkeley Springs, WV.

Robert M. Castellan, MD, MPH, Expert, Division of Respiratory Disease Studies, National Institute for Occupational Safety and Health.

Cynthia Farrier, Graphics Specialist, National Institute for Occupational Safety and Health.

Christopher Findlay, CIH, CMSP, U.S. Department of Labor, Mine Safety and Health Administration, Arlington, VA.

Ian Firth, Principal Adviser, Occupational Health, Rio Tinto Limited, Bundoora, Victoria, Australia.

Marion Molchen, Molchen Photography, Washington, PA.

Jan Mutmansky, PhD, PE, Professor Emeritus, Pennsylvania State University, University Park, PA.

Kenneth Vorpahl (retired), CIH (1973–2009), CSP, (1976–2009) General Manager/Safety & Health, Unimin Corporation, Winchester, VA.

Richard Wood, International Union of Operating Engineers, National HAZMAT Program, Beaver, WV.

ACRONYMS AND ABBREVIATIONS USED IN THIS HANDBOOK

AASHTO	American Association of State Highway and Transportation Officials
ACGIH	American Conference of Governmental Industrial Hygienists
AEK	airflow extensible kraft
AIRRS	air ring seal
APF	assigned protection factor
ASAE	American Society of Agricultural Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
B&BCD	bag and belt cleaning device
BHP	brake horsepower
CAA	Clean Air Act
CBR	California Bearing Ratio
CEL	Certified Equipment List
CEMA	Conveyor Equipment Manufacturers Association
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
COPD	chronic obstructive pulmonary disease
DOL	Department of Labor
DPM	diesel particulate matter
DSH	Dust Suppression Hopper
EK	extensible kraft
EMP	elongate mineral particle
EPA	Environmental Protection Agency
ESP	electrostatic precipitator
EVADE	Enhanced Video Analysis of Dust Exposures
FFS	form-fill-seal
FIBC	flexible intermediate bulk container
FK	flat kraft
HDPE	high-density polyethylene
HE	high-efficiency particulate air (NIOSH PAPR designation)
HEPA	high-efficiency particulate air
HVAC	heating, ventilation, and air-conditioning
IMA-NA	Industrial Minerals Association–North America
ISO	International Organization for Standardization

LEV	local exhaust ventilation
MACT	maximum achievable control technology
MERV	minimum efficiency reporting value
MLV	modified low-velocity
MSD	musculoskeletal disorder
MSHA	Mine Safety and Health Administration
NAAQS	National Ambient Air Quality Standards
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NIOSH	National Institute for Occupational Safety and Health
NK	natural kraft
NPPTL	National Personal Protective Technology Laboratory
OASIS	Overhead Air Supply Island System
OEL	occupational exposure limit
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
PAPR	powered air-purifying respirator
pDR	personalDataRAM
PEL	permissible exposure limit
PF	protection factor
PM	particulate matter
PPE	personal protective equipment
PSE	particle size efficiency
PTFE	polytetrafluoroethylene
PVC	polyvinyl chloride
REL	recommended exposure limit
RI	Report of Investigations
SDS	Safety Data Sheet
SOP	standard operating procedure
SP	static pressure
TLV	threshold limit value
TP	total pressure
TSP	total suspended particulates
TWA	time-weighted average
USBM	U.S. Bureau of Mines
VEM	video exposure monitoring
VP	velocity pressure

UNIT OF MEASURE ABBREVIATIONS USED IN THIS HANDBOOK

acph	air changes per hour
acfm	actual cubic feet per minute
cfm	cubic feet per minute
cfm/ft	cubic feet per minute per feet
cfm/ft^2	cubic feet per minute per feet squared
ft	feet
fpm	feet per minute
ft/min	feet per minute
ft^2	feet squared
ft^3	cubic feet
gpm	gallons per minute
gal/yd^2	gallons per square yard
gr/cf	grains per cubic foot
gr/dscf	grains per dry standard cubic foot
l	liters
l/min	liters/min
lb	pound or pounds
lbs/ft	pounds per foot
lbs/ft^2	pounds per feet squared
lbs/ft^3	pounds per feet cubed
lbs/hour	pounds per hour
lbs/min	pounds per minute
$\mu g/m^3$	micrograms per cubic meter
µm	micrometers
mph	miles per hour
mg/m^3	milligrams per cubic meter
mm	millimeters
NPT	national pipe taper
pH	potential of hydrogen
psig	pounds-force per square inch gauge
RPM	revolutions per minute
scfm	standard cubic feet per minute
TPH	tons per hour
wg	water gauge

Glossary

GLOSSARY

Accelerated silicosis. A form of silicosis resulting from exposure to high concentrations of crystalline silica and developing 5–10 years after the initial exposure. While accelerated silicosis presents with the nodular characteristics that typify chronic silicosis, accelerated silicosis generally progresses more rapidly than chronic silicosis.

Access road. A road that is generally used for utility or maintenance purposes. This is usually a secondary road, which is smaller in design than a haul road. An access road is not normally used for moving ore between the pit and crusher locations.

Acute silicosis. A form of silicosis resulting from exposure to unusually high concentrations of respirable crystalline silica dust. Symptoms develop within a few weeks to 4–5 years after the initial exposure. In contrast to the more common chronic and accelerated forms of silicosis, acute silicosis involves a flooding of the alveolar region of the lungs with abnormal fluid containing fats and proteins, which gives rise to an alternative term for the disease—silicoproteinosis. Acute silicosis is uniformly fatal, often within several months of diagnosis.

Aerodynamic diameter. The diameter of a spherical particle that has a density of 62.4 pounds per feet cubed (lbs/ft^3) (the standard density of water) and the same settling velocity as that of the particle in question. Although particles have irregular shapes, this is an expression of a given particle's behavior as if it were a perfect sphere.

Agglomeration. The act or process of gathering into a mass.

Air atomizing. Mixing compressed air with a liquid to break up the liquid into a controlled droplet size.

Airborne dust prevention. Control measures taken to prevent dust from becoming airborne.

Airborne dust suppression. Control measures taken to suppress dust after it has become airborne.

Air quantity. The amount of air used in ventilating a process, which is a combination of the air velocity or speed and the area of the duct, measured in cubic feet of air per minute (cfm).

Air to cloth ratio. In dust collection systems, a measure of the volume of gas per minute per unit area of the bag collecting dust.

Air velocity. The speed of air traveling in an area or duct measured in feet per minute (ft/min).

Alveoli. Tiny air sacs in the lungs where the exchange of oxygen and carbon dioxide takes place.

Annulus. The open area of the drill hole between the drill steel and the wall of the drill hole.

Articulated positioner. A mechanical device that transfers product to a loading spout while also moving the loading spout from side to side as well as forward and back to ensure proper positioning of the spout discharge.

Asbestosis. Pulmonary fibrosis (scarring of the lungs) caused by the inhalation of asbestos fibers.

Autogenous. Size reduction of materials accomplished by impact and compressive grinding of the material by large units of the material itself—i.e., no balls or rods are employed.

Axial-flow fan. A fan that moves air in a direction parallel to the axis of the rotation of the fan. Axial-flow fan types include propeller, tubeaxial, vaneaxial, and two-stage axial-flow.

Backflushing. The action of reversing the flow of air or water in a system to remove contaminants from a filter.

Bagging. Loading of product into some type of paper, cloth, or plastic bag to be shipped/delivered to customers.

Baghouse collector. In dust collection systems, a type of collector that captures the particulate in an air stream by forcing the air through filter bags.

Bag perforations. Vent holes integrated into bags of product to allow air to escape rapidly and to reduce bag failures (e.g., rupturing or exploding).

Bag valve. Sleeve placed inside 50- to 100-lb product bags to allow for the insertion of the fill nozzle during bag loading and the sealing of the bag when loading is completed.

Bailing airflow. Compressed air blown down the drill stem through the bit in order to flush the cuttings out of the hole.

Blowback. Product spewing out from the bag valve during bag filling.

Bonding strength. The ability of material to adhere to itself and to the material to which it is applied.

California Bearing Ratio. A test that provides results as a ratio from the comparison of the bearing capacity of a material to the bearing capacity of a well-graded crushed stone.

Capture velocity. A measure of the airflow necessary to seize dust released at a source and then pull this dust-laden air into a (capturing) hood. Capture velocity is measured in feet per minute (ft/min).

Capturing hood. A hood positioned as close to a dust source as possible to capture the dust-laden air and pull it into an exhaust ventilation system.

Carryback. Material that sticks or clings to a conveyor belt after passing over the head pulley.

Cartridge collector. In dust collection systems, a type of collector that captures particulate from an air stream by forcing the air through filter elements, which are arranged in a pleated configuration.

Centrifugal collector. In dust collection systems, a device that separates particulate from the air by centrifugal force. Also called a cyclone.

Centrifugal fan. A fan in which the airflow is drawn into the rotating impeller and discharged radially from the fan blade into the housing. Centrifugal fans include radial, backward, and forward blade types.

Chimney effect. The behavior of heated air or gas rising in a vertical passage or area, as in a chimney, due to its lower density compared to the surrounding air or gas.

Chronic silicosis. A slowly progressive, nodular form of silicosis that typically develops after 10–30 years of exposures to respirable crystalline silica dust.

Coanda effect. The tendency of a moving fluid to be attracted to a nearby surface.

Collaring. The preliminary step in drilling, which forms the beginning of a drill hole, or collar.

Contact angle. The angle at which a liquid meets a solid surface.

Control efficiency. A standard of measure, usually expressed as a percentage, used to compare the results of two or more outcomes.

Cure. The hardening of a chemical additive and base material.

Cuttings. Material that is produced during the drilling process. Cuttings are usually a fine-sized material.

Cyclone. A conical device that uses centrifugal force to separate large- and small-diameter particles.

Depth loading. In dust collection systems, a method of collecting particulate on a fabric by maintaining a filter cake on the fabric to optimize collection efficiency. When depth loading is used on a particular fabric, dust is intentionally allowed to penetrate into the fabric to form a layer of dust on the bag.

Diffusion. The spread of dust particles from high concentration areas to lower concentration areas. Many times, this is achieved in ventilation systems by dust-laden air being mixed with clean, dust-free air.

Dorr-Oliver cyclone. A compliant sampling device approved by the Mine Safety and Health Administration (MSHA) designed to separate respirable-sized particles from a dust-laden air stream.

Drifter drill. A drill used in underground mining to drill horizontal holes.

Drill deck (drill table). A deck or table on the drill located 2–3 feet above the ground surface and adjacent to the drill operator's cab. This deck is used by the operator to gain access to the drill rods when needed to add more rods or to change drill bits.

Drill rods. Metal rods, also called "steels," used to connect the rotary head to the drill bit as drilling proceeds through the ground.

Dual-nozzle bagging system. A type of fill nozzle for filling 50- to 100-lb bags of product where the inner nozzle is used for filling and the outer nozzle is used to exhaust excess pressure from the bag.

Dust. Small solid particles, often created by the breaking up of larger particles.

Dust collector. An air cleaning device used to remove air-entrained particles.

Dust collector airflow. The quantity of air that flows through a dust collector.

Dust collector airflow to bailing airflow ratio. A ratio of dust collector airflow and bailing airflow, mathematically represented as the dust collector airflow divided by the bailing airflow.

Dust suppressants. Chemicals or substances applied to a surface to prevent airborne dust from being released from the surface.

Elastic limit. The maximum stress that can be applied to a material without causing permanent deformation.

Electrostatic charge. The physical electrical property of a dust particle that will cause it to experience a force, either attracting or opposing, from another charged electrical component or device.

Electrostatic precipitator. A particulate control device that uses electrical forces to move particles from the air stream to collection plates.

Elutriation. The process of separating lighter from heavier particles by flow between horizontal plates.

Enclosing hood. A hood that either partially or totally encloses an area to capture the dust source or dust-laden air and prevent it from flowing out into a mine or plant environment where it could contaminate workers.

Entrainment. The process of particles being captured and carried with the airflow.

Epitropic fiber. A fiber whose surface includes embedded particles designed to modify the fiber properties, typically electrical conductivity. Commonly used epitropic fiber materials include carbon, graphite, and stainless steel.

Exhaust. In ventilation systems, to directionally move air using an energy source (typically a fan).

Exhaust ventilation system. An engineered system designed to use negative pressure to draw air through a network of openings via a fan.

Filter cake. A solid mass of substances remaining on a filter which becomes thicker as particulate matter is retained on the filter media. This mass then improves filtration while increasing flow resistance/pressure and decreasing airflow through the filter media. Over time, this filter cake should be removed using some type of mechanical or air pulse system.

Flexible intermediate bulk containers (FIBCs). Large product containers, normally 1,000 lbs and greater when filled, used to ship bulk material to customers. Also called “bulk bags,” “mini-bulk bags,” “semi-bulk bags,” and “big bags.”

Fogger spray. Compressed air and water forced through a nozzle to create a fogged-in area, resulting in a mist that aids in dust suppression.

Fugitive dust. Solid airborne particulate matter that escapes from any dust-generating source.

Gradation. The distribution of different particle sizes in aggregate material.

Gravity separator. In ventilation systems, a large chamber where the velocity of the air stream is drastically reduced in order to facilitate the vertical drop of particles. Also called a “drop-out box.”

Haul road. A road used for hauling ore to and from pit and crusher locations at a surface mine. Hauling is generally conducted using large off-road haul trucks.

Hydraulic (airless) atomization. Controlling droplet size by forcing liquid through a known orifice diameter at a specific pressure.

Hydraulic flat fan nozzles. In wet spray systems, nozzles used to produce relatively large droplets over a wide range of flows and spray angles, normally used in narrow enclosed spaces.

Hydraulic full cone nozzles. In wet spray systems, nozzles used to produce a solid cone-shaped spray pattern with a round impact area that provides high velocity over a distance.

Hydraulic hollow cone nozzles. In wet spray systems, nozzles used to produce a circular ring spray pattern, typically producing smaller drops than other hydraulic nozzle types of the same flow rate.

Hydrogen embrittlement. A process by which metal (high-strength steel) can become brittle and fracture due to exposure to a hydrogen source.

Hygroscopic. The ability to absorb moisture from the air.

Impingement plate scrubber. A type of wet scrubber in which dust-laden air passes upward through openings in perforated plates, which hold a layer of water.

Induction. Airflow or product movement that creates sufficient momentum energy to pull additional surrounding dust-laden air into the airflow or product movement.

Inhalable dust. A fraction of airborne dust intended to represent those particles likely, when inhaled, to be deposited in the respiratory tract from the mouth and throat to the deep lung. The collection efficiency of an inhalable dust sampler varies by the aerodynamic diameter of the particles—to demonstrate, about 50 percent of 100-micrometer particles (but nearly 100 percent of particles less than 1 micrometer) are collected.

Inlet loading. In ventilation systems, the amount of dust traveling to the collector.

Intake air. In ventilation systems, the clean air supplied into an area or space to replace existing (contaminated) air.

Laminar. Sometimes referred to as streamline flow, the occurrence of air flowing in parallel paths with no disruptions between the paths.

Local exhaust ventilation (LEV). A system used to capture dust and remove it from a mine or plant environment. The concept is to capture dust-laden air, pull this air into an exhaust hood, transport the dust-laden air through ductwork to some type of dust collection system, and duct the dust-free air to some type of exhaust fan, which creates negative pressure, resulting in the airflow for the entire system.

Makeup air. In ventilation systems, the clean air necessary to supply a specific ventilation application (e.g., a local exhaust ventilation system).

Mechanical shaker collector. In dust collection systems, a type of collector that uses mechanical shaking to remove the excess dust cake from the collection media.

Mesothelioma. A lung disease that originates in the mesothelium—a thin layer of tissue lining most of the internal organs—attributed to occupational overexposure to asbestos fibers and certain other mineral fibers, such as erionite.

Musculoskeletal disorder (MSD). Health problems in the body's muscles, joints, tendons, ligaments, and nerves. When work-related, these problems are caused by the work process or environment.

Open structure building design. A processing structure or building designed without exterior solid walls in an effort to lower respirable dust and noise levels.

Overhead Air Supply Island System (OASIS). A filtration system located over a worker at a stationary position to filter dust-laden air from the work environment and deliver a clean envelope of air down over the worker.

Palletizing. In the mineral processing industry, when bags of product, normally ranging in weight between 50 and 100 lbs, are loaded onto a pallet for shipment to customers.

Percussion drilling. Rock penetration through rotation and down-pressure with a pneumatic drill, which contains a piston that delivers hammer blows to the drill column or the drill bit to enhance the drilling effectiveness and rate.

Photo eye. A photoelectric sensor that detects a change in light intensity for the purposes of controlling or detecting something, such as the presence of ore on a conveyor or piece of machinery.

Pitot tube. A pressure-measuring instrument normally made out of two concentric metal tubes that can be used in conjunction with a manometer to measure the static pressure (SP), total pressure (TP), and velocity pressure (VP) due to airflow in the duct.

Protection factor. A numeric value comparing outside to inside dust concentrations. Examples of where protection factors apply include personal protective equipment and environmental enclosures.

Pulse jet collector. In dust collection systems, a type of collector that uses timed or pressure-induced blasts of compressed air to recondition filter bags by removing the filter cake.

Push-pull ventilation system. The technique of using an air jet (blowing system) directed toward a dust source and receiving hood (exhaust system) to capture and move dust-laden air into the hood.

Respirable crystalline silica. Particles smaller than 10 µm in aerodynamic diameter that, when airborne, can be inhaled deep into the lungs and cause serious health issues.

Respirable dust. A fraction of airborne dust intended to represent those particles likely to be deposited in the alveolar region of the lungs when inhaled. The collection efficiency of a respirable dust sampler varies by aerodynamic diameter of the particles—to demonstrate, only about 1 percent of 10-micrometer particles (but nearly 100 percent of particles less than 1 micrometer) are collected.

Reverse air collector. In dust collection systems, a type of collector that uses a traveling manifold to distribute low-pressure cleaning air to the filter bags for reconditioning.

Roof ventilators. Either axial or centrifugal fans placed on the roof of a building and used to pull air out of the structure and discharge it into the atmosphere.

"Rooster tail." Product spewing from the fill nozzle and bag valve as the bag is ejected from the bag filling machine.

Rotary drilling. Penetration through rock and ore by a combination of rotation and high down-pressures on a column of drill pipe with a roller drill bit attached to its end.

Scarify. To break up or loosen the ground surface.

Semi-autogenous. Size reduction of materials accomplished by impact and compressive grinding of the material by large units of the material itself, with the use of balls or rods to provide additional crushing force.

Silicosis. A progressive and incurable lung disease that belongs to a group of lung disorders called the pneumoconioses. Silicosis is caused by repeated inhalation of respirable crystalline silica (e.g., quartz) dust.

Skirting. On conveyors, a horizontal extension of the loading chute used to contain ore and dust within the transfer point. On loading spouts, strips of belting or fabric installed on the spout discharge end, creating a physical seal with the product pile to reduce dust liberated during bulk loading.

Spoon. When material is being conveyed, a curved plate that helps steer the material in the desired direction.

Spray tower scrubber. A type of scrubber that employs water, which falls counter-current through a rising dust-laden air stream, to remove dust particles.

Spreader box. An implement used in road construction to spread road material (typically gravel or sand) in a uniform layer. The implement, commonly in the shape of a box, is attached to and moved by mobile equipment, such as a bulldozer.

Static pressure (SP). In ventilation systems, a measure of the pressure in a ventilation duct relative to the atmospheric pressure. Static pressure can be either a positive (expansion) or negative (contraction) value. Static pressure summed together with velocity pressure (VP) provides the total pressure (TP) for a duct in a ventilation system.

Stilling zone. An enlarged area beyond the transfer zone of a belt conveyor designed to slow the airflow and allow airborne dust to return to the ore being transported.

Stoper drill. A hand-operated drill typically used in underground mining to drill vertical holes overhead. Also referred to as a jackleg drill.

Sub. A short length (usually 2–3 ft) of drill collar assembly, made of the same drill steel material, which is placed between the drill bit and the drill steel.

Subbase. In road construction, the layer between the subgrade and the wearing surface.

Subgrade. In road construction, the underlying soil or rock that serves as the foundation for the road.

Surface loading. In dust collection systems, a method of collecting particulate on the surface of a fabric to create a dust cake.

Surfactants. Substances that, when dissolved in water, lower the surface tension of the water, allowing the water to “wet” the dust more easily.

Table bushing. A bushing used to seal the opening where the drill steel passes through the drill deck.

Tilt sensor. On bulk loading spouts, a vertically mounted sensor designed to prevent blockages during loading. As the product pile grows and moves the sensor off of vertical by a predetermined amount (e.g., 15 degrees), an electronic signal is transmitted to initiate the raising of the spout.

Total pressure (TP). In duct ventilation systems, the sum of static pressure (SP) and velocity pressure (VP).

Total structure ventilation system. The use of exhaust fans high on the outside walls or roof of a structure to bring in clean outside air at the base of a building, which sweeps up through the structure to clear dust-prone areas.

Tri-cone roller drill bit. A rotary drill bit with three roller cones. As the drill bit rotates, the roller cones, which have carbide components, roll against the bottom of the drill hole, causing the material to break into small particles. This type of drill bit requires high down-pressure on the drill bit.

Velocity pressure (VP). In ventilation systems, the pressure required to accelerate air from being at rest to a given velocity. Velocity pressure added to static pressure (SP) provides the total pressure (TP) in a duct.

Venturi eductor. In pneumatic conveying systems, a device that converts blower output into suction to entrain dust-laden air, product material, or both into the conveying line.

Venturi effect. A reduction in static pressure resulting from a liquid or gas flowing through a constricted space.

Venturi scrubber. A type of wet scrubber consisting of a venturi-shaped inlet and a separator.

Water cartridges. A plastic or polyvinyl chloride (PVC) bag filled with water and inserted into the blasthole along with the explosive, resulting in dust suppression during blasting.

Water separator sub. A short length of a drill collar assembly placed between the drill bit and the drill steel. A water separator sub uses inertia to remove the injected water from the bailing air prior to reaching the drill bit to prevent hydrogen embrittlement.

Wear liner. A hardened or otherwise extended-life sacrificial material used to prevent premature wear on mining equipment.

Wearing surface. The top layer of the road surface that is exposed to traffic.

Wet cyclone scrubber. A type of scrubber that uses centrifugal force to throw particles on the collector’s wetted walls.

Wet drilling. In surface drilling, the injection of water along with air to flush the cuttings out of the hole.

Wet scrubber. An air pollution control device used for particulate collection. Wet scrubbers employ water or another liquid as the collection media.

Wet spray systems. A system of water sprays used to wet fines so that each dust particle’s weight increases, thus decreasing the particle’s ability to become airborne.

Windrow. A long linear pile of material.

Chapter 1: Overview of Dust Exposure Assessment and Control

CHAPTER 1: OVERVIEW OF DUST EXPOSURE ASSESSMENT AND CONTROL

When mining and processing minerals, the mined ore undergoes a number of crushing, grinding, cleaning, drying, and product sizing operations as it is processed into a marketable commodity. These mechanized operations can generate large amounts of dust, potentially exposing workers to elevated levels of airborne dust. Therefore, federal regulations are in place to help to protect workers by limiting their respirable dust exposure, and mining operations implement engineering controls in an effort to reduce dust generation and limit worker exposure.

This overview chapter describes some of the potential adverse health impacts of dust overexposure, relevant federal regulations and assessment tools, common dust sampling practices, and practical and proven approaches that operations can use to help lower a worker's dust exposure.

RESPIRABLE CRYSTALLINE SILICA EXPOSURE AND POTENTIAL ADVERSE HEALTH IMPACTS

Protecting our nation's workforce from respiratory diseases is a paramount issue, especially when dealing with any type of dust containing respirable crystalline silica. The National Institute for Occupational Safety and Health (NIOSH) has classified respirable crystalline silica as a potential occupational carcinogen[1] [NIOSH 2002]. NIOSH [1991] has long discussed that occupational overexposure to respirable crystalline silica dust can result in health problems that include pneumoconiosis, silicosis, chronic obstructive pulmonary disease, tuberculosis, chronic bronchitis, emphysema, and chronic renal disease. Many of these diseases are life-threatening and can be traced directly to the workplace, so addressing their root causes and preventing exposure is of great benefit to our nation's workers [Haas and Cecala 2015].

Worker overexposure to dust—especially respirable dust containing crystalline silica—has long been a serious concern for the health of our nation's miners and other workers. Silicosis was not recognized as a disease until the early 1900s. Although chest x-rays and other methods were not available to detect silicosis, reports by the Miner's Phthisis Prevention Committee [1916] and the South African Institute for Medical Research [Lanza 1917] were still able to link silica exposure to severe lung diseases in miners. Then, in 1937, the Department of Labor's National Silicosis Conference distinctly identified the health hazards of respirable silica dust and the development of silicosis. A key discussion focused on the Hawk's Nest Tunnel Disaster where, in a relatively short amount of time, 764 worker deaths were attributed to occupational silicosis as a result of the development of this tunnel [Cherniack 1986; Stalnaker 2006]. Ultimately, 1,500 workers developed the disease, attributed to inconsistent dust control methods, including minimal observed time to let dust settle after a blasting, minimal use of water, and no respiratory protection [Thomas and Kelley 2010].

[1] For a detailed definition and an explanation of the NIOSH position in relation to potential occupational carcinogens, see "Appendix A—NIOSH Potential Occupational Carcinogens," at https://www.cdc.gov/niosh/npg/nengapdxa.html.

Silicosis is the most common among the pneumoconiosis diseases associated with respirable crystalline silica overexposure in mining. Silicosis is an incurable and often fatal lung disease caused by the inhalation of respirable crystalline silica (see Figure 1.1 for a photo of a normal and a silicotic lung). The three most common forms (polymorphs) of respirable crystalline are quartz, tridymite, and cristobalite. Quartz is a common mineral in the earth's crust, and many mining operations involve direct contact with overburden and ore containing quartz. Thus, workers throughout much of the mining industry are potentially exposed to respirable-sized crystalline silica through routine mining activities such as drilling, blasting, crushing, sizing, transporting, and loading.

Photos by NIOSH

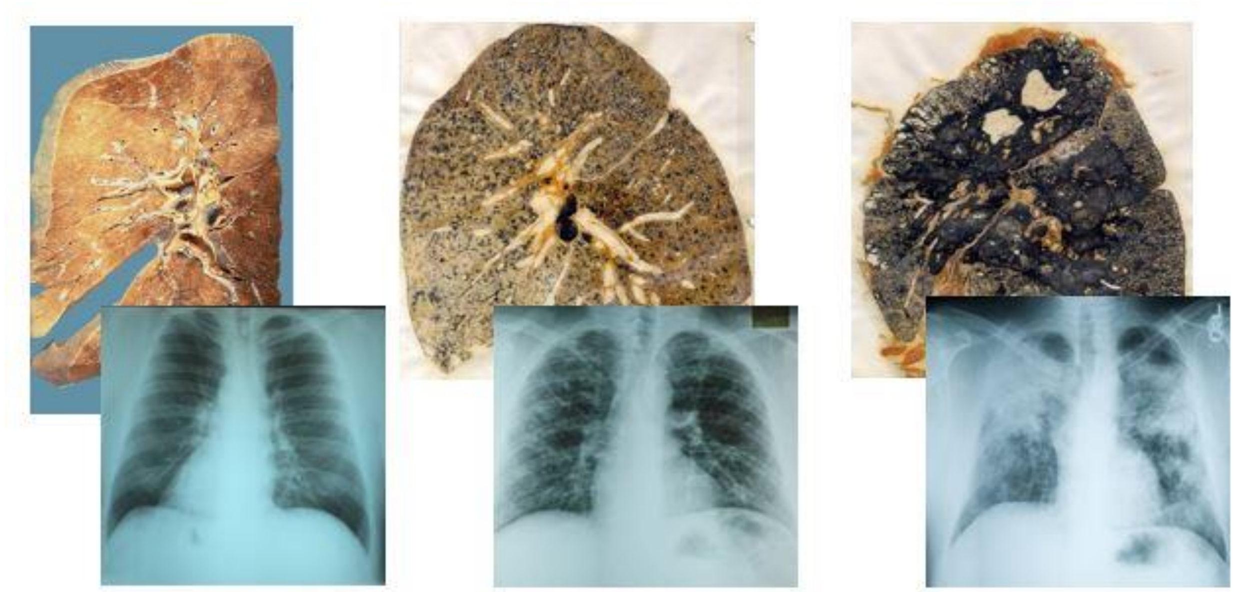
Figure 1.1. Sections of freeze-dried lungs. The left photo shows a normal lung and the right photo shows a silicotic lung.

When workers inhale respirable dust, the particles can penetrate the body's defense mechanisms and reach the gas exchange region of the lungs. Respirable crystalline silica particles that deposit in the gas exchange region stimulate an inflammatory and toxic process that can ultimately develop into clinically recognizable silicosis. Depending on the concentration of respirable crystalline silica and duration of exposure, workers may develop any of three forms of silicosis (Figure 1.2) [NIOSH 2002]:

- *Chronic*—resulting from long-term excessive exposures, first clinically apparent 10–30 years after first exposure.
- *Accelerated*—resulting from exposure to higher concentrations of respirable crystalline silica, first clinically apparent 5–10 years after the initial exposure.
- *Acute*—resulting from exposure to unusually high concentrations of respirable crystalline silica, clinically apparent within weeks to 5 years after the initial exposure.

Chronic silicosis, the most common form of the disease, typically results in characteristic nodular scarring in the lungs. Over time, the initial small nodules can eventually coalesce into large fibrotic masses—a condition called progressive massive fibrosis. Accelerated silicosis, much less common than chronic silicosis but progressing more rapidly, results from inhaling very high concentrations of respirable crystalline silica over a shorter period of time. Acute silicosis, a rarely occurring form of the disease, is the most serious and most rapidly fatal form, and it results from inhaling extremely high concentrations of respirable crystalline silica over a very short time period, as was the case in the Hawks Nest Tunnel Disaster in the 1930s. Unlike chronic and accelerated silicosis, where a chest x-ray examination typically reveals scattered discrete small (and possibly also large) opacities, the chest x-ray appearance of acute silicosis resembles that of diffuse pneumonia. This appearance results from extensive damage to the lining of the air spaces of the lungs, causing the alveoli (tiny air sacs in the lungs) to become filled with an abnormal fluid containing protein, degenerating cells, and other materials [Davis 2002].

Not all workers diagnosed with silicosis will be symptomatic; some with chronic disease will have no notable symptoms despite characteristic abnormalities on their chest radiograph. However, many workers with chronic silicosis will develop symptoms over time, and essentially all those with accelerated and acute forms of the disease will be symptomatic even before they are diagnosed.



Photos by NIOSH

Figure 1.2. Photos and radiographs of lungs. The left photo shows a normal lung, the center photo shows a lung with simple silicosis, and the right photo shows a lung with complicated silicosis.

Silicosis can result in various symptoms, including chest irritation with uncontrollable coughing and shortness of breath, and can be debilitating and warrant therapeutic intervention. Additionally, those with silicosis are at substantial risk for developing tuberculosis or other mycobacterial diseases [NIOSH 2002; Davis 2002].[2]

[2] Additional information on silica and silica-related diseases can be found at the NIOSH website at http://www.cdc.gov/niosh/topics/silica/.

ASBESTOS EXPOSURE AND POTENTIAL ADVERSE HEALTH IMPACTS

In addition to silicosis, the mining industry is concerned about preventing other work-related lung diseases among miners, including asbestosis, mesothelioma, and lung cancer. Exposure to asbestos can cause these and other diseases [NIOSH 2011]. Asbestos is a generic term for a number of asbestiform hydrated silicates that, when crushed or processed, separate into flexible fibers made of fibrils. Asbestos is a naturally occurring mineral that can be a contaminant coincidently mined with the desired commodity or can be found as a commercially installed building material on mine sites.

Asbestosis specifically refers to pulmonary fibrosis caused by the inhalation of asbestos fibers. The disease is progressive over time and—as with silicosis—can lead to respiratory failure and death [Hoy and Brims 2017]. Risk for asbestosis increases with both length of exposure and exposure concentration to asbestos fibers, with a latency period between 5 and 40 years from first exposure [Lippmann 2014].

Mesothelioma originates in the mesothelium—a thin layer of tissue lining most of the internal organs—and risk increases with increasing amounts of exposure to asbestos fibers. Diagnosis of mesothelioma is usually made at a late stage in the disease, and once diagnosed the median survival is less than one year [Robinson 2012]. It is well established in the scientific literature that asbestos can cause or contribute to malignant diseases such as mesothelioma and lung cancer as well as non-malignant lung diseases such as asbestosis [Barlow et al. 2017; Wylie 2016; NIOSH 2011]. For both lung cancer and mesothelioma, the latency period can be very long—upwards of 40 years. Therefore, avoiding intrusions of naturally occurring asbestos when mining and identifying and closely monitoring commercial installations, along with defining any overexposure, will protect mine workers and reduce the incidence of asbestos-related diseases.

While asbestos is no longer mined in the U.S. as a primary commodity, it can be encountered as a trace or accessory mineral in certain types of mineral deposits that are routinely mined [Van Gosen 2009]. During the extraction, processing, and use of these principal mineral deposits, accessory asbestos can be aerosolized—i.e., converted into particles and liberated into the air—potentially resulting in worker exposure. The National Occupational Health Survey of Mining [NIOSH 1996] has recorded detectable asbestos fibers in settled dust collected from mines involved in the extraction of 21 different non-asbestos commodities.

Both the Mine Safety and Health Administration (MSHA) and the Occupational Safety and Health Administration (OSHA) regulate six different types of airborne asbestos fibers in occupational environments. NIOSH, OSHA, and MSHA all agree on an exposure limit of 0.1 fibers per cubic centimeter, reported as an 8-hour time-weighted average (TWA) for these six regulated fibers. Nevertheless, it is important to recognize that this exposure limit is based on limitations of the phase contract microscopy-based method commonly used to measure exposures, and therefore, some risk remains for asbestos-related disease among those exposed to this level of asbestos over a working lifetime [NIOSH 2011].

In addition to the mineralogical composition of the asbestos fiber, NIOSH defines asbestos fibers as (1) having an aspect ratio of 3:1 or greater and (2) a length of greater than 5 µm morphology.

A continuing issue with the regulation of asbestos fibers is determining what is or is not regulated and the potential exposure of miners to analogs of asbestos minerals occurring in different growth forms, or "habits," usually referred to as "cleavage fragments" [NIOSH 2011].

In Current Intelligence Bulletin 62, NIOSH distinguishes between asbestos and non-asbestiform minerals [NIOSH 2011] and clarifies which particles are included in NIOSH's recommended exposure limit (REL). NIOSH recommends that cleavage fragments from asbestos minerals, crystallized in massive form, be counted as asbestos fibers as long as they meet the above dimensional criteria. However, those elongate mineral particles (EMPs) that do not crystallize in the asbestiform habit are not currently included as asbestos under MSHA and OSHA regulations.

Although the control strategies discussed in this handbook should be effective for asbestos and other EMPs, it is important for mine operators to be aware of these potential exposures to their workers. It is possible that the shape and hydrophobic nature of some rock-forming silicate minerals may require enhanced dust control measures that are beyond the scope of this handbook. Conscientious air quality monitoring, coupled with appropriate mineralogical analyses, will help operators to determine whether standard practices are adequately controlling emissions of asbestos.

DUST AND DUST STANDARDS

For the purposes of this handbook, dust can be broadly defined as small solid particles created as a consequence of the breaking up of larger particles. Depending on their size, these particles can become hazardous to worker health, particularly when suspended in air. The largest size particle that can be suspended in air for long periods of time from wind velocity acting upon it is about 60 micrometers (µm), which is about the thickness of a human hair. Particles ranging from about 60 to 2,000 µm can also become suspended in air, but they only reach heights up to approximately three feet above the ground surface before they fall back to the ground. Particles larger than about 2,000 µm generally creep or roll along the surface due to wind velocity acting upon them [EPA 1996]. These larger particles of dust can affect the nasal passages, causing an irritated and congested nose, and might also cause an irritant cough should they deposit in the throat.

Smaller airborne particles of dust, which can remain suspended in air for hours, pose a greater risk to the respiratory system when inhaled. In general, the smaller the aerodynamic diameter of the inhaled dust particle, the more likely it will be deposited more deeply in the respiratory tract.

Established industrial hygiene sampling procedures measure various fractions of airborne dust according to aerodynamic diameter. For example, inhalable dust samplers collect dust that tends to deposit from the upper airways to the alveolar region of the lungs. Inhalable dust samplers collect approximately 97 percent of particles less than 1 µm aerodynamic diameter, but only about 50 percent of particles of 100-µm aerodynamic diameter [ACGIH 2007].

Respirable-sized dust samplers more selectively collect dust that tends to deposit in the gas exchange region of the lungs. Respirable dust samplers collect about 50 percent of particles of 4-µm aerodynamic diameter. Their collection efficiency for other particle sizes ranges from about

1 percent of 10-µm particles to approximately 97 percent of particles less than 1 µm in diameter [ACGIH 2007]. Individually, such particles cannot be seen by the unaided eye.

Federal Regulations

In the United States, the federal regulation of the mining, construction, agriculture, and oil and gas industries fall within the U.S. Department of Labor (DOL). The mining industry is regulated by the U.S. Mine Safety and Health Administration, established in 1977; the other three industries listed above are regulated by the Occupational Safety and Health Administration, established in 1971. Providing oversight enforcement and compliance assistance on exposure limits are some of the tasks undertaken by MSHA and OSHA. Occupational exposure limits (OELs) are established concentration limits that give industries guidance on hazardous airborne contaminant concentrations that workers can be exposed to during their working lifetime at an acceptably low risk of adverse health effects.

There are two types of OELs—authoritative and regulatory exposure limits. Authoritative exposure limits are those established by organizations devoted to research-based limit development. Examples include NIOSH, which publishes recommended exposure limits (RELs), and the American Conference of Governmental Industrial Hygienists (ACGIH), which publishes threshold limit values (TLVs). The limits published by these organizations do not take into consideration economic or technological feasibility when determining their recommendations. Rather, research and epidemiological studies are used to set limits to best protect human health. For example, NIOSH has an REL for respirable crystalline silica of 50 $\mu g/m^3$, as a time-weighted average for up to a 10-hour day during a 40-hour week [NIOSH 1974].

Current OSHA Dust Standards for General and Other Industries

Regulatory limits, like those published by regulators such as MSHA and OSHA, are enforceable under federal law. Regulatory entities consider a combination of variables to determine appropriate exposure limits. Some variables include the authoritative limits published by the aforementioned organizations, feedback from the public, and feedback from the scientific and mining communities on technological feasibility. The enforceable regulatory limits are called permissible exposure limits (PELs).

OSHA’s original respirable crystalline silica dust regulations were established when the agency was formed in 1971. OSHA recently promulgated a new rule [Occupational exposure to respirable crystalline silica, 2016]. This rule went into effect on June 23, 2016, and contains varying enforcement dates by industry, as shown in Table 1.1. When proposing an update to the rule, OSHA stated that workers who inhale very small crystalline silica particles are at increased risk for developing serious silica-related diseases, including silicosis, lung cancer, chronic obstructive pulmonary disease (COPD), and kidney disease [OSHA 2016]. OSHA estimates that approximately 2.3 million workers are exposed to respirable crystalline silica each year.

Table 1.1 Enforcement dates for OSHA rule, "Occupational Exposure to Respirable Crystalline Silica" [adapted from OSHA 2018]

Classification	Enforcement date	Applicable Code of Federal Regulations (CFR)
Enforcement of obligations for the construction industry	June 23, 2017	29 CFR Section 1926.1153(k)(2)
Enforcement of obligations for the general and maritime industries	June 23, 2018	29 CFR Section 1910.1053(l)(2)
Exceptions applicable to hydraulic fracturing operations within the oil and gas industry include enforcement of medical surveillance obligations for employees exposed at or above the action level for 30 or more days per year	June 23, 2020	29 CFR Section 1910.1053(l)(4)
Enforcement of engineering controls for hydraulic fracturing	June 23, 2021	29 CFR Section 1910.1053(l)(3)(ii)

The key provisions of the OSHA regulation are the following:

- Reduction in the PEL for respirable crystalline silica to 50 µg/m^3, averaged over an 8-hour shift.
- The use of engineering controls to limit worker exposure to the PEL.
- Providing respirators when engineering controls cannot adequately limit exposure.
- Limiting access to high-exposure areas.
- Offering medical exams to workers exposed above the action level of 25 µg/m^3.
- Training workers on silica risks and how to limit their exposures.

Current MSHA Dust Standards for the Metal/Nonmetal Mining Industry

Currently, the U.S. metal/nonmetal mining industry airborne dust standard is regulated and defined by the Federal Mine Safety and Health Act of 1977. Federal regulations set PELs for airborne contaminants for surface and underground metal and nonmetal mines incorporating by reference the 1973 edition of the American Conference of Governmental Industrial Hygienists threshold limit values.[3] That publication lists a 10 mg/m^3 "nuisance particulate" exposure limit for dust containing no asbestos and less than 1percent respirable crystalline silica. If the sampling history at a mine indicates that the dust contains no asbestos and less than 1 percent respirable crystalline silica, total dust sampling should be considered [MSHA 2018]. Otherwise,

[3] Federal regulations pertaining to the mining industry are listed in the Code of Federal Regulations (CFR) Title 30, Mineral Resources. Part 56 of this CFR is titled Safety and Health Standards—Surface Metal and Nonmetal Mines; Part 57 is titled Safety and Health Standards—Underground Metal and Nonmetal Mines. Subpart D of each of these sections is Air Quality and Physical Agents. Sections 56.5001(a) and 57.5001(a) govern exposure limits for airborne contaminants for surface and underground metal and nonmetal mines, respectively. These sections are identical and say, "the exposure to airborne contaminants shall not exceed, on the basis of a time-weighted average, the threshold limit values adopted by the American Conference of Governmental Industrial Hygienists, as set forth and explained in the 1973 edition of the Conference's publication entitled 'TLV's Threshold Limit Values for Chemical Substances in Workroom Air Adopted by ACGIH for 1973,' pages 1 through 54, which are hereby incorporated by reference and made a part hereof." The terms TLV and PEL are therefore used interchangeably as MSHA's respirable silica dust occupational exposure limit.

respirable dust samples should be collected and analyzed for respirable crystalline silica content. Silica analysis is not performed by MSHA on total dust samples.

Respirable crystalline silica can be found in three different forms: quartz (Q), cristobalite (C), and tridymite (T). Quartz is the most common form of respirable crystalline silica and is the form routinely analyzed for by MSHA, unless the presence of cristobalite and tridymite is suspected and analyses are specifically requested. When quartz is present in concentrations greater than or equal to 1 percent in a respirable dust sample, MSHA uses the following formula to calculate a respirable dust TLV based upon the quartz content [MSHA 2018]:

$$Respirable\ Dust\ TLV = \frac{10\,mg/m^3}{\%\,\mathrm{Q} + 2} \tag{1.1}$$

If cristobalite or tridymite is present in a respirable dust sample, the TLV would be calculated by dividing 5 mg/m^3 by the (%C + 2) or the (%T + 2), depending upon which form of silica is present in the sample. If multiple forms of respirable crystalline silica are present in the same sample, the following formula is used to calculate a respirable dust TLV based upon the mixed silica content:

$$Respirable\ Dust\ with\ Mixed\ Silica\ TLV = \frac{10\,mg/m^3}{(\%\mathrm{Q}) + 2(\%\mathrm{C}) + 2(\%\mathrm{T}) + 2} \tag{1.2}$$

Personal Dust Sampling

The airborne dust to which mine workers are exposed is generally considered to be in one of four classes:

- *Total dust*—particles that are small enough to remain suspended in the air.
- *Inhalable*—particles that are small enough to remain suspended in the air, enter the respiratory tract through the nose or mouth, and be deposited anywhere in the respiratory tract. These particles are generally considered to be 100 µm in diameter or smaller [ACGIH 2007].
- *Thoracic*—particles that are small enough to remain suspended in the air, enter the respiratory tract through the nose or mouth, pass through the trachea, and be deposited in the lung airways and the gas-exchange region. These particles are generally considered to be 25 µm in diameter or smaller [ACGIH 2007].
- *Respirable*—particles that are small enough to remain suspended in the air, enter the respiratory tract through the nose or mouth, pass through the trachea, reach the respiratory bronchioles, and be deposited in the inner regions of the lungs where gas exchange occurs (alveolar regions). These particles are generally considered to be 10 µm in diameter and smaller [ACGIH 2007].

With respect to respirable crystalline silica, quartz and cristobalite have been classified as Group 1 carcinogens—i.e., “carcinogenic to humans”—by the International Agency for Research on Cancer (IARC) [IARC 2012]. Health hazards associated with overexposure to respirable crystalline silica arise from the inhalation of respirable particles. Respirable crystalline silica consists of particles that are smaller than 10 µm in aerodynamic diameter [Ziskind et al. 1976].

Personal gravimetric dust sampling is conducted to quantify a worker's average exposure to respirable dust exposure over his or her working shift. A dust sampling inlet is placed within the breathing zone of the worker to obtain a representative measure of the worker's exposure. Results from this sampling show that the worker's exposure is either above or below acceptable levels or that action needs to be taken to lower respirable dust levels in the worker's breathing environment. If elevated dust levels are encountered, personal protective equipment (PPE) is required while engineering or administrative controls, or both, are being implemented to reduce respirable dust levels below the PEL.

Conventional gravimetric sampling utilizes a size-selective device to separate the respirable fraction of dust from the sampled air stream. The respirable particles are then deposited onto a filter, which is sent to a laboratory in order to determine the total mass collected. The sample can also be analyzed for silica content.

For industrial minerals operations, personal gravimetric sampling (Figure 1.3) utilizes the following equipment in accordance with the ISO/CEN/ACGIH/ASTM respirable aerosol convention:

- *A 10-mm Dorr-Oliver cyclone assembly*. This assembly classifies the respirable portion of the dust particles. As air is drawn into the cyclone through the inlet, the particles larger than 10 µm in diameter fall out of the air stream and deposit in the sampling pot on the bottom of the cyclone. The particles less than 10 µm in diameter are able to remain in the air stream and work their way to the center of the cyclonic flow pattern. They are then carried out of the top of the cyclone and deposited onto the filter.
- *A 37-mm filter cassette assembly*. The filter cassette assembly sits on the top of the cyclone and contains a pre-weighed 37-millimeter-diameter polyvinyl chloride (PVC) filter media with a 5.0-µm pore size. A backup pad is used to support the PVC filter inside the cassette assembly. The respirable fraction of dust is captured on the filter media via impaction.
- *A self-adjusting sampling pump*. This person-wearable, battery-operated sampling pump is calibrated to draw 1.7 liters per minute (l/min) of air using a vacuum effect through the sampling assembly. The self-adjusting flow compensation feature automatically adjusts operation to overcome the pressure increases as dust loads on the filter media. These pumps have proven to be accurate and reliable as long as they are properly maintained.

Photos by NIOSH

Figure 1.3. Two workers wearing personal gravimetric sampling assemblies. The pump connects to the cyclone/filter unit via Tygon tubing. In these examples, note that the cyclone unit for the worker on the right should be raised to ensure that it is closer to his breathing zone, as it is for the worker on the left.

A worker's average respirable dust concentration exposure is determined by the mass of dust collected on the filter for a known volume of air sampled. This concentration is determined by Equation 1.3 and is equal to the respirable net dust weight on the filter divided by the sampling volume (sampling time multiplied by the pump flow rate).

$$Resp. Dust\ Conc.(mg/m^3) = \frac{Net\ dust\ weight\ (mg)}{Sample\ time\ (min) \times Pump\ flow\ rate (l/min)} \times \frac{1{,}000\ \text{l}}{1m^3} \quad (1.3)$$

Respirable Crystalline Silica Exposure

If potential exposure to respirable crystalline silica dust is suspected in a mineral processing operation, a respirable dust sample is obtained using the gravimetric equipment described above. X-ray diffraction following NIOSH Analytical Method 7500 [NIOSH 2003] is then used to quantify the respirable crystalline silica content within the sample. If the sample contains greater than 1 percent quartz, a respirable PEL is calculated with Equation 1.1.

Compliance with the calculated respirable PEL effectively limits quartz exposure to less than 100 µg/m^3. For cristobalite and tridymite, Equation 1.1 modified for C or T content as mentioned above would effectively limit exposure to less than 50 µg/m^3. To be in compliance, the concentration of the collected sample used to calculate the respirable dust PEL must be equal to or below the PEL.

Unfortunately, the time required to receive results from the silica analysis can be days to weeks after the sample has been collected. If elevated silica levels are present, the worker may continue to be exposed until receiving the silica analysis results. To address this problem, NIOSH is conducting research to develop an end-of-shift silica analysis technique that would provide the silica content of samples in a few minutes through utilization of a portable analytical instrument [Cauda et al. 2016].

General Area Dust Sampling

In addition to personal sampling, sampling can be used to quantify respirable dust levels found in a particular area or from a particular source. This type of area sampling is useful when evaluating the effectiveness of an engineering control. Area samples can be collected before and after the implementation of a control to determine the impact on dust liberation from the dust source of interest.

The use of a gravimetric sampler provides the average dust concentration over the sampling period but does not provide information on fluctuations/spikes in dust levels. Direct reading instruments with recording capabilities can provide a time-correlated record of dust concentrations and illustrate times of peak dust concentrations. Operational information can then be examined to determine specific activities occurring at these times to identify issues that need attention. Additional information on the use of direct reading instruments will be discussed later in this chapter.

Once gravimetric sampling has determined that a worker has elevated respirable dust exposure levels, the priority is to determine the most effective way to lower these levels to protect the worker. Since gravimetric analysis only provides the average respirable dust exposure over the worker's entire shift, it offers no insight into the possible contributing factors that created the elevated exposure level. Before a control strategy can be designed to protect the worker, an optimal approach is to determine key and causative factors that contributed to this elevated exposure. Using video exposure monitoring to assess worker exposure in real time is a well-tested and valuable approach.

In metal/nonmetal mines, MSHA conducts full-shift exposure sampling. The total sampling time is the full length of the actual worked shift. Sampling results are calculated as shift-weighted averages (SWAs). SWAs calculate sampling concentration on the basis of 480 minutes, regardless of the actual sampling time. This "shift-weighting" for work schedules less than or greater than eight hours provides direct comparison with the 8-hour-based exposure limits (TLVs). This 8-hour equivalent shift-weighted averaging can make it more difficult for miners working longer than 8-hour shifts to be in compliance.

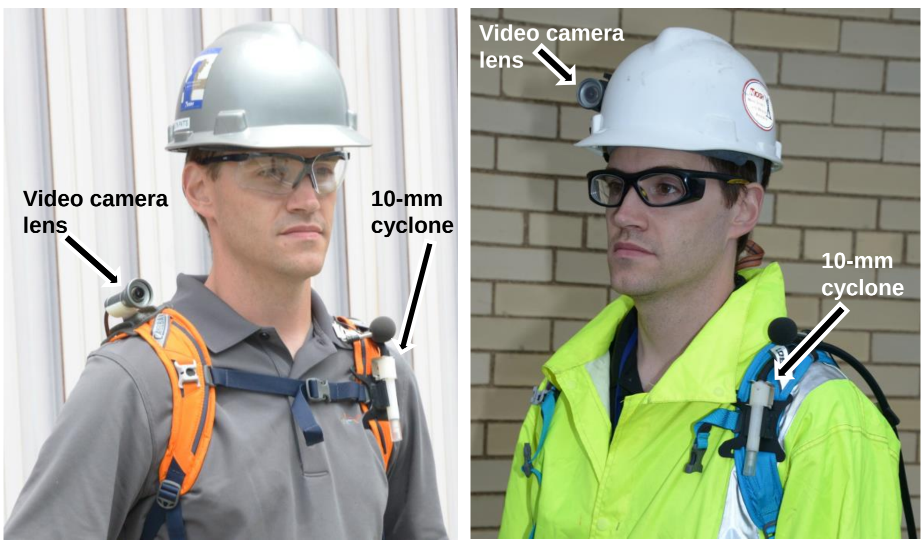
Video Exposure Monitoring

Although video exposure monitoring (VEM) to evaluate worker exposure to different types of contaminants is not a new concept [e.g., Gressel et al. 1988; NIOSH 1992; Rosen and Lundstrom 1987; Rosen and Andersson 1989; Rosen et al. 2005], a recent and effective option for mobile workers is available. In published NIOSH studies, VEM is also referred to as "Helmet-CAM."

A VEM method consists of a lightweight video recording system that provides a standard video output, used in conjunction with a personal monitoring device or devices. For respirable dust exposure, this is accomplished by integrating a person-wearable video recorder with a real-time data-logging aerosol monitor worn by the worker.[4]

A VEM setup requires some type of wearable means for workers to carry the video camera and dust monitor so they can perform their duties with minimal interference. Viable options include the following:

- *A lightweight backpack with a number of pockets to hold the camera's logger unit and instantaneous dust monitor.* A backpack affords the ability to adjust the two shoulder harnesses, as well as a chest and waist strap to securely tighten the backpack to the wearer, regardless of the worker's height or shape. (Figure 1.4). This is especially beneficial for mobile workers whose duties require them to travel throughout the plant.
- *A typical miner's belt with shoulder straps.* This allows the video data logger and instantaneous dust monitor to be strapped onto the sides of the belt, similarly to how a cap lamp battery pack or self-rescuer would be worn on an underground metal/nonmetal miner's belt. The belt's shoulder straps redistribute the weight of the instruments from being on the worker's waist and also allow the cyclone to be connected within the worker's breathing zone.



Photos by NIOSH

Figure 1.4. Video exposure monitoring options. The left photo shows a video camera lens attached to the worker's backpack shoulder harness and a 10-mm cyclone attached to the shoulder harness. The right photo shows a video camera lens attached to the worker's hardhat and a 10-mm cyclone attached to the shoulder harness.

The video camera lens can be attached to the worker's hardhat or backpack strap using a flashlight clip or duct tape. Importantly, the video lens must be properly aligned to document the

[4] For the instantaneous respirable dust monitor, one option is the Thermo Fisher Scientific pDR-1500 Aerosol Monitor (personal DataRAM) (Thermo Fisher Scientific, Waltham, MA). For more information about this unit and its ability to provide comparable dust data to what would be obtained with in-house gravimetric dust sampling, see Reed et al. [2012]. Other instantaneous monitors could be used as well.

worker's activities. Duct taping the lens in place is the best method to ensure that the lens does not lose its alignment as workers move around and perform their work duties. The video cable and the tubing for the dust monitor should also be duct taped to the backpack or belt to eliminate the possibility of their being caught or tangled in the work environment.

Finally, with all the instrumentation attached, when using the original EVADE (Enhanced Video Analysis of Dust Exposures) 1.0 software, it is recommended that both the video camera and dust monitor are started simultaneously in order to sync the action with the data collection. With the release of EVADE 2.0, it is not necessary to sync the start of both devices. This video and real-time data-logging combination allows workers to record their activities while monitoring their exposure. Subsequently, when coupled with the appropriate software described below, VEM provides insight into how, when, and where workers are exposed to contaminants.

Enhanced Video Analysis of Dust Exposures (EVADE) Software

Once the dust monitor and video camera data are downloaded to a computer, the NIOSH-developed EVADE software[5] merges the video and dust data to assess the areas, tasks, and functions that impact the individual's respirable dust exposure. EVADE provides an easy-to-use interface for synchronizing playback of recorded video and dust exposure data (Figure 1.5).

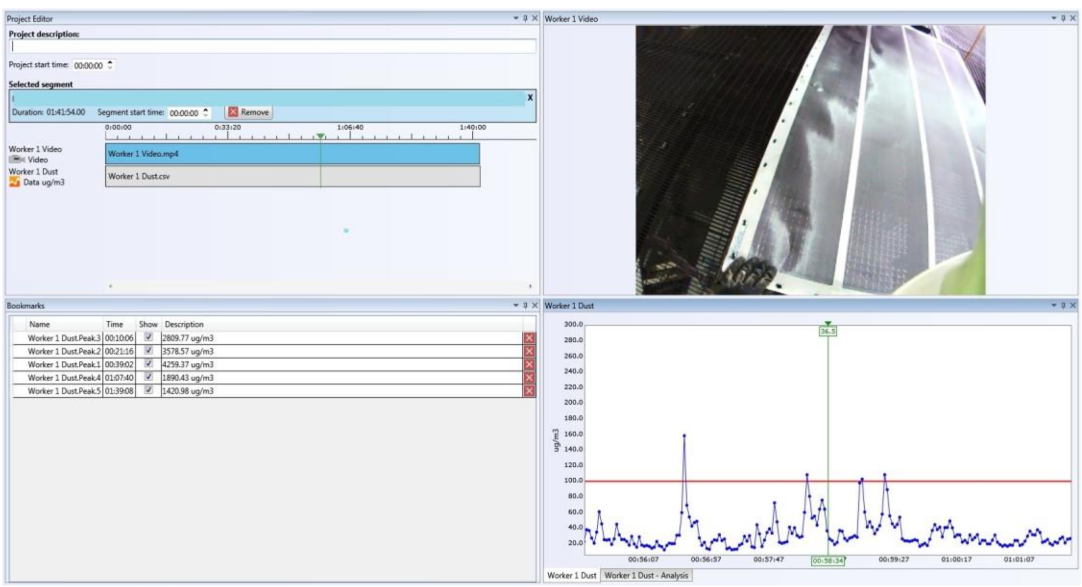


Figure 1.5. EVADE 2.0 screenshot. The top left panel shows the software project editor window. The top right panel shows the job task being completed by the worker. The bottom left panel shows the worker's five highest exposure peaks while wearing the video exposure monitoring device. The bottom right panel shows a line graph representing the worker's exposure while completing the task.

Beyond respirable dust exposure, this VEM setup can also be used to assess exposure to other contaminant types, such as diesel particulate matter, noise, and chemicals, when a real-time

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[5] Features of the EVADE version 1.0 software are explained in detail in the NIOSH Report of Investigations (RI) 9696, "Guidelines for Performing a Helmet-CAM Respirable Dust Survey and Conducting Subsequent Analysis with Enhanced Video Analysis of Dust Exposures (EVADE) Software" [NIOSH 2014a]. For the most up-to-date information on the EVADE software, visit http://www.cdc.gov/niosh/mining/Works/coversheet1867.html.

person-wearable sampler is available to monitor the contaminant. Additionally, EVADE 2.0 allows for multiple contaminant assessments and cameras to be used and viewed simultaneously, as well as the ability to sync all video and exposure assessments. As one example, Figure 1.6 shows an assessment of a worker's respirable dust and noise exposure simultaneously and the dual contaminant output in EVADE 2.0.

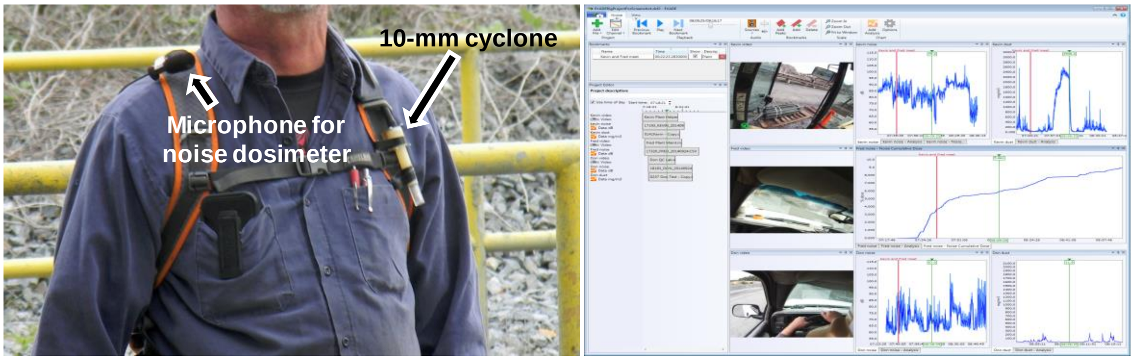

Photo by NIOSH

Figure 1.6. Simultaneous assessment of a worker's respirable dust and noise exposure and the dual contaminant output in EVADE 2.0. The left photo shows a microphone and 10-mm cyclone attached to a worker's left and right shoulder harness. The right screenshot from EVADE 2.0 shows videos and graphs representing a worker's respirable dust and noise exposure.

From April 2011 through July 2012, NIOSH researchers performed 12 different studies at mining operations with the purpose of evaluating the effectiveness of the VEM technology at assessing miners' elevated respirable dust exposures [Cecala and O'Brien 2014; Cecala et al. 2013; Joy 2013]. The system was tested with more than 100 different workers, including some for noise [Cecala et al. 2015].

Additionally, from April 2015 through September 2016, NIOSH researchers performed five intervention studies with 48 workers with the purpose of identifying effective controls for elevated respirable dust exposures [Haas and Cecala 2015; Cecala et al. 2017; Haas and Cecala; 2017]. Several simple workplace modifications were identified through these research efforts (see Chapter 9—Controls for Secondary Sources).

TACTICS FOR CONTROLLING WORKER DUST EXPOSURE

The Hierarchy of Controls Approach

After quantifying the worker's exposure to airborne dust, conventional control mechanisms can be implemented to control the dust concentrations present in the area. Certain industrial processes, such as those found in the production of industrial minerals, may utilize similar control mechanisms—e.g., engineering controls, work practices, and the use of personal protective equipment—to protect workers from excess dust exposures. A common way to develop control strategies is to use the longstanding and proven hierarchy of controls approach (see Figure 1.7). In this inverted pyramid, essentially, the higher up in the pyramid one goes, the more effective and preferred the control.

The top of the inverted pyramid begins with the most effective method of controlling the hazard. The expected level of efficiency associated with that method of control ultimately decreases as one moves down the inverted pyramid. Eliminating the hazard from the process completely or substituting it with a material that presents a lesser hazard are two of the most ideal means to prevent worker overexposure. Unfortunately, in the mining industry, it is unlikely the dust hazard can be eliminated or substituted due to the nature of the industry. Therefore, controlling dust within industrial mineral applications typically begins at the engineering control level within the pyramid.

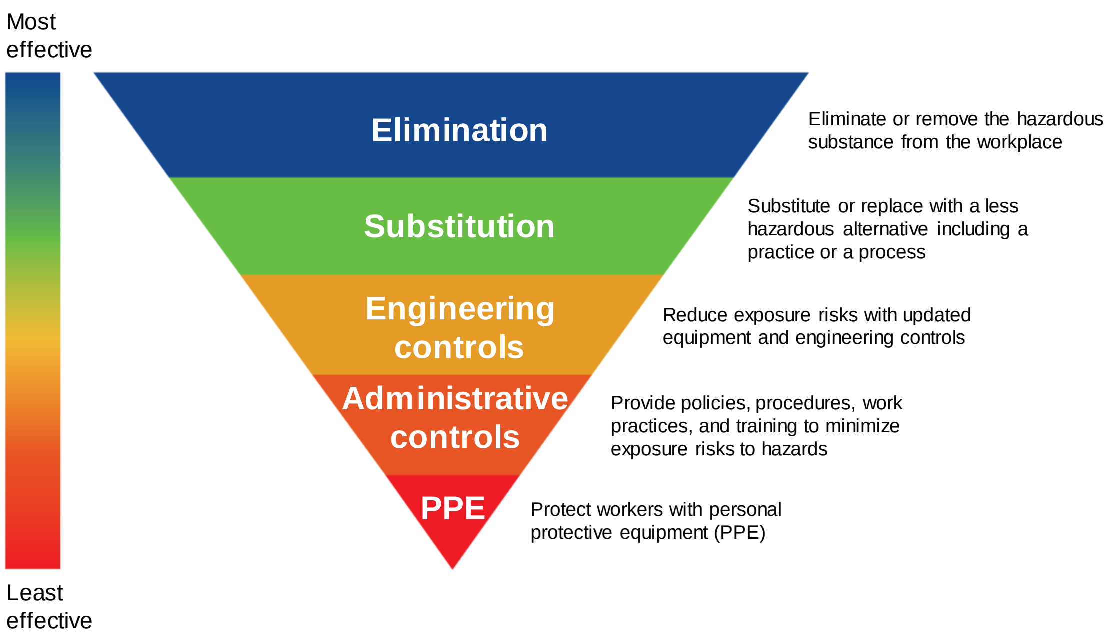

Figure 1.7. Illustration of the hierarchy of controls approach. This is a well-established method for lowering workers' respirable dust exposures in industrial applications [adapted from NIOSH 2018a].

Elimination and Substitution

Elimination is the only true, proactive control to eliminate exposure sources before they enter the workplace. Therefore, elimination—by way of designing out the hazard—should always be the first option considered. However, elimination tends to be the most difficult (if not impossible) to implement, particularly in industrial mineral processing. In fact, to eliminate the hazard of silica dust from silica sand production, silica must be entirely eliminated from the process. A NIOSH report [NIOSH 2014b] discusses the importance of looking for specific ways to eliminate hazards that may be inexpensive to incorporate into a design or development stage of a new process.

If the dust cannot be eliminated from the work environment, then a less hazardous material can be used in order to offer better protection [NIOSH 2014b]. Silica dust control coating is an emerging technology that may serve as an effective method of substitution, although it could also be viewed as an engineering control. Sand is treated with a dust-prevention chemical designed to trap the dust to the sand grain to prevent particulates from becoming airborne.[6] This dust control coating technology is relatively new and therefore caution should be taken to verify that it does not introduce any hazards.

Although little research has been done in this area, some industrial mineral companies have developed their own coating procedures. One study found a reduction in respirable crystalline silica by more than 95 percent for employees involved in hydraulic fracturing processes in the oil and gas industry [Jackson et al. 2017]. The authors detail three field trials in which airborne dust concentrations were evaluated by the use of real-time data-logging aerosol monitors (personalDataRAMs, or pDRs) and conventional gravimetric samples, utilizing size-selective samplers.[7]

In addition, Bedford et al. [2017] claimed an airborne dust reduction of up to 99 percent by the use of a chemical dust suppressant in a glass manufacturing environment. Specifically, during the sand batching process, samples were collected using chemically dust-suppressed sand and compared to batching using untreated sand.[8]

Although exploratory research is still being completed in the industry to better understand ways to suppress airborne dust in work environments, the substitution of chemically dust suppressed sand for untreated quartz sand shows potential as a method to reduce employee exposure to respirable crystalline silica in the workplace. If this technology can be further researched and validated, then significant dust reduction could result, specifically to industrial materials that are transferred by way of belt conveyors, as discussed in Chapter 6—Conveying and Transport. Figure 1.8 illustrates one use of this control, showing the impact of minimizing airborne dust on treated versus untreated sand.

Photos by ArrMaz

Figure 1.8. Untreated and treated sand being loaded off a conveyor. The left photo shows untreated sand; the right photo shows sand treated with a silica dust control coating technology to reduce silica dust generation.

[6] ArrMaz Products, www.ArrMaz.com. The company reports that this product is made from naturally occurring biodegradable/biorenewable substances, and that its use has resulted in reductions in silica dust generation of up to 99 percent when used in hydraulic fracturing operations.
[7] Conventional gravimetric samples were analyzed via the NIOSH Method 7500, Respirable Crystalline Silica via XRD. The first two trials showed airborne dust reduction of 87 percent to 98 percent and respirable crystalline silica reduction of 97 percent to 99 percent based on general area samples collected at point source sand discharge locations.
[8] Conventional gravimetric samples were analyzed via the NIOSH Method 7500, Respirable Crystalline Silica via XRD.

Although this specific coating technology has not been tested or compared to other similar substitution methods, this technology is currently being used in the industry. Because this technology has not been tested in a comparative study by NIOSH with similar forms of technology, the information provided comes with the caveat that the most effective forms of substitution for coating are still to be determined.

Engineering Controls

Engineering controls are preferred over administrative and PPE controls because they are designed to reduce the hazard at the source or sources before the worker comes in contact with the hazard [NIOSH 2018a]. Although initial costs to develop and integrate engineering controls can be higher, over time, operating and process costs can be lower. These types of controls should be utilized and considered as the first line of defense whenever feasible as they provide the highest level of protection for the worker when elimination and substitution are not feasible. One of the reasons they are so effective is that although they may require maintenance, they often operate independently of worker decisions and actions on the job.

This handbook primarily addresses the application of engineering controls during design, redesign, and retrofit activities typically found within the industrial minerals industry. As this handbook shows throughout each subsequent chapter, specific engineering controls for respirable crystalline silica exposure can be effective in protecting workers. When engineering controls have not been implemented, do not fully mitigate the hazard, or have been deemed impractical or infeasible, then the application of administrative or PPE controls may be appropriate.

Administrative Controls

Administrative controls are often used as a supplement to existing engineering controls, used during the installation and testing of engineering controls, or used in cases where hazards cannot be well controlled but it is infeasible to rely on engineering controls as the primary mechanism of worker protection [NIOSH 2018a]. Administrative controls chiefly depend on the worker's constant application of the controls and require more supervisory oversight, making them less desirable [Plog et al. 1996]. Examples of common administrative controls found in the industrial minerals industry that rely on worker engagement to reduce dust exposures include proper work practices, housekeeping, maintenance, and personal hygiene. Hazard awareness training, job rotation, and written job procedures also fall within administrative controls.

Job rotation and reduction of work periods can help manage worker exposure, but this method of controlling the exposure to dust must be used with care. As an example, decreasing the exposure duration for one employee below exposure limits may increase the number of other employees exposed to a contaminant.

Housekeeping and work practices can have a dramatic effect on minimizing airborne dust concentrations, discussed in further detail in Chapter 9—Controls for Secondary Sources. Using wet methods in housekeeping and work practices can be very effective when applied appropriately. Other applications of using wet methods to control dust are discussed in more detail in Chapter 3—Wet Spray Systems. If feasible, hosing or vacuum cleaning dust from work areas instead of dry sweeping are the preferred methods of housekeeping. Using water or other suitable liquids to wet the floor before sweeping, when feasible, is one of the simplest ways to control dust.

In addition to the administrative controls previously discussed, maintaining good personal hygiene is also an important control measure that heavily relies on worker engagement. In this case, maintaining good personal hygiene refers to managing the dust contamination of worker clothing and other equipment. Once a worker's clothes or other equipment comes into contact with dust, it can be unintentionally carried from one place to another and can contaminate an otherwise clean environment such as a control room or a break room.

To avoid contamination using good personal hygiene practices, conveniently locating cleaning areas to be near workers can help minimize the presence of dust and contamination generated from their clothing. Using a high-efficiency particulate air (HEPA)-filtered vacuuming system to remove dust from work clothes can be effective, but because it is difficult and time-consuming, workers may avoid this practice. The use of unregulated compressed air to remove dust is strictly prohibited by MSHA as this practice creates airborne dust that could be inhaled by the worker or could create airborne debris that could injure workers.

Alternatives to either of these methods may include using protective clothing that can be removed and washed or disposed of, leaving the worker's clothing free of dust buildup. Clothes cleaning booths, also discussed in Chapter 9—Controls for Secondary Sources—are another excellent alternative that allow workers to clean their clothing throughout the workday. Clothes cleaning booths have been granted a safety variance by MSHA, allowing an air spray manifold within a booth equipped with exhaust ventilation to be used to clean worker's clothing using compressed air. The cleaning booth provides workers with a quick, easy, and acceptable method to clean their clothes prior to entering a clean environment (e.g., a break room or control room) to avoid contamination or excess dust exposures.

Personal Protective Equipment (PPE)

PPE, specifically respirators, should only be used as a last line of defense when the control of inhalation hazards has not been achieved through the means preferred within the hierarchy of controls described above, and they should not be considered a replacement for other controls [NIOSH 2018a].[9] Although engineering controls are the preferred method of addressing workplace hazards, there are many situations in which PPE is essential:

- when engineering controls are not feasible,
- in emergencies,
- to provide extra protection,
- while engineering controls are being established, and
- for occasional entry into hazardous atmospheres to perform investigation or maintenance.

[9] The Mine Safety and Health Administration does not recognize respiratory PPE in the mining industry as an acceptable means of achieving compliance levels. MSHA does require the use of respiratory protection as an interim means of protecting workers until engineering controls or new technology can be implemented to eliminate the respiratory hazard and the health concern.

When properly selected, maintained, and employed, respirators offer an effective interim means to protect the health and safety of those who need to work in environments until the contaminant hazard is addressed. However, relying on PPE also has some inherent disadvantages, as detailed below.

- Although PPE methods are initially inexpensive, they tend to be costly to maintain over time. Administration of such a program can be very costly.
- Workers who wear respirators need to be enrolled in a respiratory protection program which entails training, annual fit testing, and medical evaluations to determine the enrollees' fitness to wear respirators.
- Consistent respirator use is difficult to monitor and enforce, especially if respirator-required areas are not clearly marked.
- To analyze exposure concentrations effectively, both area and personal sampling need to be conducted in zones that are respirator-required areas.
- To prevent degradation of masks and ensure that their protective capacity is not diminished during use, respirators need to be inspected before and after each use, and to be properly stored.

Respirator Selection

As with other PPE, the first need in selecting respiratory protection is identifying the specific hazard that exists. Several considerations must be weighed in selecting a NIOSH-approved respirator, as follows:

- characterizing the hazardous environment,
- respirator types for solid particulates,
- respirator protection classifications,
- NIOSH respirator selection criteria, and
- respirator fit testing and training.

Characterizing the Hazardous Environment

The industrial hygiene techniques outlined earlier can be relied upon to help characterize the environment in individual work areas. First, a complete exposure assessment of all possible respiratory hazards is necessary. Although comprehensive air sampling may not be needed, a thorough review of all materials present and an analysis of their use should be conducted. Once the respiratory threats are determined, the NIOSH Respirator Selection Logic resource [NIOSH 2004] can be used as a guideline for proper respirator selection. Following this logic early in the selection process provides a view of the broadest spectrum of threats possible, including eliminating those that do not pertain to the mining environment. A thorough hazard analysis may reveal that particulate matter is not the only respiratory threat to the worker. In these cases, the respirator selection logic helps to identify classes of NIOSH-approved respirators that provide protection against other agents in other forms, including circumstances, for example, where a full facepiece respirator might be necessary for eye protection or might offer a better fit to the wearer.

Next, appropriate air sampling techniques can be employed to characterize respirable hazard concentrations. Using these data, a hazard ratio and protection factor can be calculated by assessing the ambient concentration of the respirable hazard—including particulates as described in the next section—and dividing it by the PEL established for the aerosol of concern.[10] Once the hazard level is determined, respirator selection can begin.

The broadest characteristic for respirator selection is the assigned protection factor (APF). The APF assignment can easily be determined through OSHA's website resources.[11]

Respirator Types for Solid Particulates (Dust)

NIOSH-approved respirators designed to protect from particulates[12] are available in two broad classes: powered and non-powered. Powered respirators are most typically referred to as PAPRs (powered air-purifying respirators), and non-powered are sometimes referred to as negative-pressure respirators. This terminology can lead to confusion about which type to choose, but a consideration of the APF can be used to help determine the best respirator for the circumstances.

For the powered and non-powered respirators most frequently used, several options exist:

- A filtering facepiece respirator (APF = 10).
- A half-mask facepiece that is tight-fitting and available on both powered and non-powered respirators (APF = 10).
- A full facepiece that is tight-fitting and available on both powered and non-powered respirators (APF = 50).
- A full facepiece that is loose-fitting and is available only on powered respirators—some facepieces provide no head protection while others provide full head protection (APF = 25).

For examples of workers wearing these types of respirators, see Figure 1.9.

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[10] OSHA maintains comprehensive information on PELs for all recognized contaminants and makes that information available online (see Permissible Exposure Limits—Annotated Tables at https://www.osha.gov/dsg/annotated-pels/). The NIOSH Pocket Guide to Chemical Hazards [2005] provides additional details related to planning for exposure mitigation.

[11] See "Assigned Protection Factors for the Revised Respiratory Protection Standard," OSHA 3352-02 2009, at https://www.osha.gov/Publications/3352-APF-respirators.html.

[12] Contaminant protection capabilities for respirators are individually evaluated against performance criteria established in Title 42, Code of Federal Regulations, Part 84 [Approval of respiratory protection devices, 2004]. Each respirator approval granted is characterized according to respirator type and individual contaminant protections.

Photos by 3M

Figure 1.9. Four types of respirators that offer protection against particulates. The top left photo shows a worker wearing an N95 filtering facepiece respirator. The top right photo shows a worker wearing an elastomeric half-mask respirator with a P100 particulate filter. The bottom left photo shows a worker wearing a tight-fitting full facepiece respirator with a P100 particulate filter. The bottom right photo shows a worker wearing a powered air-purifying respirator equipped with a welding helmet.

Respirator Protection Classifications

Importantly, protection classifications for PAPRs and non-powered air-purifying respirators are different. NIOSH classifies non-powered respirators by their ability to remove aerosols based upon their physical characteristics. Non-powered respirator filters are classified as N-series, R-series, or P-series based on their ability to protect against oily or non-oily aerosols.[13] The classification scheme is shown in Table 1.2., and the following simple mnemonic can be used to help remember the filter series:

- **N** for **n**ot resistant to oil.
- **R** for **r**esistant to oil.
- **P** for oil-**p**roof.

[13] Dry particulate matter of the type typically encountered at mining operations is effectively removed by all 42 CFR 84 NIOSH-approved filter types. However, oily aerosols—for example, those that may be produced in cutting and machining environments—are degrading to filter media, meaning that filter replacement may have to be more frequent.

Table 1.2. Description of filter classes certified under 42 CFR 84

Class of Filter	Service Time*	Efficiency (%)
N-Series	Nonspecific ‡	
N100		99.97
N99		99
N95		95
R-Series	One work shift ‡	
R100		99.97
R99		99
R95		95
	Nonspecific ‡	
P-Series		
P100 ‡‡		99.97
P99		99
P95		95

* NIOSH is conducting and encouraging other researchers to conduct studies to ensure that these service time recommendations are adequate. Additional service time limitations may be recommended by NIOSH for specific workplace conditions.

‡ Limited by considerations of hygiene, damage, and breathing resistance.

‡‡ The P100 filter must be color-coded magenta. The Part 84 Subpart KK HEPA filter on a PAPR will also be magenta, but the label will be different from the P100 filter, and the two filters cannot be interchanged.

These filters can be used without particle size analysis or filter penetration testing in the workplace. R- or P-series filters must be selected if there are oily (e.g., lubricants, cutting fluids, glycerine) aerosols present, and they may be selected for protection against non-oily aerosols. N-series filters should be used only for non-oily aerosols (i.e., solid particles or liquid aerosols known to be water-based).

Selections from any of the N- , R- , or P-series filters are appropriate where industrial minerals are handled because the particulate threats exist as aerosols composed of solid particulate matter.

For filtration media evaluated for PAPRs, there is only one classification. The protection classification of PAPRs is designated as HEPA, or high-efficiency particulate air. Similar to non-powered, P-series filters in their ability to withstand high loading of filtration-degrading aerosols, HE[14]-class filters protect users from all types of particulates, including both dry and oily aerosols. Their filtration efficiency is most similar to the 100 class of N, P, and R filters.

[14] The acronym HE refers explicitly to the NIOSH protection designation for PAPR particulate filters. Used since 1995, the HE designation helps underscore the fact that particulate filters employed in NIOSH-approved PAPRs meet a different technical standard than those generally classified as HEPA, a term used extensively throughout this handbook to refer to high-efficiency particulate air filters.

NIOSH Respirator Selection Criteria

The NIOSH Certified Equipment List (CEL) is a very useful resource for those looking to make proper respirator selections[15]. Using the online CEL, users can define search criteria based upon many different characteristics of the approved respirators, but a search based upon the least number of pertinent criteria will offer the largest number of suitable choices.[16] In addition to the online CEL offering pre-defined and selectable characteristics of the listed respirators, users can be assured that the respirators listed there are currently NIOSH-approved.

Respirator Fit Testing

With the notable exception of loose-fitting PAPRs, all of the respirator types discussed here need to be fit tested on the employees who need to wear them. From a regulatory standpoint, this is a requirement maintained by OSHA and MSHA, and the regulatory stance of both agencies is further supported by NIOSH recommendation [NIOSH 2018b]. Importantly, the most widely used type of particulate respirator—the filtering half-mask facepiece respirator—is considered to be tight-fitting and must be fit tested on employees who are assigned to wear them.

Both employer and employee benefit from respirator wearers being able to perform their work duties without giving much thought to the fact that they are wearing a respirator. This is accomplished through ensuring that the worker can see and hear well while wearing the respirator and feel comfortable with its fit. Otherwise, workers could be tempted to remove the respirator to maintain their comfort, level of work effort, or both.

Annual fit testing, which should be addressed in the company's respiratory protection program, helps to ensure that wearers of approved respirators receive protection at the recognized APF. It can be assumed that compliance with OSHA's extensive fit testing requirements[17] will ensure compliance with MSHA standards.

In addition to the resources available through OSHA and MSHA, there are many health and safety specialists, industrial hygiene companies, and consultants who offer fit testing assistance or fit testing services.

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[15] To perform a Certified Equipment List search, see https://www.cdc.gov/niosh/npptl/topics/respirators/cel/.

[16] The NIOSH approval schedule is one of the three following types: 84A, 21C, or 23C. 84A applies to any non-powered air-purifying respirator approved to provide protections against particulates only, or to those approved to provide combinations of protections including particulates along with gasses and vapors. 21C applies solely to PAPRs approved to provide protection against particulates only, the aforementioned HE protection class. 23C applies to non-powered respirators approved to provide protections against only gasses and vapors, or to PAPRs approved to provide combinations of protections which include gasses and vapors along with particulates.

[17] OSHA has a substantial volume of fit testing resources available online. A good starting-point reference can be found on OSHA's respirator fit testing webpage at https://www.osha.gov/video/respiratory_protection/fittesting_transcript.html.

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Chapter 2: Fundamentals of Dust Collection Systems

CHAPTER 2: FUNDAMENTALS OF DUST COLLECTION SYSTEMS

Dust collection systems are the most widely used engineering control technique employed by mineral processing plants to control dust and lower workers' respirable dust exposure. A well-integrated dust collection system has multiple benefits, resulting in a work environment with improved air quality that increases productivity and reclaims valuable product.

The most common dust control techniques at mineral processing plants utilize local exhaust ventilation (LEV) systems. These systems capture dust generated by various processes such as crushing, milling, screening, drying, bagging, and loading, and then transport this dust via ductwork to an air cleaning device. Capturing the dust at the source prevents it from becoming liberated into the processing plant and contaminating the air breathed by workers.

LEV systems use a negative pressure exhaust ventilation technique to capture the dust before it escapes from the processing operation. Effective systems typically incorporate a capture device (enclosure, hood, chute, etc.) designed to maximize the collection potential.

As part of a dust collection system, LEV systems possess a number of advantages, as described below.

- The ability to capture and eliminate very fine particles that are difficult to control using wet suppression techniques.
- The option of reintroducing the material captured back into the production process or discarding the material so that it is not a detriment later in the process.
- Consistent performance in cold weather conditions as compared to other technologies that are greatly impacted by low temperatures, such as wet suppression systems.

In addition, LEV systems may be the only dust control option available for some operations whose product is hygroscopic or suffers serious consequences from even small percentages of moisture (e.g., clay or shale operations).

In most cases, dust is generated in obvious ways. Anytime an operation is transporting, refining, or processing a dry material, there is a great likelihood that dust will be generated. It also follows that once the dust is liberated into the plant environment, it produces a dust cloud that may threaten worker health. In addition, high dust levels can impede visibility and thus directly affect the safety of workers.

The five areas that typically produce dust that must be controlled are detailed below.

1. The transfer points of conveying systems, where material falls while being transferred to another piece of equipment. Examples include the discharge of one belt conveyor to another belt conveyor, storage bin, or bucket elevator.
2. Processes such as crushing, drying, screening, mixing, blending, bag loading, and truck or railcar loading.

3. Operations involving the displacement of air such as bag filling, palletizing, or pneumatic filling of silos.
4. Outdoor areas where potential dust sources are uncontrolled, such as core and blast hole drilling.
5. Outdoor areas—such as haul roads, stockpiles, and miscellaneous unpaved areas—where potential dust-generating material is disturbed by mining-related activities and high-wind events.

While areas 4 and 5 can be significant sources of dust, they are generally not included in plant or mill ventilation systems design because of the vast area encompassed and the unpredictability of conditions. Therefore, dust control by methods alternative to LEV systems is required, as discussed in later chapters of this handbook.

Dust control systems involve multiple engineering decisions, including the efficient use of available space, the length of duct runs, the ease of returning collected dust to the process, the necessary electrical requirements, and the selection of optimal filter and control equipment. Further, key decisions must be made about whether a centralized system or multiple systems are best for the circumstances. Critical engineering decisions involve defining the problem, selecting the best equipment for each job, and designing the best dust collection system for the particular needs of an operation.

This chapter makes a number of references to the industry handbook *Industrial Ventilation: A Manual of Recommended Practice for Design*, by the American Conference of Governmental Industrial Hygienists [ACGIH 2010], with several figures from that handbook adapted for use here. The ACGIH handbook should be considered as a primary resource for anyone interested in protecting workers from dust exposure in the minerals industry using dust collector systems, and especially for engineers who are involved in designing such systems. The material in this chapter complements the information available in the ACGIH handbook.

BASICS OF DUST COLLECTION SYSTEMS

Well-designed dust collection systems need to consider not only the dust as a potential contaminant to the work area, but also the attributes of the dust and the collection system itself. In defining the nature of dust as a potential contaminant to workers, a number of issues must be examined. These include the particle size and distribution, shape, physical characteristics, and the amount of dust emitted. Particle size describes how coarse or fine particles are, and is normally defined by their upper and lower size limits. Particle sizes are measured in micrometers (µm) (1/1,000th millimeter). The respirable dust range harmful to workers' health is defined by those particles at or below the 10-µm size range. To put this size in perspective, 325 mesh is approximately 44 µm and is the smallest micrometer size that one can see with the unaided human eye. In dust collection systems, the larger particle sizes are easy to collect, often aided significantly by gravity.

The shape of particles affects how they are collected and how they are released from the collection media. *Particle shape* is common terminology used in aerosol technology, while the term *aerodynamic diameter* is frequently used to describe particle diameters. The aerodynamic diameter of a particle is the diameter of a spherical particle that has a density of 62.4 lbs/ft^3 (the standard density of water) and the same settling velocity as the particle [Hinds 1999]. Aerodynamic diameter is used in many designs of filtration systems and air cleaners. Additional properties of the material that are key design considerations for dust collection systems are moisture, temperature, and abrasion. Moisture and temperature, as well as sensitivity to changes in temperature and moisture of the exhaust stream, play a significant part in equipment selection for dust collection systems. Abrasiveness of the dust impacts the equipment material selections as well as duct shaping.

AIRFLOW AND DUST CONTROL

To control how air flows in a ventilation system, one must manage air velocities, air quantities, and temperature, as well as apply basic principles of static pressure (SP) and velocity pressure (VP).

Air velocity is measured in feet per minute (fpm) and impacts the size of particle that can be carried by the air stream. *Air quantity*, which is the amount of air used in ventilating the process, is measured in cubic feet of air per minute (cfm). Air temperature is measured in degrees Fahrenheit or degrees Celsius. It is used to determine the type of gaskets and filter media needed. The change in air temperature through the dust collection system is also used to size ducts appropriately. Many applications where dust is being collected are thermal in nature, with examples including furnaces, kilns, and dryers.

Pressure (or head) in ventilation design is generally measured in inches of H_2O, also referred to as inches water gauge (wg). In a ventilation system, this pressure is known as the static pressure and is generally created by a fan. Static pressure is the difference between the pressure in the ductwork and the atmospheric pressure.

Static pressure values are used to overcome the head loss (H_l) of the system, which is made up of two components: frictional resistance to airflow in the ductwork and fittings (frictional losses (H_f)) and the resistance of obstacles such as cyclones and dust collectors (shock losses (H_x)) [Hartman et al. 1997]. Static pressure is measured by inserting a pitot tube into the ductwork, perpendicular to the side walls, to determine the difference between atmospheric and duct pressures (Figure 2.1).

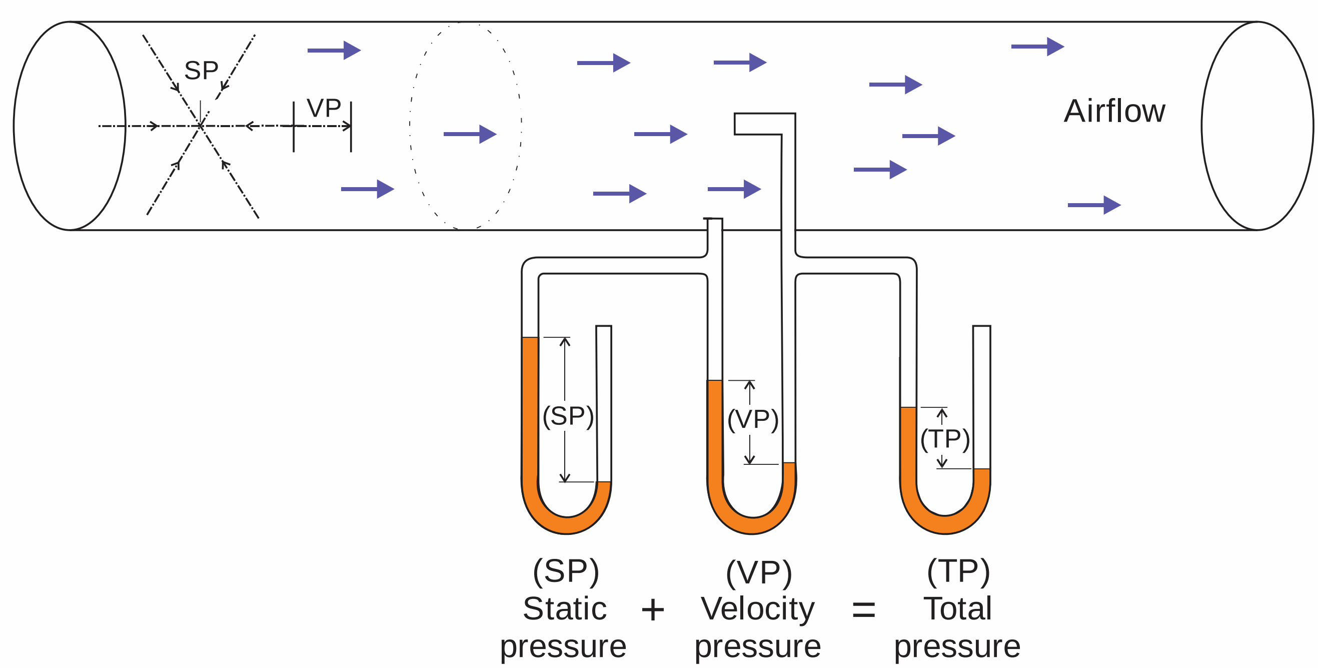


Figure 2.1. Illustration of the relationship between static pressure, velocity pressure, and total pressure [adapted from ACGIH 2010]. Example represents suction side of the fan.

Air traveling through a duct at a specific velocity will create a corresponding pressure known as the velocity pressure (VP). Velocity pressure is the pressure required to accelerate the air from rest to a particular velocity. It only exists when air is in motion, always acts in the direction of airflow, and always has a positive value. For ventilation purposes, VP is measured with a test probe facing directly into the air stream. The algebraic sum of static pressure and velocity pressure is total pressure (TP) [Hartman et al. 1997], as expressed by the following equation:

$$TP = SP + VP \tag{2.1}$$

where *TP* = total pressure, inches wg;
SP = static pressure, inches wg; and
VP = velocity pressure, inches wg.

The ACGIH handbook [ACGIH 2010] gives a number of definitions and equations that are useful for describing airflow in an operation's ventilation system. The handbook also details fundamental characteristics in relation to blowing and exhausting air through a plant ventilation system. A handbook from Martin Engineering, *Foundations: The Practical Resource for Cleaner, Safer, More Productive Dust & Material Control* [Swinderman et al. 2009], also devotes a chapter to the control of air movement, including a section on effective measurement of air quantities. Finally, a recommended journal article is "Dust Control System Design: Knowing Your Exhaust Airflow Limitations and Keeping Dust Out of the System" [Johnson 2005].

EXHAUST SYSTEM DESIGN

All exhaust systems, whether simple or complex, have in common the use of hoods, ductwork, and an air cleaning and collection device that leads to the exhaust fan (Figure 2.2). The ACGIH handbook [ACGIH 2010] discusses all aspects of these systems in great detail. To supplement the ACGIH handbook, the discussion below outlines some basic system design parameters and sets forth some important considerations about air velocity.

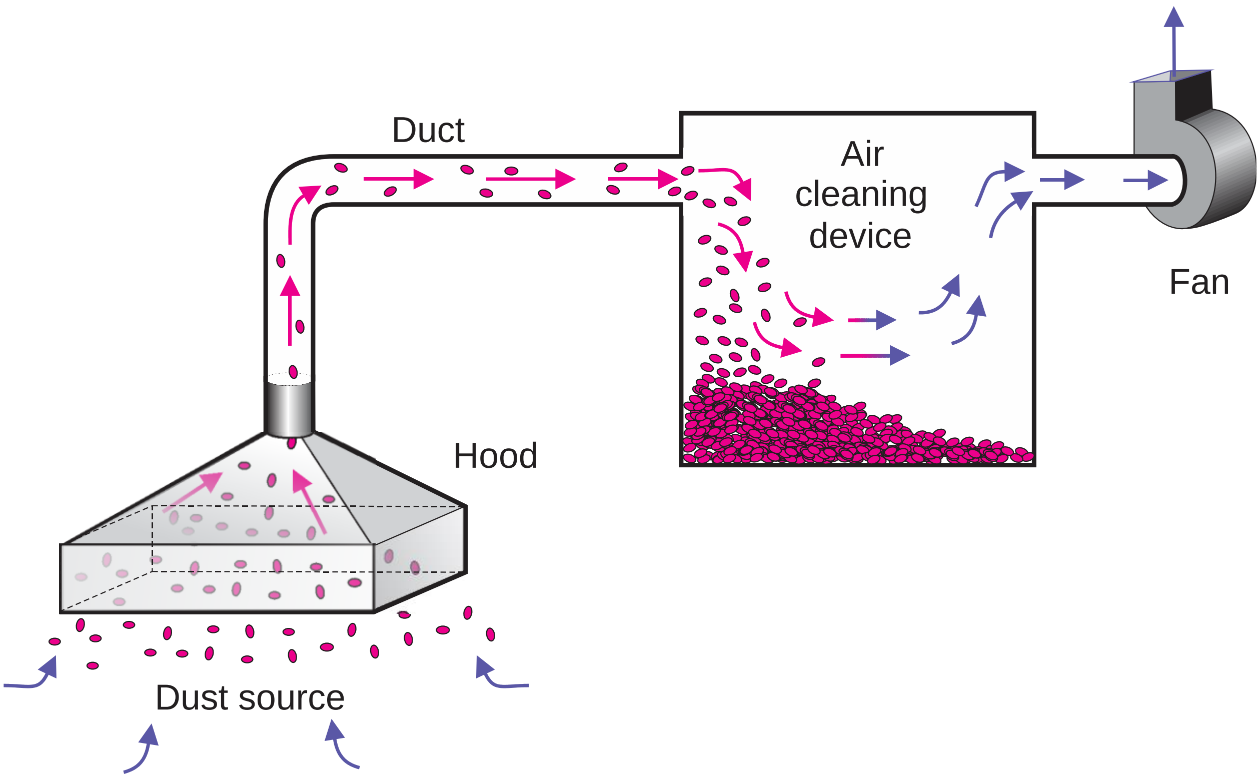


Figure 2.2. Basic illustration of a simple exhaust system with the major components of the hood, duct, air cleaning device, and fan.

HOODS

Hoods are specifically designed to meet the characteristics of the type of ore or product being processed. An effective hood is a critical part to any system because if the hood does not capture the dust, the rest of the exhaust ventilation system becomes meaningless. A properly designed hood will create an effective flow rate and airflow pattern to capture the dust and carry it into the ventilation system. The effectiveness of the hood is determined by its ability to induce an inward airflow pattern for the dust-laden air in the work environment.

Hoods and Blowing versus Exhausting Ventilation

The limitations of exhausting systems need to be considered when determining the effectiveness of a hood at capturing dust. This issue is most evident when comparing the characteristics of blowing versus exhausting air from a duct. With a blowing system, the air delivered from the fan maintains its directional effect for a substantial distance once exiting the duct. With a blowing system, at a distance of 30 diameters (dimension of the exiting duct), the air velocity is reduced to approximately 10 percent of the exiting velocity (Figure 2.3). This blowing air tends to maintain its conical shape and actually entrains additional air, a process commonly referred to as induction. When one compares a blowing system to an exhaust system, the air velocity reaches this approximate 10-percent level at only one duct diameter from the exhaust inlet.

The airflow characteristics for an exhaust system are substantially different. The air exhausted, or pulled into the duct, is captured from all directions around the duct opening and thus forms a nearly spherical shape, as opposed to the conical shape of the blowing system. Another major difference is the air velocity. The air velocity for an exhaust system is approximately 10 percent of the intake velocity at the duct opening at only 1 diameter away, as compared to 30 diameters away at the 10-percent level for the blowing system. These ventilation principles underscore how critical it is for an effective hood design to be very close to the dust generation source.

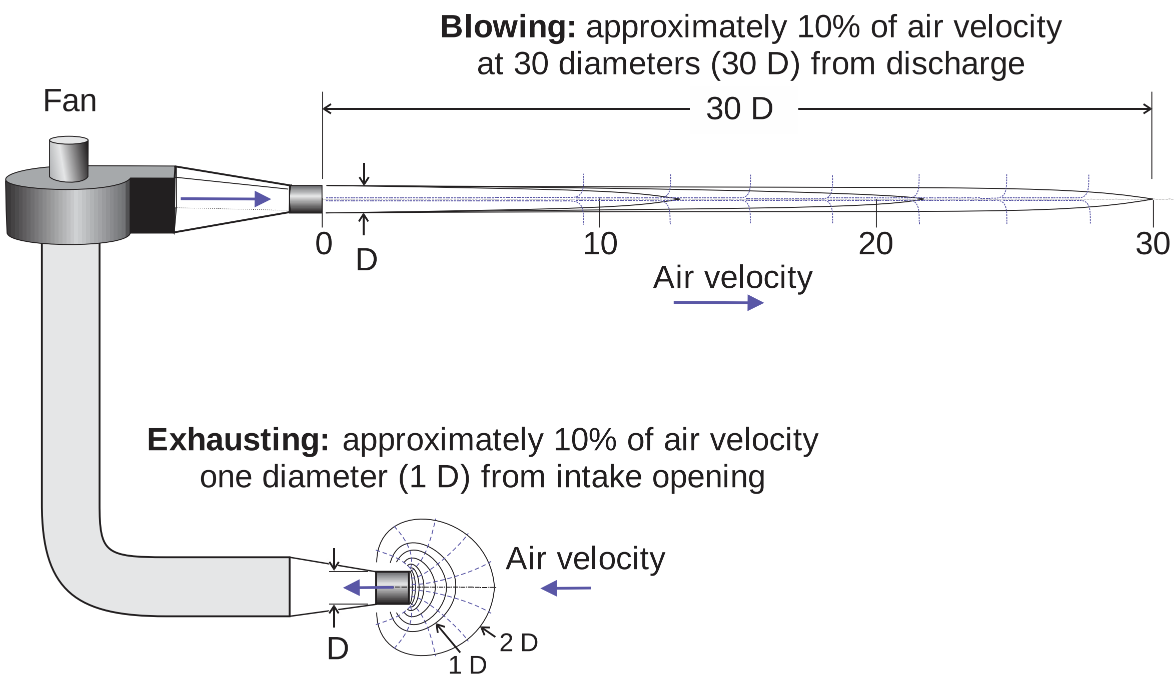


Figure 2.3. Illustration comparing the ventilation characteristics for a blowing versus an exhausting system [adapted from Hartman et al. 1997].

Hood Types

Hoods have a vast range of different configurations, but usually fall into three different categories: *enclosing*, *capturing*, and *receiving*.

Enclosing hoods are those in which the source is either partially or totally enclosed to provide the required airflow to capture the dust and prevent it from contaminating the work environment. The most effective way to capture dust generated is a hood that encompasses the entire dust generation process. Openings into the enclosure (hood) are minimized with doors and access points into the contaminated work process. This situation is normally used when worker access is not necessary and openings are only necessary for the product to enter and exit a piece of machinery or a work process. These types of enclosing hoods can have numerous applications throughout the mining and mineral processing sequence, and are most often used in crushing, grinding, milling, and screening applications.

When access is necessary into the dust generation process or area, it is then common to use some type of booth or tunnel—a type of partial enclosure application. In these partial enclosure systems, the key is to provide sufficient intake airflow to eliminate, or at least minimize, any escape of dust from the enclosed area. This is best accomplished by enclosing the dust generation area or zone as much as possible. One common method to do this is with clear plastic stripping, which allows workers to have ingress and egress while maintaining an effective seal to the contaminated area. A partial booth or tunnel (hood) requires higher exhaust volumes to be effective than do totally enclosed systems.

When it is not practical to either totally or partially enclose the dust generation source or area, *capturing hoods* are normally used and are located as near as possible to the dust source. Because the dust generation source is exterior to the hood, the ability of the hood to capture the dust-laden air is paramount to the success of the system. These types of hoods must be able to overcome any exterior air current around this area. They can be very effective when the dust is emitted in a specific area and the exhaust hood is placed in relatively close vicinity to this area. The capture velocity of the hood decreases inversely with the square of the distance from the hood. In cases where this distance becomes too great, one should consider the use of a push-pull ventilation system (Figure 2.4). In a push-pull ventilation system, a blowing jet of air provides a blast of air movement to provide the necessary quantity to overcome the distance from the hood. This air jet is normally directed across a contaminant source and toward the exhaust hood. As this jet travels toward the exhaust hood, this airflow entrains additional air which helps to capture and move the dust-laden air. The goal is to move this total volume of air into the exhaust hood. This blowing jet coupled with an exhaust (capturing) hood provides a very effective ventilation design.

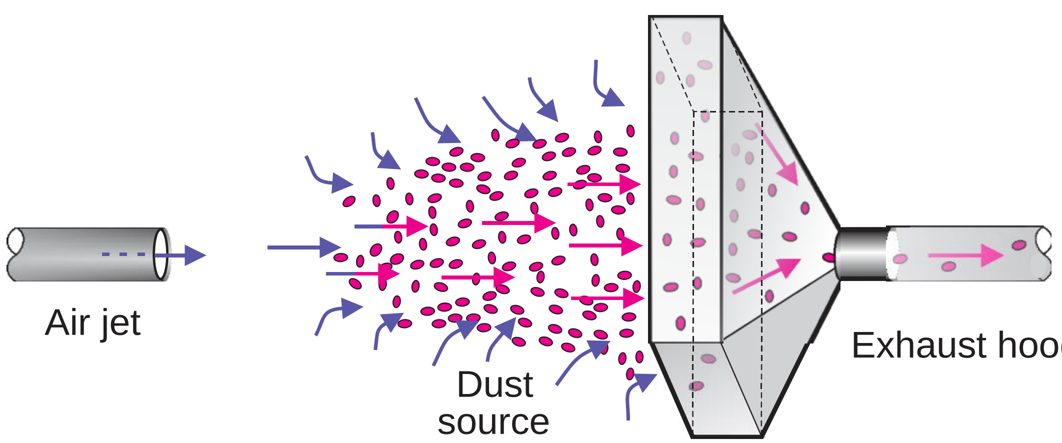


Figure 2.4. Illustration of a simple design of a basic push-pull ventilation system.

The third and most infrequently used type of hood is a *receiving hood* (Figure 2.5). Receiving hoods are normally located close to the point of generation to capture the dust and not allow it to escape. In most cases, these hoods are relatively small in size. The hood uses the directional inertia of the contaminant to lower the necessary capture velocity. These types of hoods have only minor applications in mining and mineral processing and are most common in small machinery and tool applications in laboratory and shop areas.

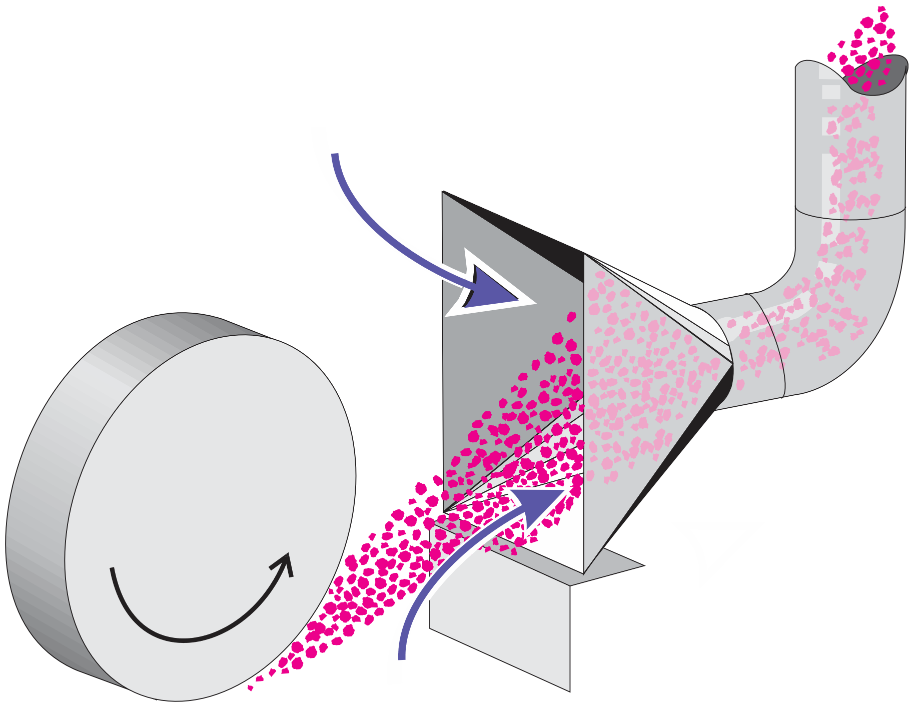


Figure 2.5. Illustration demonstrating a basic setup for a type of receiving hood.

Hood Design

Three important considerations in the design of an exhaust hood are as follows:

- the rate of airflow through the hood,
- the location of the hood, and
- the shape of the hood.

Of these three parameters, the rate of airflow through the hood is the most important. As previously mentioned, if the hood is not able to capture the dust, the rest of the dust collection system becomes meaningless. Without an adequate air velocity, dust capture may not be sufficient. In order to maintain an acceptable negative internal pressure, new or “tightly” enclosed equipment needs less airflow than older or “loosely” enclosed equipment. Because of this, the airflow volume (in cfm) for similar pieces of equipment can vary widely yet still maintain good dust control ability.

As an approximation, the quantities of airflow in Table 2.1 will generally provide good dust control when applied to the listed pieces of equipment, properly hooded.

Table 2.1. Typical quantities of airflow in dust collection system components

Equipment	Airflow, cfm
Bucket elevator—sealed	400 at top and bottom
Bucket elevator—sealed	800 if top-only
Belt conveyor	1,000–1,500 per transfer point
Low-speed oscillating screens	300–500 hood
High-speed vibratory screens	Length of the hood seal x 250 cfm/ft
Screens	300–500 on each discharge chute
Loading spouts	800–1,200
Storage bins	300–400
Hoods, hoppers, and canopies	250 cfm/ft^2 of vertical curtain area around perimeter of unit

When using the air quantities in Table 2.1, one should note that feed rate into the bin (in tons per hour, or TPH) is to be taken into account when sizing hood air volume to allow for air that is entrained by incoming material.

Other equipment fitted with dust control hoods, such as baggers, packers, crushers, magnetic separators, palletizers, etc., will likely include a manufacturer's recommended airflow. In some instances, it may be difficult to install hoods on processing equipment and maintain high collection efficiencies and easy access for operation and maintenance. In these rare cases, it may be necessary to build an enclosure for the entire piece of equipment, possibly by erecting a dust control hood above the equipment and surrounding it with flexible curtains.

There are two issues that need to be considered when determining the rate of airflow to a hood: *air induction* and *capture velocity*.

Air Induction

Air induction is based on the concept that material falling through air imparts momentum to the surrounding air (Figure 2.6). Due to this energy transfer, a stream of air always travels with the falling material. For example, a chute feeding sand to an elevator will drag air into the elevator. This air must be removed from the elevator through an exhaust hood or it will escape and carry dust with it into the plant through openings in the elevator casing, creating dust emissions.

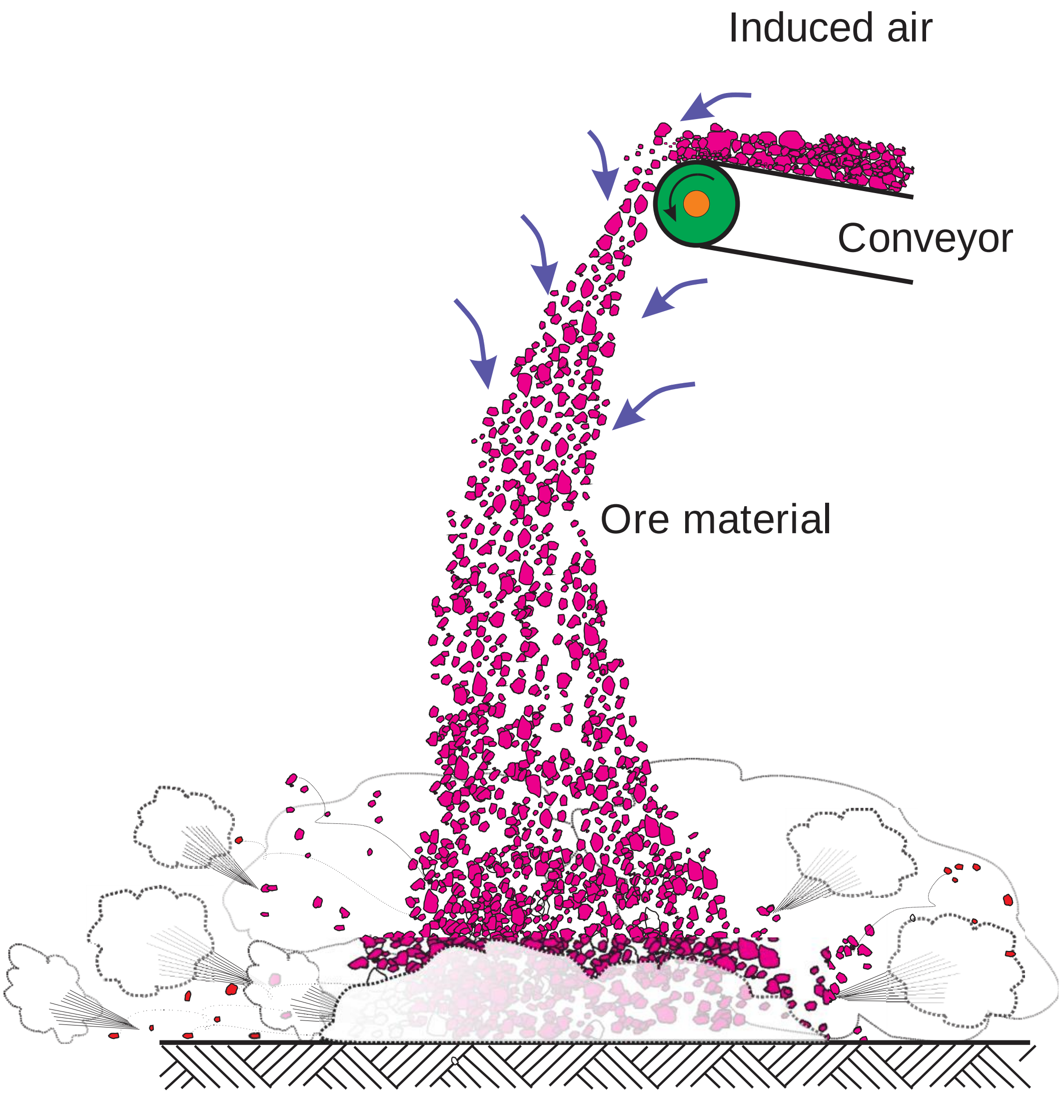


Figure 2.6. Illustration demonstrating air induction as material falls from a conveyor.

The following air induction equation can be used to estimate exhaust volumes for hoods based on material feed rate, height of free fall, size, and feed open area:

$$Q = 10 \times A_U \sqrt[3]{\frac{RS^2}{D}} \tag{2.2}$$

where Q = air quantity, cubic feet per minute;
A_U = enclosure upstream open area, square feet;
R = rate of material flow, tons per hour;
S = height of material fall, feet; and
D = average material size, feet.

The most important parameter in the air induction equation is A_U, the opening through which the air induction occurs (i.e., the cross-sectional area of the feed inlet). The tighter the feed enclosure, the smaller the value for A_U and the smaller the exhaust quantity required. Also, the lower the value for S, the smaller the exhaust quantity required. In designing a materials handling circuit, it is important to keep the values for A_U and S as low as possible to prevent excessive dust generation and to reduce the quantity of ventilation air. The values for R and D also affect exhaust quantity requirements, but are typically a constant in the mining or processing operation and cannot be altered.

The air quantity (Q) for exhaust hoods can also be estimated using the air induction approach. This concept is important because it relates various factors that affect the required air volumes, which may not be accounted for in standard tables or charts. The airflow required using air induction calculations should be compared to the published standards, with corrections made if deemed necessary.

Capture Velocity

Capture velocity is a measure of the required airflow necessary to seize the dust released at the source and then pull this dust into the exhaust hood. The capture velocity must be large enough to overcome all the opposing factors and air currents in the surrounding area. There are various tables available that provide a range of recommended air velocities under a variety of conditions. For mining and mineral processing, this range is normally between 100 and 200 fpm, but can increase up to 500 fpm in special cases. Most operations establish their own capture velocities for their exhaust hoods based on years of experience.

After this capture velocity is determined, the exhaust volume for the hood can be calculated. The following "DallaValle" equation is used to determine the exhaust volume needed for a basic freestanding hood arrangement (Figure 2.7) [DallaValle 1932; Fletcher 1977]:

$$Q = V_X(10X^2 + A_h) \tag{2.3}$$

where Q = the rate of air exhausted, cubic feet per minute;
V_x = the required air velocity at the most remote point of contaminant dispersion, feet per minute;
X = distance in feet from the face of the hood to the most remote point of contaminant dispersion; and
A_h = the area of hood opening, square feet.

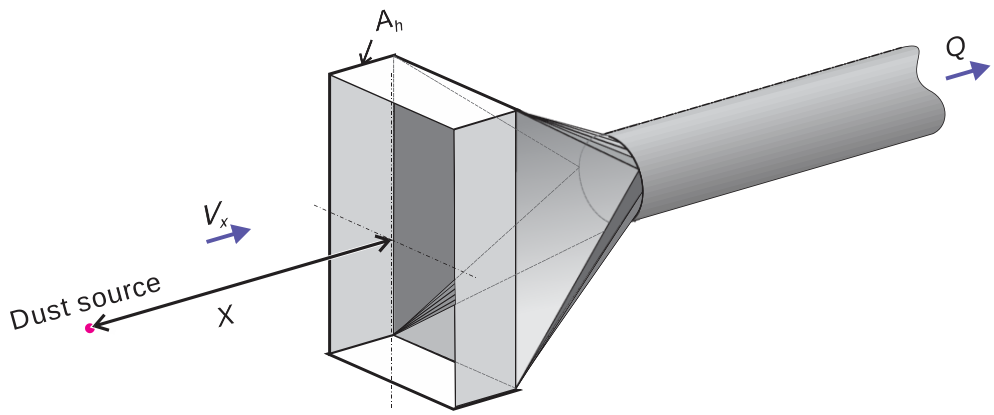


Figure 2.7. Illustration demonstrating the use of a hood entry loss calculation to determine the exhaust volume needed for a basic freestanding hood arrangement [adapted from ACGIH 2010].

From this equation, it becomes obvious that the air velocity, the size of the hood, and the distance from the hood to the dust source are all critical factors for the required air volume. The distance (X) from the dust source to the hood is extremely important because it is a squared relationship.

Another issue that should be noted is that for a freestanding hood, air is also being pulled from behind the hood. This lessens the hood's ability to capture and pull the dust-laden air in the source area. In order to minimize this effect, there are several approaches that need to be considered. First, if the hood is positioned on a tabletop, the airflow requirement is reduced to the following equation:

$$Q = V_X(5X^2 + A_h) \tag{2.4}$$

Another simple technique to improve the airflow from around a hood is to place a flange around it. By doing so, the equation becomes:

$$Q = 0.75V_x(10X^2 + A_h) \tag{2.5}$$

A flange provides a barrier that prevents unwanted air from being drawn from behind the hood and is a very simple design modification to improve the effectiveness of the hood, as well as reducing operating costs. Numerous other factors and considerations for capture velocities can be found in the ACGIH handbook [ACGIH 2010].

Other Hood Considerations

When dust is captured and pulled into a hood from a dust source, the hood converts static pressure to velocity pressure and hood entry losses. Hood entry loss is calculated with the following equation:

$$H_e = (K)(VP) = |SP_h| = VP \tag{2.6}$$

where H_e = hood entry loss, inches wg;
K = loss coefficient;
VP = velocity pressure in the duct, inches wg; and
SP_h = absolute static pressure about 5 duct diameters down the duct from the hood, inches wg.

Air flowing through an exhaust hood will cause pressure changes that need to be calculated when evaluating the impact on each individual hood in a multiple-hood system. Figure 2.8 provides the hood entry loss coefficients for three different types of hoods commonly used in mining and mineral processing facilities. The first case shows three different hood types: circular, square, and rectangular with plain openings. The second case shows loss coefficients with flanged openings, and the last case shows a bell mouth inlet for just a circular duct. This figure demonstrates the significant improvement in the design, and thus the lowering of the hood entry loss coefficient, with each improvement in the hood type.

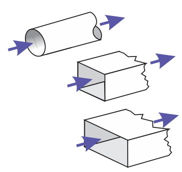
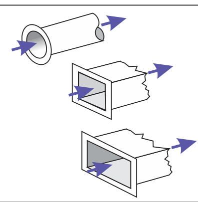
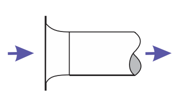
Hood type	Description	Hood entry loss coefficient (K)
	Plain opening	0.93
	Flanged opening	0.49
	Bell mouth inlet	0.04

Figure 2.8. Hood entry loss coefficients for different hood types [adapted from ACGIH 2010].

Guidelines for Hood Effectiveness

The following is a list of effective practices or considerations for the use of hoods in exhaust ventilation systems.

- The most effective hood design is one that encompasses the entire dust generation process. This virtually eliminates dust escaping and contaminating mine/plant air and the exposure of workers.
- Openings/doors/access points into the hood should be minimized as much as is reasonably possible. When access is necessary, a partial enclosure application, normally referred to as a booth or tunnel, is then recommended. When access points are not able to

be closed, sealing these areas with clear plastic stripping is a common and effective technique.

- When neither total nor partial hood enclosures are possible, capture hoods should be used. The hoods need to be located as close to the dust source as feasibly possible. Remember that the distance component is a squared relationship that affects the required hood air volume.
- Hood capture velocities must be able to overcome any exterior air current between the dust source and the hood.
- The use of a push-pull ventilation system should be considered when the distance between the dust source and the hood becomes too great, or when there are significant exterior air currents in the area.
- It is critical that makeup air drawn past a worker before entering an exhaust hood be essentially dust-free. If the air is drawn from a contaminated area, the potential exists to increase a worker's respirable dust exposure. Dust-laden air from a dust source should never be pulled through a worker's breathing zone as it is being drawn into an exhaust hood.
- Flanges on hoods should be used because they significantly improve the airflow from the front of the hood area, which should be directed toward the dust source. In cases where bell-shaped hoods and ducts can be used, they provide the optimum design.
- All hoods should be designed to meet the criteria established by the ACGIH handbook.

DUCTWORK AND AIR VELOCITIES

There are three basic types of systems used to transport dust to the collector: high-velocity, low-velocity, and modified low-velocity. Most common in the industry is the high-velocity system, where air-carrying velocities are in the range of 3,000–4,500 fpm. Fundamentally, this is a dust *collection* system, while a low-velocity system can best be described as a dust *containment* system, with duct velocities always less than 1,800 fpm. Low-velocity systems are designed so that they will not transport nonrespirable-sized dust particles (generally particles larger than 10 µm). It is important to keep in mind that low-velocity transport does not imply low airflow. Capture velocities (the air velocity at the hood opening required to capture the contaminant) and hood air volumes are the same in all designs, be they high-velocity, low-velocity, or modified low-velocity systems. Figure 2.9 depicts the basic differences between high- and low-velocity systems.

The implication of the figure is that, in a high-velocity system, the dust will be carried to the collector regardless of the slope or angle of the duct. However, in a low-velocity system, it is necessary to slope the duct to an inlet hood or discharge point, because some of the larger particles, inadvertently collected, will settle out in transport and must be removed.

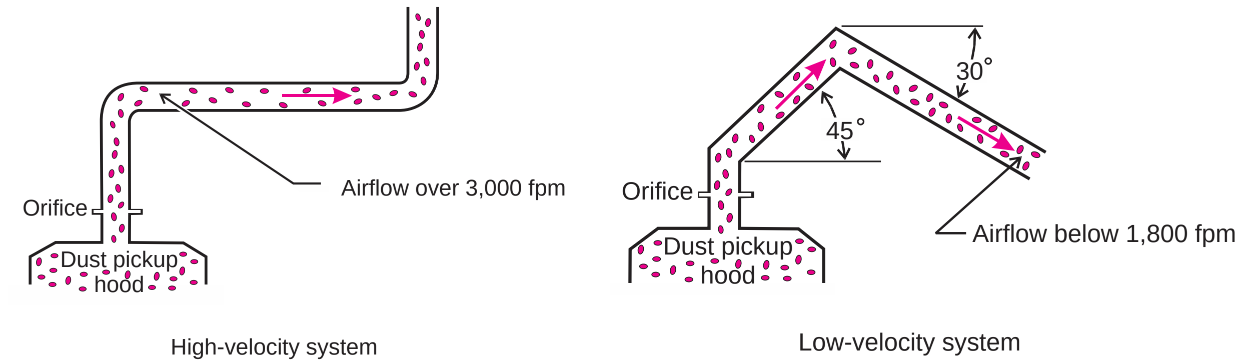


Figure 2.9. Illustration depicting the basic differences between high- and low-velocity systems.

High-velocity Systems

The high-velocity system is characterized by its ability to carry dust-laden air (particles larger than 10 µm) from the entry points of the system to the dust collector without having the particles settle out in the duct. To keep the particles from settling, high transport velocities are required.

Because the ducting in a high-velocity system can be run both horizontally and vertically, there are few engineering restrictions. Effective ducting layouts can be easily designed, normally with a central horizontal duct and smaller collection ducts branching off to the dust-producing equipment/hood.

A major disadvantage of the high-velocity system is that the ductwork is subjected to highly abrasive "blasting" by the dust particles moving at a high rate of speed, especially when the air changes direction. Elbows and branch entries are particular areas subjected to high wear. Abrasion first shows in these areas of air directional change. This wear or abrasion, if not addressed through additional engineering design or maintenance, will result in the long-term deterioration of the collection system due to the formation of holes or openings in the ductwork (Figure 2.10). Because of this abrasive wear, most ductwork and fittings have to be fabricated from heavier materials and the fittings require longer radii. The high wear rate also results in high maintenance labor and material costs. Any system with holes in the ducting loses its effectiveness at the pickup point, and even a single hole in the duct can have a strong impact on the system. Because high-velocity systems are prone to required maintenance, they may not always be operating at optimum efficiency.

Photos by NIOSH

Figure 2.10. Photos showing multiple holes created along an elbow from wear and abrasion when a high-velocity system is used.

High humidity, coupled with inadequate airflow, leads to further wear problems on systems with ducts that are run horizontally. Upon shutdown, the dust in the air stream settles in the horizontal runs of duct. As the air cools to the dew point, moisture can form on the surface of the duct, causing some attachment of dust particles to the wall. Over time, this buildup robs the system of airflow due to increased friction losses in the system and increases in velocity through the narrower opening. The loss of airflow in the system reduces collection efficiency, and the resulting increased velocity increases wear and can cause an even more rapid deterioration to the system than would normally be expected. In addition, the moisture in the dust that builds up on the ductwork can cause increased corrosion within the system.

Finally, high velocity means high pressure drops throughout the system. This equates to increased horsepower and higher power consumption, raising overall operating costs. Also, although the initial installation costs for high-velocity systems are comparatively low, higher maintenance and operating costs lead to high overall lifetime costs of the system.

Low-velocity Systems

The basis of the low-velocity collection system is to create the same negative static pressure in the area surrounding the dust source and to maintain the same airflow into the collection hood, as in a high-velocity system. The difference between the systems is that, after collection, the air transport velocity in the low-velocity system is much lower. Thus, the pipe is always sloped to allow the oversized particles to slide to a discharge point for easy removal. Transport velocity is designed to move only the particles in the respirable-sized range, generally smaller than 10 μm. Respirable dust is carried through the ductwork by the low-velocity airflow, while heavier particles fall out into the ductwork and slide back into the process.

Ductwork in the low-velocity system cannot be run horizontally. The ductwork is designed so that the larger particles that fall from the air stream are reintegrated into the process. Therefore, a sloped sawtooth design (Figure 2.11), commonly referred to as a “grasshopper,” is used instead of long horizontal runs. In order to control the airflow, a fixed orifice plate or blast gate is positioned in the duct segment, preferably on a downward run, so as not to trap material above the high-velocity flow through the orifice.

Photo by Unimin

Figure 2.11. Sawtooth ("grasshopper") design of a low-velocity system with a drop-out duct back into the process at the base of each leg.

The particle-carrying ability of a low-velocity system is confined to particles smaller than 10 µm. Because of the absence of larger particles, as well as the lower velocities involved, abrasion is low even at points of air directional change. This allows for the use of short radius or mitered elbows without fear of extreme wear.

From a design standpoint, dust control systems are engineered for expected pressure losses within the system. These losses are due to air friction and pressure losses across the dust collection unit. By reducing the air velocity, frictional losses in the ductwork and fittings are reduced, lowering overall power requirements.

Because of the behavior of low-velocity air, moderate orifice size changes can be made without completely upsetting the system. Even opening a branch completely will not drastically change the airflow in other branches because the pressure drop change is minimal. Should one branch of the network fail or change airflows dramatically, the system tends to stay in balance and other branches do not lose effectiveness. Therefore, the airflow can vary substantially within two identical pieces of equipment while maintaining excellent dust containment. Thus, overall losses through the dust collection system are lower.

The disadvantages of low-velocity systems are the higher initial cost and more complex design. In these systems, the ability to pass a certain volume of air (cfm) through the duct at a predetermined velocity in fpm dictates the diameter of the duct, requiring larger-diameter ductwork. Also, because ductwork cannot be run horizontally, a sawtooth design is used, which adds expense and complicates installation.

A common misconception when designing a low-velocity system is that an exhaust hood is not required due to the low-velocity ducting design. To the contrary, a properly designed exhaust hood on a low-velocity system is still a requirement for a good dust containment system. A properly designed hood will help maintain lower pressure losses within the system by minimizing the shock loss that occurs from the incoming airflow. Hood design is essentially the same for both high- and low-velocity systems. However, all exhaust hoods should be located away from the point of material impact to lower the likelihood of material being drawn into the hood. The principle of low-velocity dust containment is to exhaust air from a well-enclosed area. This will impart a negative inward pressure, trapping fugitive dust within the enclosure. The shape of the exhaust hood is also important for two reasons:

1. A well-designed hood has a lower resistance to air movement.
2. A well-designed hood prevents material from being vacuumed into the dust containment system. Even with low-velocity ducting, coarse material can still be drawn into the system. It is therefore important to have a hood with a face velocity of 200 to 300 fpm or less in order to avoid entraining saleable product.

Finally, the design and layout for a low-velocity system require more engineering. Because of the constraint that runs cannot be made horizontally, it is sometimes difficult to physically find room for the required sawtooth design of the ducting. However, a properly designed and balanced low-velocity system provides a virtually nonplugging and low-maintenance dust control system. More specific engineering principles for low-velocity systems are detailed below.

Airflow Velocity Target of 1,800 fpm

Because of the nature of a low-velocity system, it is not necessary to maintain a specific air velocity within the ductwork. However, the desired target of 1,800 fpm should move most of the respirable dust particles (smaller than 10 μm) through the system to the air cleaning equipment while containing it within the confines of the individual pieces of dust-producing equipment/hood. The basic goal of low-velocity dust control is to minimize the amount of contaminants (respirable dust) that escape the system, thus becoming a hazard or nuisance. The 1,800-fpm target maintains a slightly negative pressure within the piece of equipment, while providing adequate airflow to discourage dust particles from escaping the unit. This ensures that any airflow at the equipment is moving inward rather than outward.

Avoidance of Horizontal Ductwork

As a result of the system's low-velocity airflow, it is imperative that ductwork is not run horizontally. This is because the heavier dust particles drawn into the air stream may drop out and attach themselves to the sides of these ducts. The net result is an eventual narrowing of the duct opening, leading to an increase in velocity and ductwork erosion. Therefore, ductwork should be designed for a minimum upflow angle of 45 degrees and a minimum downflow angle of 30 degrees (Figure 2.12). This allows any particles drawn into the air stream to slide back to their source. This design also requires that a drop-out point be located at the low point of all duct runs to allow these particles to fall out, as shown in Figure 2.11.

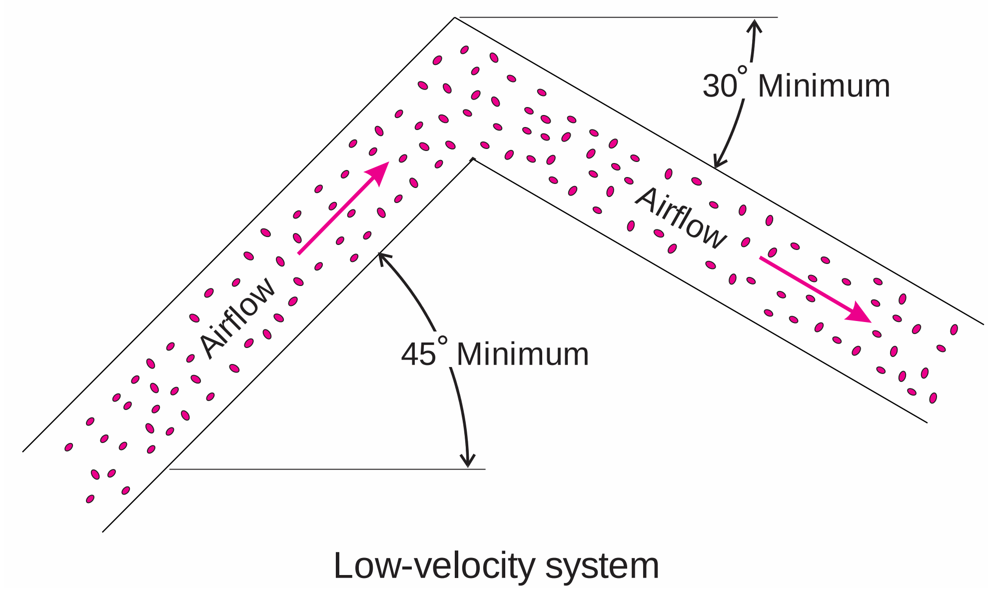


Figure 2.12. Illustration of duct design angles for low-velocity systems.

The Use of Main Duct Trunk Lines

From a design standpoint in low-velocity systems, consideration should be given to using one or more main duct trunk lines, running from the air cleaner to a centrally located proposed dust control point in the plant. This allows for smaller branch duct lines to emanate from the main duct trunk line and enables easy connection to individual pieces of equipment. These trunk lines can be either rectangular or round. In areas where space is a problem, rectangular duct cross sections that are shallow in depth and wide are easier to install. Many times these trunk lines can be run vertically up the side of an existing column or bucket elevator. As previously noted, a drop-out point—possibly the bucket elevator—must be provided at the low point of all duct runs.

Minimizing Field Fits and Welds

New ductwork and fittings should be shop fabricated and be as complete as possible before being sent to the field for erection. Welding and cutting duct joints in the field are costly, and proper engineering design can minimize the welding required. Extra time spent at the design stage preplanning and prefabricating hoods, fittings, and duct segments pays dividends later during installation.

Frequently, field fits must be made, and these can be anticipated before the material is sent to the field. It is best to make field cuts and welds at the flange point of the ductwork. In these instances, the ductwork can intentionally be shop fabricated to lengths longer than necessary. Also, a rolled angle ring can be shop installed at the end of the duct and then tack welded. This keeps the ductwork from becoming distorted during handling and transit, and the tack weld can be cut in the field, the duct shortened, and the flange moved, rotated, and welded as needed.

Flanged connections are an efficient and easy means to install ductwork in the field. Rolled angle ring flanges are readily available, inexpensive, and easy to install. These flanges should normally be used on all shop fabricated fittings, hoods, and duct segments. These types of connections also help eliminate costly welding requirements and allow for easy replacement of sections should maintenance be required.

Avoiding Mitered Elbows Greater Than 90 Degrees

As with high-velocity systems, pressure losses increase rapidly in ductwork with abrupt directional changes greater than 90 degrees. Since duct pressure losses are a squared function of the velocity, the low-velocity system still results in lower pressure losses. However, a segmented elbow can be used in areas of unusually abrupt air directional change if maintaining low pressure losses in the system is critical.

Sizing and Locating Orifice Plates

In many complex ventilation systems, orifice plates are used to balance airflows by changing the pressure requirement in a selected section. It is recommended that an orifice plate, sized for a minimum pressure loss of 2 inches, be installed in each individual branch line. This allows for easy expansion of the system in the future. As additional branch lines are added to the main trunk line, the orifice plate can be resized for a larger, and therefore less restrictive, orifice opening.

For the purpose of initial airflow balancing, blast gates may be installed in place of an orifice plate. Blast gates allow for easy adjustment of airflow during initial setup as they can be slid in and out as needed. Once the system airflow is balanced, the open area on each blast gate should be measured and an equivalent orifice plate with a centered round hole should be installed.

Figure 2.13 demonstrates inappropriate locations for orifice openings. Orifice plates should be installed a minimum of 4 to 5 duct diameters upstream and 4 diameters downstream from air directional changes. This permits the airflow to become closer to laminar and to reestablish normal velocity. If an upstream orifice plate is placed too near a downstream air directional change, the higher velocities encountered through the orifice opening will produce a sandblasting effect on the far-side wall. Orifice plates should be installed in the upflow branch leg whenever possible. This helps avoid a buildup of heavier dust particles above the orifice plate, as could happen in the download branch line installation, where particles are unable to drop out through the higher velocities of the orifice plate.

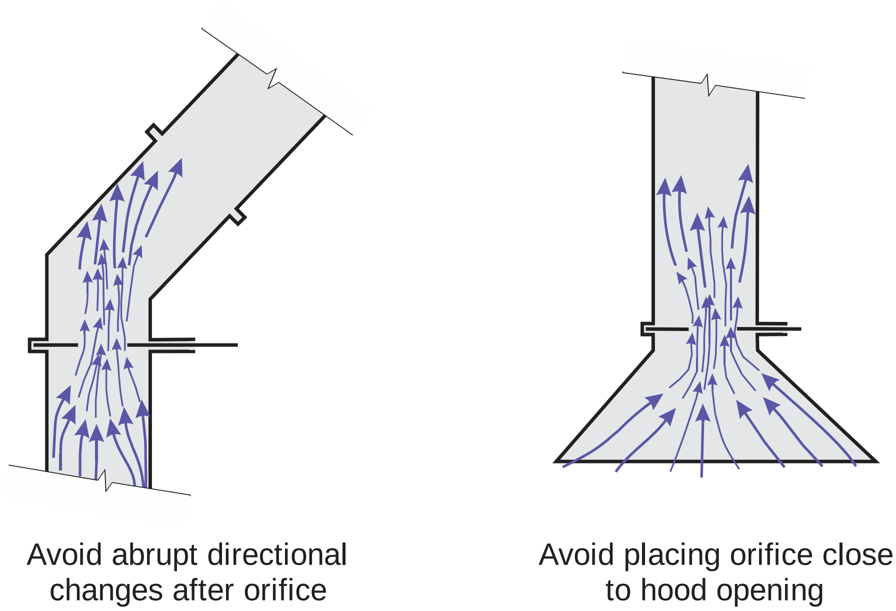


Figure 2.13. Illustration demonstrating poor orifice plate placement.

Orifice plates should also not be installed near hood inlet openings. The higher velocities near the orifice tend to capture unwanted material. Hood capture velocities below 500 fpm should be maintained. On fine-grind materials, a target capture velocity of 200 fpm is desirable.

Minimizing the Use of Flexible Hoses

As a rule, flexible hoses should not be used as part of the ductwork in low-velocity systems. A failure could compromise the dust control ability of the branch lines in the general area. Flexible hoses also increase frictional losses in the system. If flexible hoses are used, they should be placed between the orifice plate and the inlet hood where their failure would have the least impact.

Modified Low-velocity (MLV) Systems

The objective of the modified low-velocity (MLV) system is to combine the advantages of the high- and low-velocity systems, while avoiding the disadvantages of both. The key to the success of the MLV system resides at the pickup hood. Here, the first duct run must be vertical for at least 6 feet, but preferably 8 to 10 feet or as long as is practicable. The velocity in this first vertical run is extremely low, even compared to the standard low-velocity system (i.e. 1,000 to 1,200 fpm). As in other systems, dust is contained, but only the smaller-micron particles are transported. The 6- to 10-foot vertical rise is necessary to reduce turbulence, to achieve a smooth laminar flow, and to optimize elutriation (separation of lighter and heavier particles) at the first bend.

Because there are minimal particles in the air stream after this first vertical rise, the need to maintain high velocities in subsequent horizontal runs is not necessary. Similarly, there is no need for an overall sawtooth design or mid-run discharge points. Velocity in the first horizontal run following a 1,200-fpm vertical duct should be about 2,000 fpm.

Another important design consideration with MLV systems is that, as additional lateral lines are connected to the main trunk line, the exit velocity of the trunk line after the initial lateral connection should be increased by about 100 fpm (Figure 2.14). Even in long runs with many lateral lines, it is not likely that the line velocity upon reaching the collector will exceed 2,500 to 3,000 fpm. Given the low pressure drops in such a system, it is not necessary to construct expensive elbows, mitered bends, or laterals. Instead, box elbows and fittings can be used.

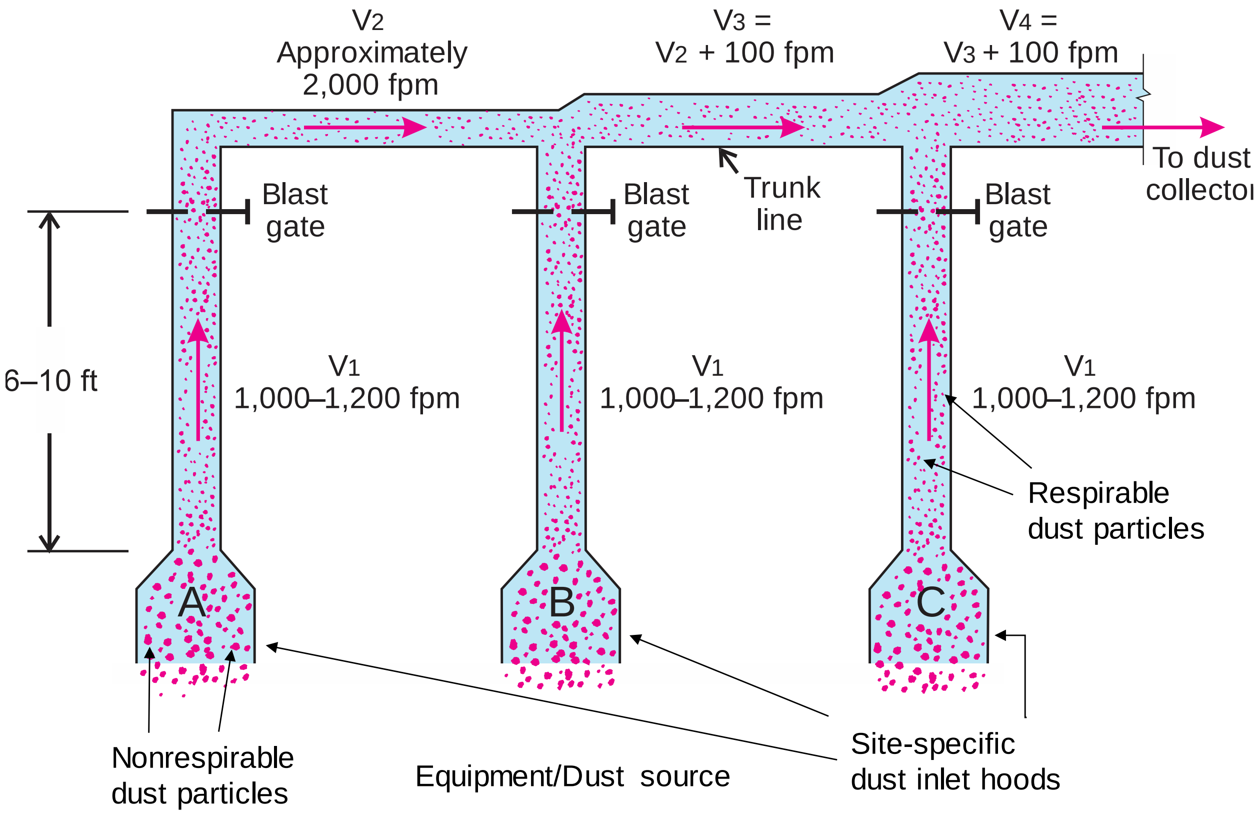


Figure 2.14. Illustration of the horizontal ($V_{2,3,4}$) and vertical (V_1) velocity relationship in a modified low-velocity system. Nonrespirable (larger) dust particles fall back into the process, while respirable (smaller) particles are transported through the ductwork to the dust collector.

The MLV system contains all the advantages of the low-velocity system relative to low abrasion, reduced maintenance, reduced power, and stability of the system balance. At the same time, it does not require the space-consuming sawtooth installation. Duct size (diameter) is a compromise between the high- and low-velocity systems, since velocities in all trunk lines will be somewhere between the two. Another advantage of the MLV system is that it can readily be used in extensions to or modifications of existing high-velocity systems. Only under certain conditions can it be used in an extension of a low-velocity system. One would need to compare velocities at the connecting points, recognizing that it is not feasible to move from a higher to a lower velocity within a duct. A low-velocity extension can, however, be made to an MLV system.

The basic design tips for low-velocity systems as detailed previously can be applied to MLV systems, with a few exceptions, as noted below.

- The reference to avoiding horizontal ducts does not apply.
- Orifice plates or blast gates should be installed at the top of the low-velocity vertical leg, not the bottom. Plates/gates should be as near to the higher-velocity leg as possible.
- Vertical leg velocity should be 1,000 to 1,200 fpm. Vertical legs need to be as long as is practicable, but at least 6 feet to 10 feet.
- Horizontal leg velocity should begin at a minimum of 2,000 fpm.

AIR CLEANING DEVICES

Air cleaning devices used within the industrial minerals mining industry are used to clean ventilation air streams of harmful particulate matter. The choice of air cleaner for any particular installation will depend on the following:

- dust concentrations and dust characteristics,
- particle size,
- efficiency of particulate removal required,
- air stream temperature,
- air stream moisture content, and
- methods of disposal.

Distinguishing dust characteristics that affect the collection process include abrasive, explosive, sticky or tacky, and light or fluffy. The shape of the dust particle is also important because it factors into whether the particles are agglomerating (irregular) or nonagglomerating (spherical), which is important when using a filter cloth. For collection purposes, agglomerating particles are ideal as they allow dust cakes to build up easily on the filter cloth, allowing for more efficient collection at the dust collector. However, agglomerating particles may have a tendency to not release from the filter cloth very easily.

The types of dust control equipment used for air cleaning range from very crude gravity separators to more sophisticated electrostatic precipitators. The following is a list of the types of collectors used for particulate removal.

- Gravity separators (drop-out boxes).
- Centrifugal collectors or cyclones.
- Baghouse collectors.
- Cartridge collectors.
- Wet scrubbers.
- Electrostatic precipitators (ESPs).

A brief overview of each type of collector, along with its advantages and disadvantages, follows.

Gravity Separators (Drop-out Boxes)

Gravity separators (also called drop-out boxes) are large chambers where the velocity of the air stream is drastically reduced in order to facilitate the vertical drop of particles. The separator works by not only slowing down the air but by changing its direction as well. Airflow enters horizontally and is immediately directed vertically downward by a target plate (Figure 2.15). As the air slows and moves downward, the large particles drop out of the air stream by the force of gravity. Finer particles not affected by this will continue to flow in the air stream and exit the separator.

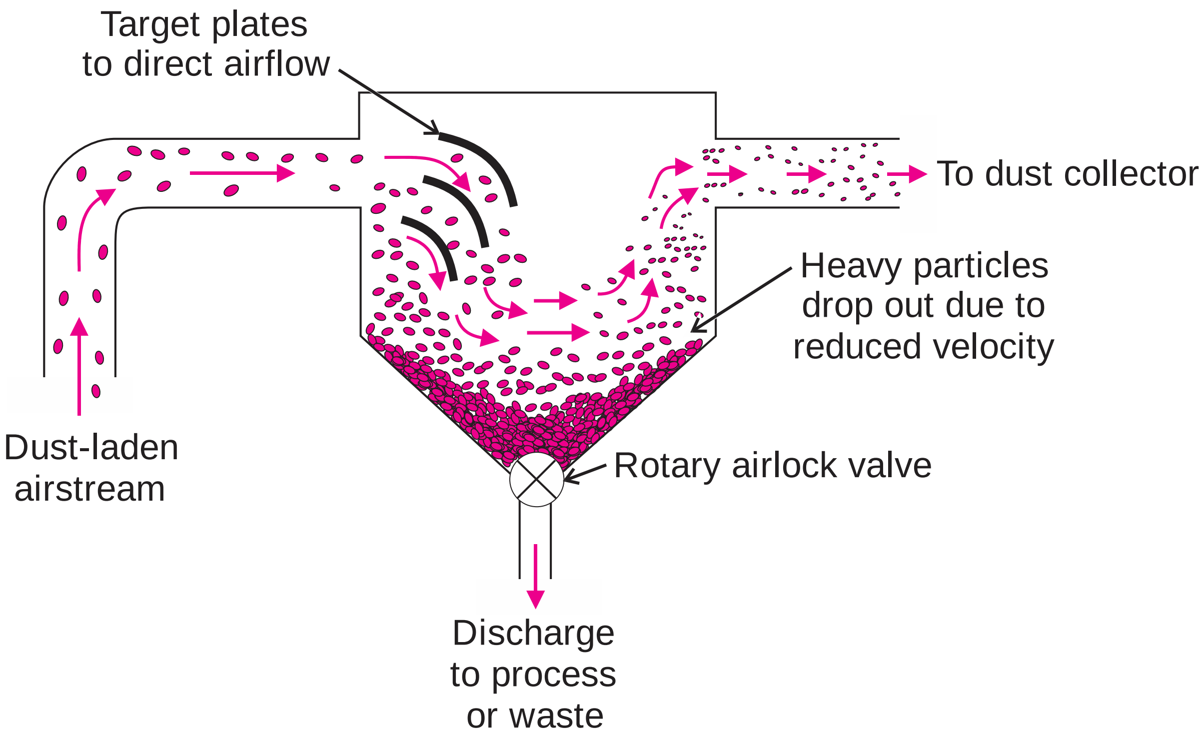


Figure 2.15. Illustration showing a typical design of a gravity separator (drop-out box).

The benefits of using gravity separators are that they require little maintenance and they reduce the load on the primary dust collector. However, they also take up significant plant space and have a low collection efficiency.

Centrifugal Collectors or Cyclones

Cyclones are a dust collection device that separates particulate from the air by centrifugal force. The cyclone works by forcing the incoming air stream to spin in a vortex. As the air stream is forced to change direction, the inertia of the particulates causes them to continue in the original direction and to be separated from the air stream (Figure 2.16). Although the cyclone is simple in appearance and operation, the interactions inside a cyclone are complex. A simple way to explain the action taking place inside a cyclone is that there are two vortices that are created during operation. The main vortex spirals downward and carries the coarser particles. An inner vortex, created near the bottom of the cyclone, spirals upward and carries finer dust particles.

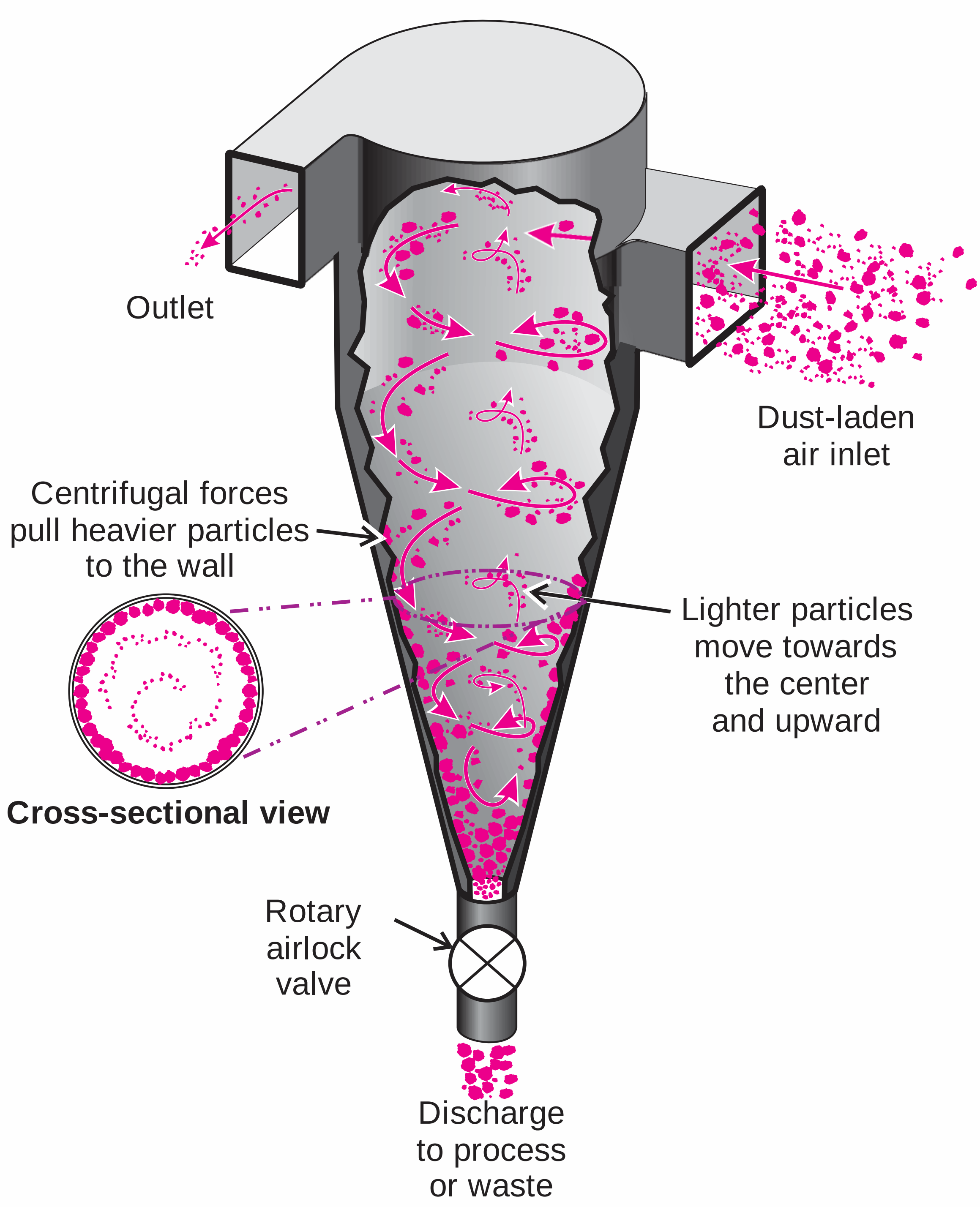


Figure 2.16. Illustration showing a typical design of a cyclone dust collector.

Cyclones are cost-effective and low-maintenance devices, and they can handle high temperatures. They also reduce loading on the primary collector and allow for the dry recovery of product. However, it is difficult to predict the performance of cyclones, and they pose particular design challenges. Accurate inlet data are necessary, and they require significant plant space.

Cyclones have low efficiencies in removing fine particulate. They are typically used as a precleaner to remove coarser particles that could otherwise damage the bags in fabric collectors or plug wet scrubbers. It should be noted that adding a cyclone to a ventilation system may not reduce overall system resistance because the drop in resistance at the baghouse (due to lower dust loading) may be more than offset by the pressure drop of the inertial cyclone collector. Pressure drops range from 3 inches wg for low-efficiency inertial cyclone collectors and up to 8 inches wg for higher-efficiency models.

Baghouse Collectors

Baghouse dust collectors capture the particulate in an air stream by forcing the airflow through filter bags. A baghouse works by taking the inlet dust-laden air and initially reducing the velocity to drop out larger particles. The baghouse then filters the remainder of the particles by passing the air through a fabric bag (Figure 2.17). Separation occurs by the particles colliding and attaching to the filter fabric and subsequently building upon themselves, creating a dust cake. Since the dust has been deposited on the outside of the bag, when the dust cake is removed from the bag or cleaned, it falls by gravity into the collection hopper located below the bag section. Collected dust is then removed from the collector through a hopper valve.

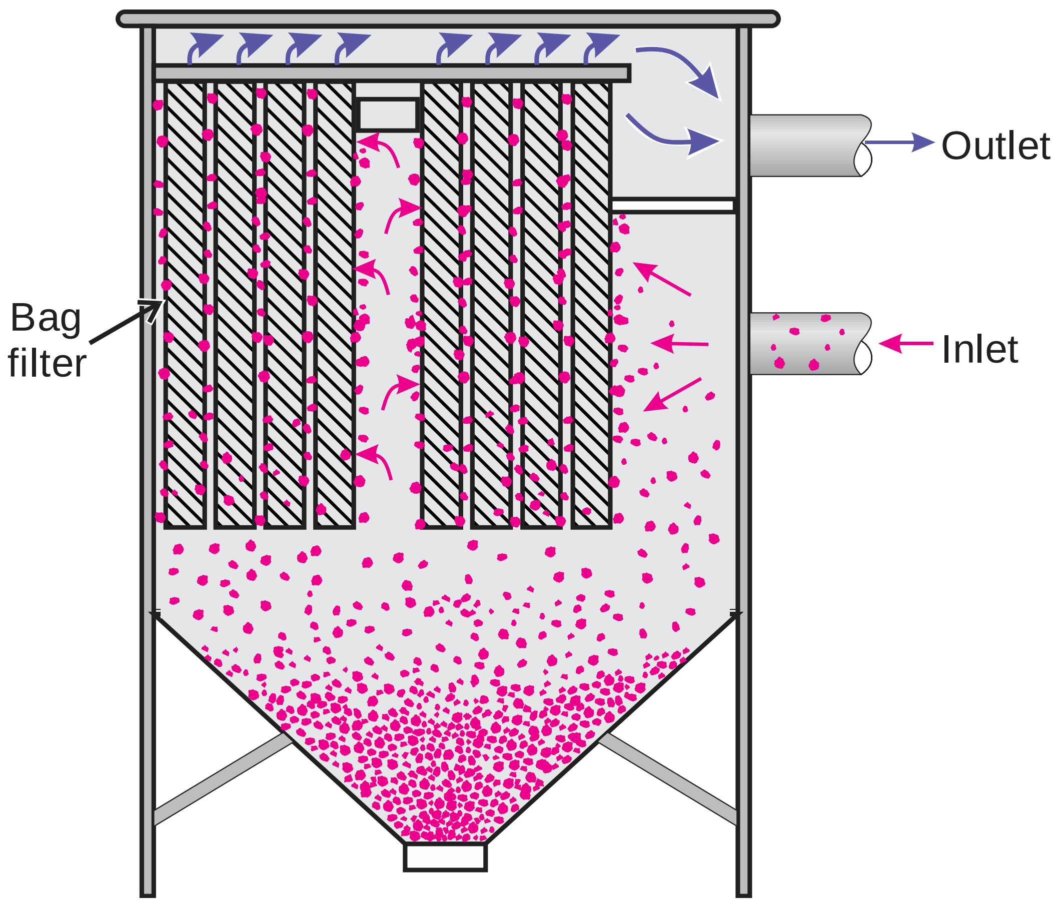


Figure 2.17. Illustration showing a basic design of a baghouse dust collector.

Baghouse collectors are generally designed and sized to operate with a differential pressure between 4 and 6 inches wg. These collectors can achieve air cleaning efficiencies of more than 99.97 percent (high-efficiency particulate air, or HEPA) for fine particles. The fabric bags can be made from cotton, synthetic materials, or glass fiber. The type of fabric bag used depends on the type of collector and application. For most applications involving ambient temperature, a cotton bag is the most economical. However, in a corrosive or high-temperature environment, a bag material other than cotton should be employed. Since bags must be changed periodically, fabric collector designs that facilitate bag changes should be chosen. Designs where the bags can be changed from outside the collector are preferred.

Baghouse systems can also be designed for economic optimization. For a given emission control problem, factors such as the overall pressure drop, filtration cleaning cycle, and total filtration surface area can be addressed simultaneously. Caputo and Pacifico [2000] provide a useful model, particularly for operations in the preliminary design phase.

Bulk density of the material requires special engineering attention. The effect that upward velocity (interstitial velocity) can have on the operation of a dust collector can be enormous. Materials with low bulk density (< 30 pounds per cubic feet) must have specialized designs. In these cases, collector designs must be modified to accommodate lower interstitial velocities. Typical modifications include wider bag-to-bag spacing, shorter-length bags, or high side inlets.

Particle size distribution plays a key role in determining the *air to cloth ratio* and filter bag selection. The air to cloth ratio is a measure of the actual volume of gas or air per minute per unit area of bag (ft^3 air per minute/ft^2 of bag area), and can be expressed mathematically as follows:

$$air\ to\ cloth\ ratio = {}^{Q}\!/_{A} \tag{2.7}$$

where Q = quantity of gas (air) in actual cubic feet per minute (acfm), and A = area of the filter cloth or total number of bags in ft^2.

It is generally understood that the finer the dust, the lower the air to cloth ratio needed. Proper bag or cartridge selection based on the material to be collected is fundamental to a successful system. The article, “Fine Filtration Fabric Options Designed for Better Dust Control and to Meet $PM_{2.5}$ Standards” [Martin 1999], provides a useful fabric characteristics and capabilities chart, matching fabric type to operating conditions. Another recommended resource is the article, “Pick the Right Baghouse Material” [Mycock 1999], which includes a chart detailing properties of textile fabrics for filtration.

Inlet loading refers to the amount of dust arriving at the inlet of the dust collector. It is typically expressed in pounds per minute (lbs/min) or pounds per hour (lbs/hour) and converted into grain loading expressed in grains per cubic foot (gr/cf) of airflow. The grain loading within an air stream is dependent on many factors, which include the number of dust sources serviced by the dust collection system, the types of dust sources (e.g., crushers, screens, etc.), the dust emissions from these individual sources, and the capture effectiveness of the dust collection system at each source. The amount of dust emitted by each source is impacted by a number of parameters, including the particle size distribution (dustiness) of the material being handled in the process, the moisture content, and the throughput rate.

The Environmental Protection Agency (EPA) has compiled data on dust emission factors for a number of processes that are involved in mineral processing [EPA 1995]. Table 2.2 lists some of these factors, which are averages of dust emissions from available data and should be viewed as a general starting point when attempting to determine inlet loading. These emission factors would have to be multiplied by the processing rate at the specific source to calculate inlet loading in lbs/min. Recommendations based on experience from dust collector manufacturers and from filter cloth manufacturers should also be utilized in efforts to effectively quantify inlet loading. This inlet loading or grain loading helps determine the air to cloth ratio, filter media, type of collector, type of inlet to be used, and how the filter cleaning system will be configured.

Table 2.2. Emission factors for crushed stone processing operations (lb/ton)*

Source	**Total PM-10****
Tertiary crushing	0.0024
Screening	0.0087
Conveyor transfer point	0.0011
Wet drilling—unfragmented stone	0.00008
Truck unloading—fragmented stone	0.000016
Truck loading—conveyor, crushed stone	0.0001

* Uncontrolled emissions in lb/ton of material throughput.

** PM-10 is particulate matter less than 10 micrometers (µm), in size.

The following formula can be used for converting lbs/min into grains/ft^3:

$$\frac{7000\ grains\ (lbs/min)}{cfm} = gr/ft^3 \tag{2.8}$$

where lb/min = loading rate of the material, and cfm = airflow of the dust collector.

The expressions listed below define various inlet loading relationships.

- Low concentration = < 1 gr/ft^3.
- Typical concentration = 1–5 gr/ft^3.
- High concentration = 5–10 gr/ft^3.
- Very high concentration = > 10 gr/ft^3.

The porosity of the filter media (cloth) will determine the amount of air that can be drawn through before the static pressure becomes too high for the collector housing or the fan capacity. By estimating the inlet loading, one can also determine the grains of dust striking each square foot of filter media per unit time.

The air to cloth ratio is also an indirect measure of the average velocity of the air moving toward the bags. Inlet loading directly affects the air to cloth ratio. The greater the inlet loading, the lower the air to cloth ratio should be. High inlet loading results in more dust being retained on the filter media and causes higher pressure drops. Air to cloth ratios below 4:1 are considered to be low, from 4:1 to 7:1 moderate, and above 7:1 high. By lowering the air to cloth ratio, the filter has more filter area to distribute the dust, thereby helping to keep the pressure drop lower on the residual dust cake.

There are basically two methods to reduce the air to cloth ratio—lowering the cfm of air or increasing the filter cloth area. However, in overall dust collection system design, changing the airflow volume can be impractical. Therefore, increasing the filter cloth area is more common.

In addition to the air to cloth ratio, inlet loading can also affect the method used for cleaning the bags. Since virtually all filter materials work better with a consistent filter cake to optimize collection efficiency, varying the duration of the cleaning cycle, in conjunction with the rest period between cycles, will allow the operator to maintain a consistent filter cake. This is manifested by a low variation in pressure drop across the filter media. This approach is called “on-demand” cleaning. Bag cleaning is initiated at a predetermined high pressure drop and stops when the pressure drop reaches a predetermined low set point. This method ensures that the bags always have a sufficient amount of dust cake. Experience and manufacturers’ recommendations are the best means of determining the optimum cleaning cycle for each system.

There are three techniques used with baghouse collectors to clean the dust cake from the filter media. These techniques are accomplished by mechanical shaker collectors, reverse air collectors, and pulse jet collectors.

Mechanical Shaker Collectors

Mechanical shakers use a mechanical rapping device to remove the excess dust cake; however, the airflow through the collector must be temporarily stopped to clean the bags. These shakers involve low maintenance and low operating costs, but they require large amounts of space, have limited design flexibility, and have low air to cloth ratios (2:1).

Shaker collectors employ tubular filter bags fastened on the bottom and suspended from a shaker mechanism at the top. Dust-laden air enters the collector and is deposited on the outside of the tubular bags. Continuous processes use compartmentalized collectors where airflow can be diverted to other compartments during the bag cleaning cycle (Figure 2.18). Bag materials must be made from woven fabrics such as cotton to withstand shaking.

Some shaker collectors have been converted to pulse jet collectors. However, this is an expensive operation and should not be necessary if the collector is properly maintained.

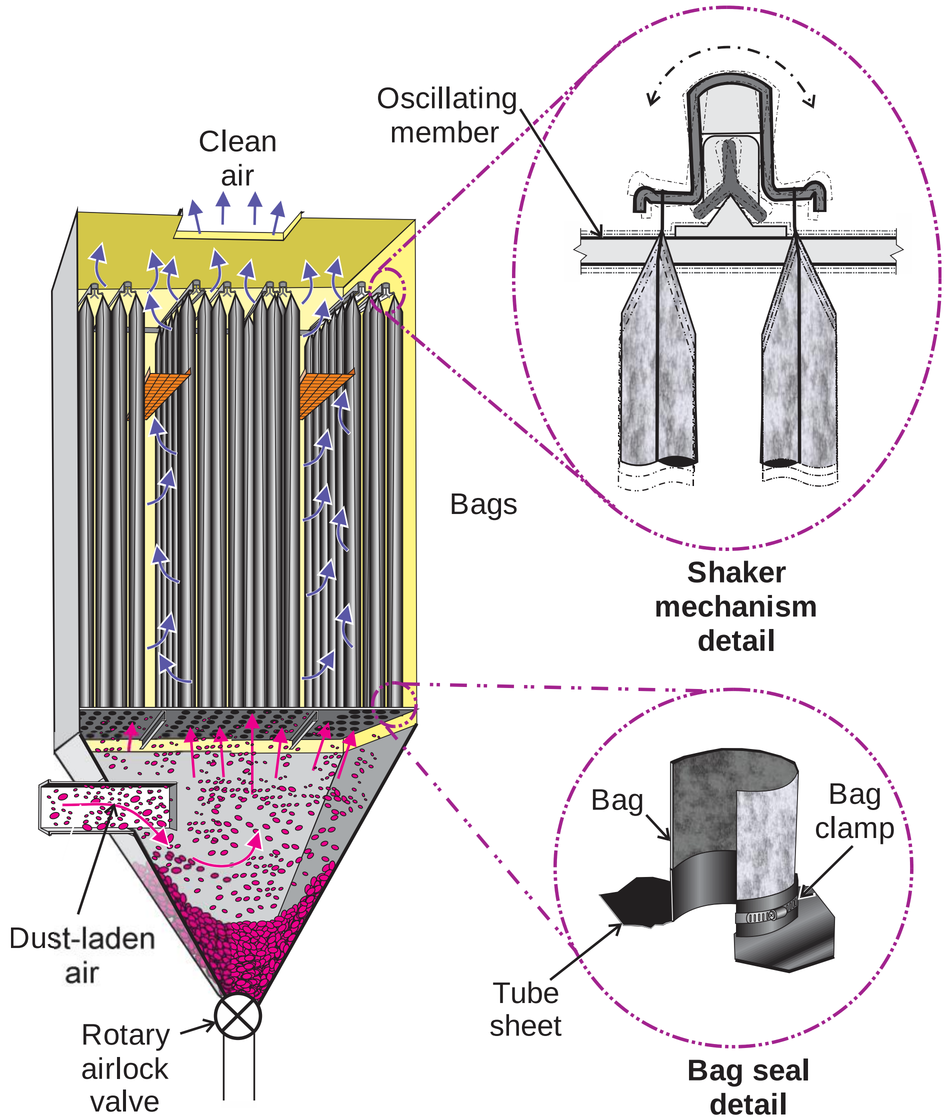


Figure 2.18. Illustration with cutaways showing a typical design of a mechanical shaker dust collector.

When using mechanical shakers, a number of recommendations should be followed:

1. Manometer gauges should be installed on each compartment to monitor differential pressures during the cleaning cycles.
2. Differential pressures should be as close as possible to 0.0-inch wg to ensure that the dust cake breaks and is released from the bags. Differential pressures above 1/4-inch wg during the cleaning cycle will dramatically interfere with bag reconditioning, which can lead to reduced airflow, high static pressures, and low bag life.
3. Bags should only be shaken when differential pressures across a section of bags have increased by 1/2-inch wg.
4. Experiments to determine the optimum time interval between the shaking of bags should be performed so that bags are not shaken excessively. This lessens wear on the bags and the mechanical parts.

Reverse Air Collectors

Reverse air collectors use a traveling manifold to distribute low-pressure cleaning air—3–7 pounds-force per square inch gauge (psig)—to the filter bags for reconditioning. They have no compressed air requirements and involve no freezing of air lines. On the negative side, they have larger footprints than conventional collectors and maintaining their cleaning mechanisms is difficult. They also perform poorly in corrosive environments.

Reverse air collectors employ tubular bags fastened onto a cell plate on the bottom and suspended from the top of the collector. The collectors must be compartmentalized for continuous service. Dust-laden air enters the collector and deposits dust on the outside of the bags. Before a cleaning cycle begins, filtration in the compartment to be cleaned is suspended. Bags are cleaned by blowing low-pressure air into the compartment in the reverse direction to normal airflow. This causes the bags to partially collapse and release the dust cake. The bags have rings located at various intervals to prevent total collapse so that the dust cake can escape and fall into the hopper (Figure 2.19).

Reverse air collectors were originally developed primarily with fragile glass cloth for use in high-temperature operations. These collectors have declined in popularity with the use of new materials that can withstand high temperatures and greater physical action. Air to cloth ratios for reverse air collectors are similar to those for shakers due to the low bag cleaning efficiency of the reverse air.

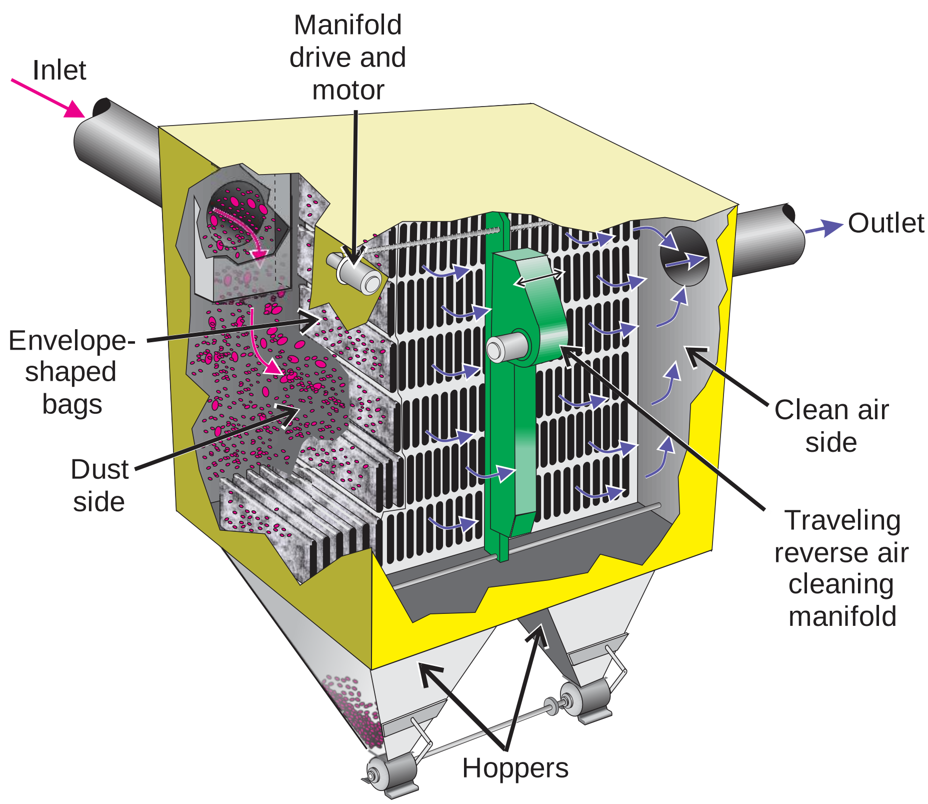


Figure 2.19. Illustration showing a typical design of a reverse air dust collector.

Pulse Jet Collectors

Pulse jet collectors use bags supported from a metal cage fastened onto a tube sheet at the top of the collector (Figure 2.20). Dust-laden air enters the collector and flows from outside to inside the bag. The dust cake deposits on the outside of the bag and is cleaned by short bursts of compressed air injected inside the bag. The burst of air sends a shockwave down the bag causing it to flex, breaking and releasing the dust cake. The compressed air must be clean and dry or moisture can build up on the bags, hindering the bag cleaning efficiency. Pulse jet collectors are not required to be compartmentalized, which allows for continuous bag reconditioning without process upset.

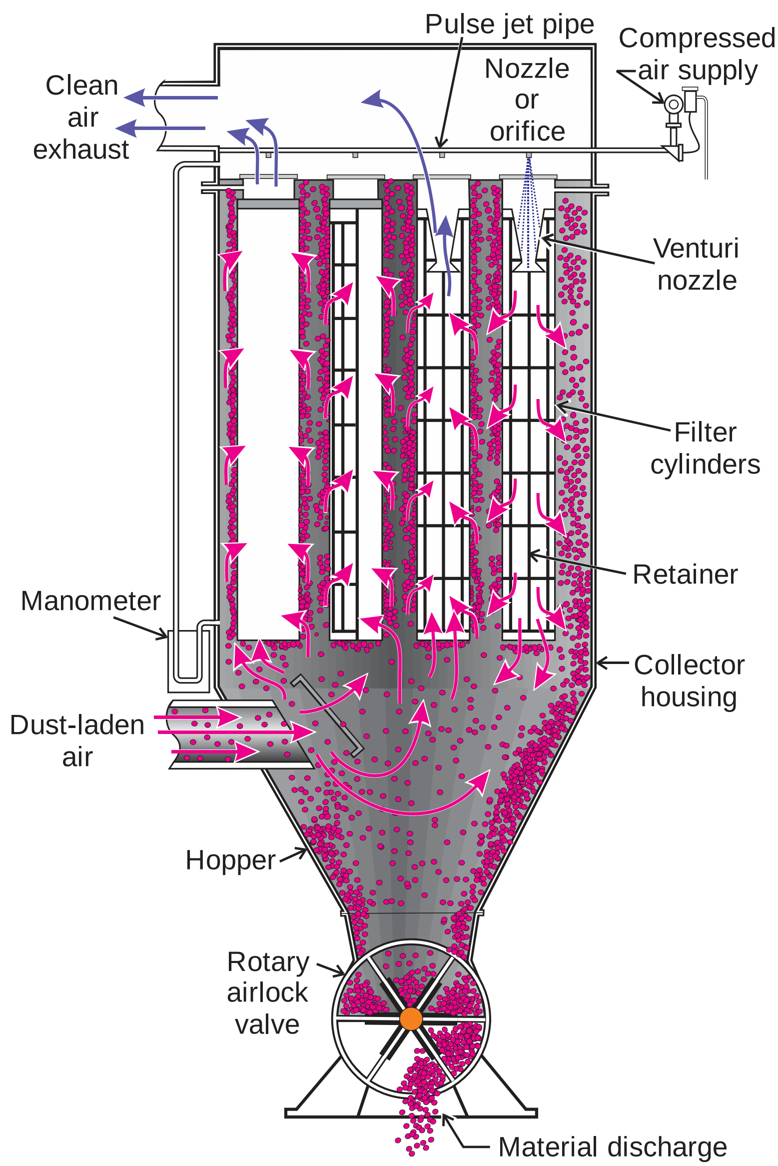


Figure 2.20. Illustration of a typical design of a pulse jet dust collector.

Pulse jet collectors are the most common type of baghouse and have been in use since the late 1950s. Pulse jet collectors use a pulse of compressed air (60–90 psig) for filter conditioning. The pulses are triggered based on differential pressure between the clean and dirty air plenums.

Adequate compressed air volume, pressure, and quality are critical for cleaning pulse jet collectors. For suitable volume and pressure, the design must accommodate for periodic demand usage on each baghouse without interruption. Typical best practice installations have demand storage or small receiver tanks incorporated into the design to ensure that a proper amount and pressure of the cleaning cycle air is delivered to the baghouse for each cycle. In some instances, it is necessary to have an independent storage to ensure proper function even during loss of electrical power.

Compressed air quality standards according to the International Organization for Standardization (ISO) 8573 [ISO 2017] are also critical in order to maintain expected moisture and oil contaminations. Foreign fluids can cause loss of function involving caking and fabric deterioration. Class 2 or 3 ISO 8573 are typical relevant design standards for pulse jet collectors.

Reconditioning or cleaning of the filter bags allows the dust collection system to maintain pressure drops and operate at designed airflows. The advantage of using pulse jet collectors is high product recovery and high collection efficiency. They also enjoy high flexibility of application with many inlet design options. Their limitation is that their performance varies with temperature and moisture.

Due to more frequent cleaning intervals, these collectors provide more complete bag cleaning than the previously discussed collector styles. Thus, the air to cloth ratios can be higher—typically, suppliers specify air to cloth ratios of 6:1 or higher. However, ratios of 4:1 should be used for applications involving abrasive minerals. High air to cloth ratios can cause high air velocity impingement on the bags, resulting in dust re-entrainment on neighboring bags after cleaning and low bag life.

Bags are typically made from nonwoven felt or polyester material. Woven materials are not used in pulse jet collectors because they require a buildup of a permanent dust layer to provide efficient air cleaning. Since pulse jet collectors aggressively clean the bags, excessive penetration of dust particles through the woven fabric can occur. Pleated bags can also be installed in place of traditional cylindrical bags. Pleated bags can offer higher cloth area in the same space as a traditional bag but at a higher initial cost.

Pulse jet collectors are more cost effective than collector styles discussed previously such as mechanical shaker collectors. They can operate with higher air to cloth ratios, have no moving parts to maintain, and involve lower capital costs.

Cartridge Collectors

Cartridge collectors capture particulate from an air stream by forcing the air through filter canisters in which the filter media is fabricated in a pleated configuration. There are two basic configurations of cartridge collectors: those that suspend the filter canisters vertically and those that are mounted horizontally (Figure 2.21).

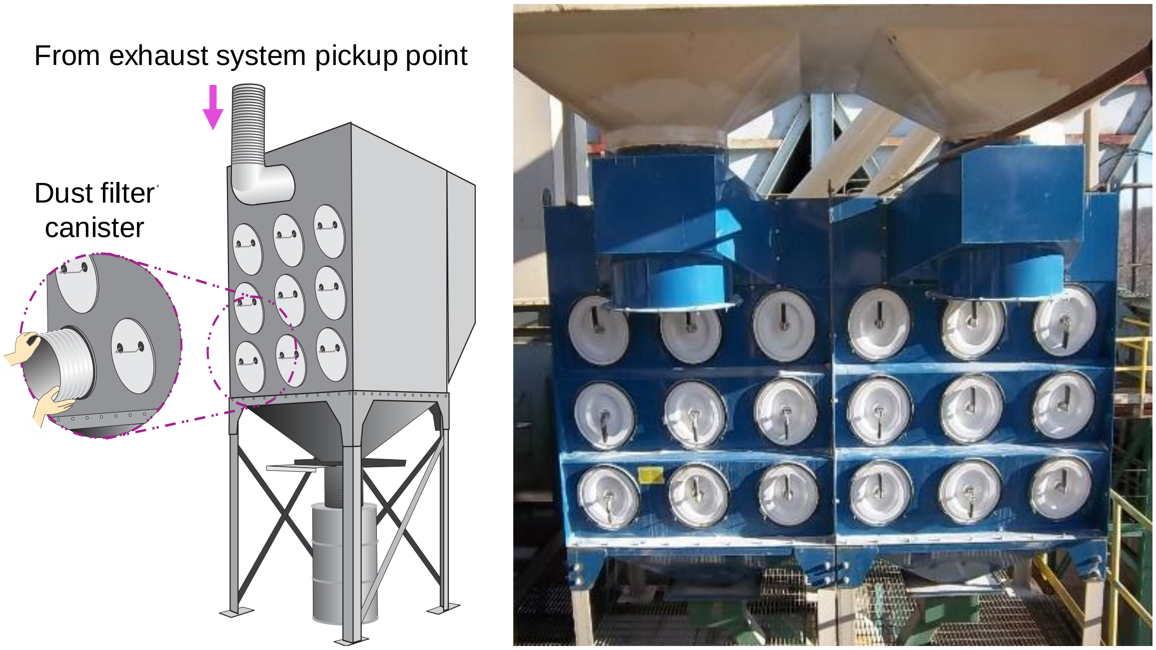


Photo by NIOSH

Figure 2.21. Cartridge collector with dust filter canisters. The left illustration shows a cutaway of a canister being replaced. The photo on the right shows a cartridge collector with the canisters mounted horizontally.

Cartridge collectors are the latest generation of fabric collector. Unlike other fabric collectors in which the filtering media are woven or felt bags, this type of collector employs cartridges that contain a pleated filtering media. The pleated cartridges can be made from a variety of media, including polyester or synthetic material. Due to the pleated design, the total filtering surface area is greater than with conventional bags of the same diameter. However, the pleated design cartridges produce very high approach velocities and therefore greater re-entrainment onto the cartridge can occur. Filtration velocities are therefore limited to air to cloth ratios of less than 2:1.

The cartridge filter works like the pulse jet or shaker baghouse collector in that dust is collected on the outside of the filter elements. Either a pulse of compressed air or a mechanical shaking mechanism is used to remove the excess collected material from the filters. Cartridge collectors involve lower capital costs than a baghouse because the cartridges have more area than bags, and therefore fewer are required. Cartridge collectors have lower headroom requirements, because the cartridges are inserted from the side of the unit as opposed to the top. Cartridges are shorter than bags, and there are fewer of them. Media can also be changed rapidly, facilitating a higher level of maintenance. Limitations to cartridge collectors include a lack of flexibility based on extreme temperature and moisture applications, since there are not as many varieties of filter fabrics available as there are for baghouses. Because of the high filter area per unit and the pleated design, media replacement costs are high on a per-cartridge basis.

The main advantages of cartridge collectors are the compact design and ease of cartridge changing, resulting in reduced dust exposure to workers. New cartridges are packaged in a cardboard box, and to change cartridges, the worker simply removes the new cartridge from the box, extracts the used cartridge and places it in the box, and then installs the new cartridge, with minimal dust exposure to the worker. In practice, the cartridges can have a two-year life in abrasive applications. However, choosing this type of collector may require the user to purchase cartridges from the equipment supplier, reducing a competitive pricing advantage.

It should be noted that cartridge collectors do not work well with moist or sticky materials, and they are generally restricted to applications with temperatures less than 180ºF. The inlet loading is typically lower than with bags because, with the pleated design, the cartridges do not clean as well. In addition, the horizontal alignment of the cartridges allows dust from the cartridges above to fall on the cartridges below during cleaning.

Electrostatic Precipitators (ESPs)

Electrostatic precipitators (ESPs) are particulate control devices that use electrical forces to move particles from the air stream to collection plates. Particles passing through the precipitator are given a negative electrical charge by being forced to pass through a region, called a corona, in which gas ions flow. Once the particle has been negatively charged, it is forced to the positively charged plate. Particles are removed from the plate by knocking action.

There are four basic types of ESPs: plate and wire (dry), flat plate (dry), wet, and two-stage. Electrostatic precipitators normally have a higher initial cost than local exhaust ventilation systems, but have a number of advantages that make them worth considering. ESPs provide a large air volume, operate favorably in various temperatures, and require little maintenance because there are no moving parts. The installation time and costs are also lower than for a local exhaust ventilation system. Another advantage is that the product is easily recovered and recycled right back into the process.

The limitations of ESPs include their physical size, operation expenses, and inconsistent collection efficiencies. A more thorough discussion of electrostatic precipitators, including distinctions between single-stage and two-stage types, is available in the ACGIH handbook [ACGIH 2010].

Wet Scrubbers

Wet scrubbers accomplish particulate collection by employing water or another liquid as the collection media. There are many scrubber designs, but most particulate scrubbers work by creating a wetted target for particle collection. This wetted target plate can be a bed of water or a zone where the particle and water droplet collide (Figure 2.22). Benefits of wet scrubbers are their ability to perform in various moisture and temperature conditions, their resistance to chemical corrosion, and their low maintenance needs. However, wet scrubbers require a significant amount of water, which must be disposed of along with the collected particulate. This lowers the collection efficiency and increases the energy costs. Settling ponds are one common method of collected particulate disposal in the mineral processing industry, and the water from these ponds can often be reused within the operation.

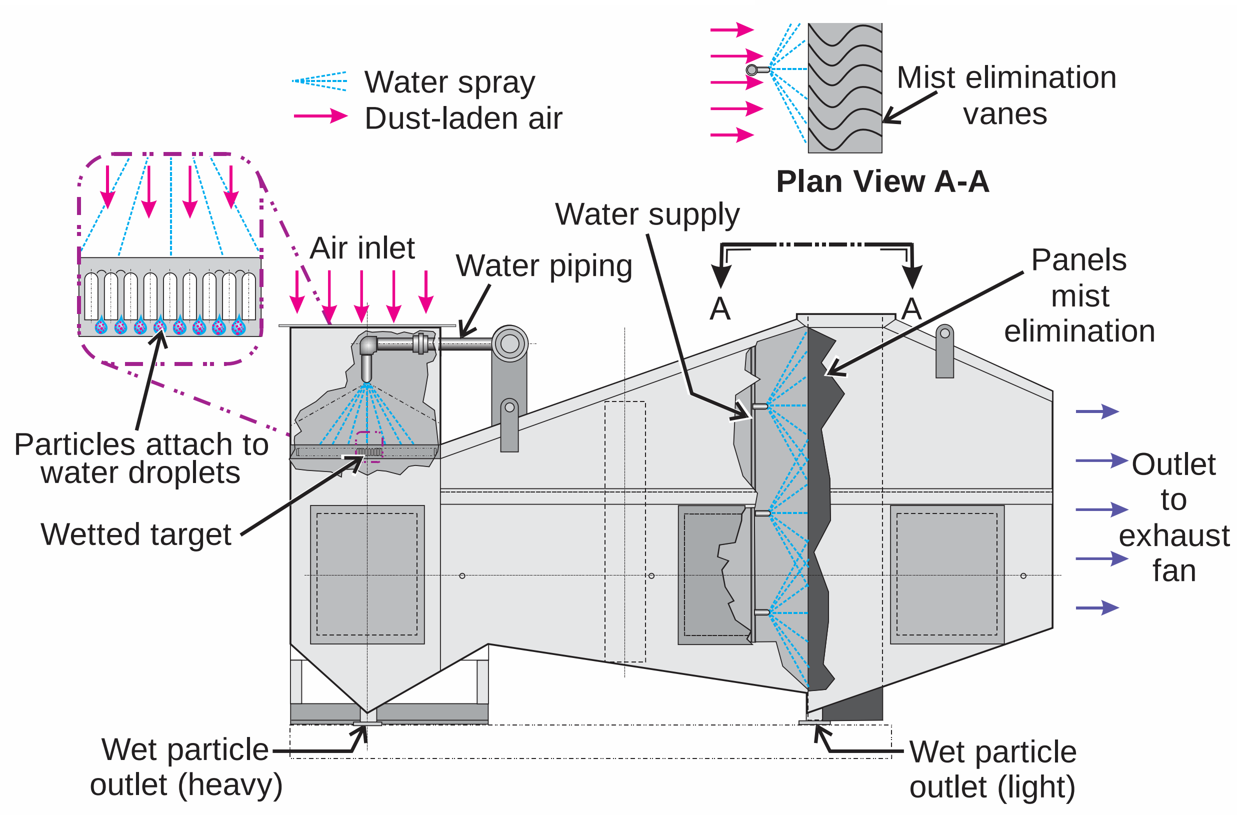


Figure 2.22. Illustration showing a typical design of a wet scrubber dust collector.

The air cleaning efficiency of this type of collector primarily depends on its pressure drop. Scrubbers with high differential pressures have higher air cleaning efficiencies than scrubbers with lower differential pressures. These pressures range from 1 to over 15 inches wg. The style of scrubber chosen for a particular application depends on the air cleaning required, the dust loading, and the particle sizes involved.

Wet scrubbers are particularly advantageous when handling moist hot gases. Problems such as bag blinding and condensation can arise when fabric collectors are used to clean moist hot gases. These problems are eliminated when using scrubbers. However, wet scrubbers discharge contaminated water, which requires further treatment in a settling pond or sewage system.

Venturi Scrubbers

Venturi scrubbers are a type of wet scrubber and consist of a venturi-shaped inlet and a separator (Figure 2.23). Dust-laden air is accelerated to velocities between 12,000 and 36,000 fpm in the throat of the venturi. These high velocities atomize the coarse water spray and create pressure drops ranging from 5 to over 15 inches wg. The venturi can be ceramic-lined for abrasive applications. The extreme turbulence promotes collision between water droplets and dust particles in the throat of the venturi. An inertial separator then removes these agglomerates.

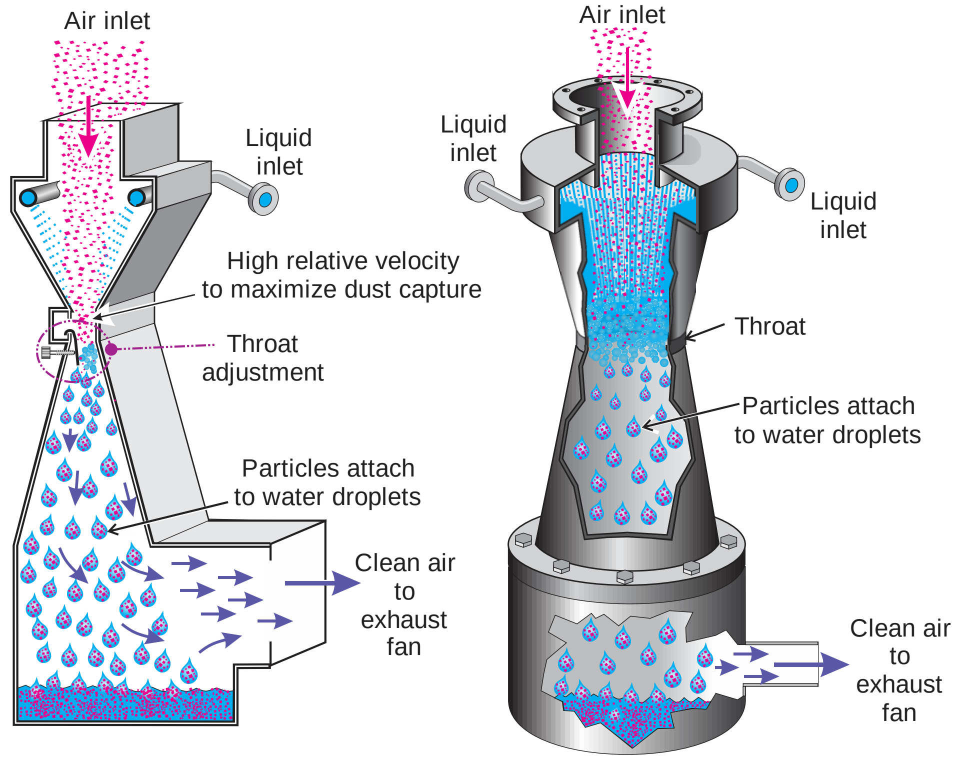


Figure 2.23. Illustration of typical designs for a venturi scrubber.

Impingement Plate Scrubbers

In another type of wet scrubber—an impingement plate scrubber (Figure 2.24)—the exhaust passes upward through openings in perforated plates, which hold a layer of water. An impingement baffle is located above each hole, resulting in the formation of small droplets. Intimate gas/liquid contact results in efficient particle collection. A pressure drop of 4 inches wg is typical.

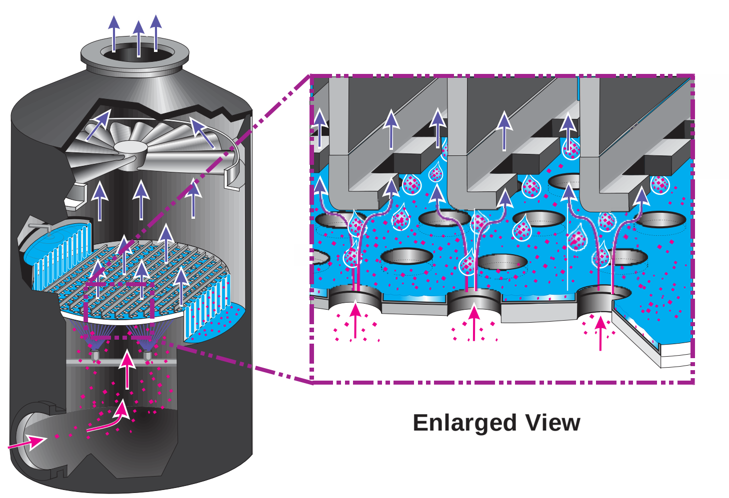


Figure 2.24. Illustration showing a typical design of an impingement plate scrubber.

Spray Tower Scrubbers

Gravity spray tower scrubbers employ atomized water, which falls counter-current through a rising dust-laden air stream, to remove dust particles. These scrubbers are generally of lower efficiency and operate at pressures of 1 to 2 inches wg. They are approximately 70 percent efficient on 10-µm particles and above with poor efficiency on particles smaller than 10 µm. However, they are capable of treating high dust concentrations without becoming plugged.

Wet Cyclone Scrubbers

Similar to a dry cyclone, wet cyclone scrubbers use centrifugal forces to throw particles on the collector's wetted walls. Water is introduced from the top of the scrubber to wet the walls and wash the particles away. Pressure drops for these collectors range from 2 to 8 inches wg with good efficiency for removing particles 5 µm and larger.

COLLECTOR DISCHARGE DEVICES

The dust collected in a baghouse falls into a hopper below the bags. This hopper must have a discharge device that not only releases the accumulated dust but also ensures a seal between the baghouse and outside air to maintain negative pressure within the unit. Common hopper waste discharge devices available for baghouses are the rotary airlock valve, double dump valve (flap valve), tilt valve, and vacuum valve (dribble valve). Each of these is readily available in various designs from several manufacturers.

Rotary Airlock Valves

A rotary airlock consists of a rotating shaft with several vanes attached to it (Figure 2.20, bottom). That assembly rotates slowly inside a housing, allowing each compartment between vanes to fill and discharge material. Rotary airlocks are a very common baghouse discharge control device. However, they can pose maintenance challenges with abrasive materials in that the vanes of the airlock can wear without any external indication of a problem. This can lead to poor performance, and maintenance costs can be high in abrasive applications.

Double Dump Valves

Double dump valves are dual flapper valves mounted in tandem off the discharge of the baghouse and can be either automated or weight-based. For automated double dump valves, an automated rotating cam or pneumatic cylinder briefly opens the normally closed spring-loaded door to each valve. The dual valves are opened individually in a sequence that allows the top door to open, dump, and close before the lower door follows the same sequence. This allows negative pressure to be maintained in the discharge hopper. The weight-based valve is very similar except that the valve opens based upon the weight of the product and not on an automated basis (Figure 2.25). Both types of double dump valves require sufficient vertical room below the baghouse hopper. Double dumps can be wear-protected well for long life with abrasive materials; however, the mechanical components of the rotating cam tend to require more maintenance.

Photo by Unimin

Figure 2.25. Double dump weight-based valves.

Tilt Valves

Tilt valves are similar to double dump valves and are normally used in pairs. These valves commonly have a near horizontal and counterweighted flap door that is adjustable for closed tension. The function of the valve is to allow material to build up on the near horizontal flap gate until it overcomes the pull of the negative pressure in the baghouse. The material then dumps to the next valve as the gate shuts behind it. Typically, a divider chute 24–30 inches long is used between the two valves to allow one valve to close completely before the other opens.

Tilt valves are less expensive than double dump and rotary valves, but can be hard to adjust. They have been known to stick open after being in service for a period of time, and they require four feet of clearance below the baghouse for installation.

Vacuum or Dribble Valves

A vacuum valve basically consists of a soft gum rubber tube mounted in a steel housing, which attaches to the bottom of a baghouse hopper discharge. Manufacturers have various designs available for purchase, some using a “fishtail” dribble bladder mounted inside a flanged pipe. The valve uses the negative pressure of the hopper to collapse the rubber tube and seal the discharge until sufficient material builds up and “dribbles” through. This valve normally has low initial cost, high reliability, and low maintenance, and it can fit in a short discharge space.

FILTER FABRICS

The majority of development work that has been done in the industry over the last 10 years has not been in the area of the collector itself but in filter fabrics. Some of these fabrics have been designed to handle the more challenging applications. Problems that particular fabrics address may be related to specific applications, or the fabrics may simply provide a more efficient way of optimizing the collector's potential.[18] A wider variety of filter fabrics are now available, giving the design engineer more options to address the problem.

One of the most critical aspects to any dust collector device is the filter fabric's ability to remove the dust particles from the air stream as the dust-laden air passes through the filter fabric material in the collector. The term "filter fabric" can be used interchangeably with the term "filter media." For use in dust collector devices, there are numerous types of filter fabrics with a wide variety of properties and characteristics produced by different manufacturers. Regardless of this variability, filter fabric effectiveness is fundamentally dependent on the ability to capture or remove dust particles from the air stream. A filter fabric's ability to let air pass through the media (i.e., its permeability) is usually defined as the volume of air that can pass through one square foot of filter fabric each minute at a pressure drop of 0.5 inches wg.

Along with permeability, another measure of a filter fabric's effectiveness is its efficiency at removing dust particles. For instance, a HEPA quality filter is one that is 99.97 percent efficient at removing 0.3-µm particles and above. A practice that is becoming more prevalent in the industry is to refer to a fabric's dust removal efficiency by its minimum efficiency reporting value (MERV) rating (see Table 2.3). As Table 2.3 illustrates, the higher the MERV rating, the more efficient the filter is at capturing the various size ranges of dust particles.

Table 2.3. Minimum efficiency reporting value (MERV) ratings according to ASHRAE Standard 52

Group	MERV Rating	**Average Particle Size Efficiency (PSE)** 0.3–1.0 µm	**Average Particle Size Efficiency (PSE)** 1.0–3.0 µm	**Average Particle Size Efficiency (PSE)** 3.0–10.0 µm
1	1			< 20%
	2			< 20%
	3			< 20%
	4			< 20%
2	5			20–34.9%
	6			35–49.9%
	7			50–69.9%
	8			70–84.9%
3	9		< 50%	≥ 85%
	10		50–64.9%	≥ 85%
	11		65–79.9%	≥ 85%
	12		80–89.9%	≥ 90%
4	13	< 75%	≥ 90%	≥ 90%
	14	75–84.9%	≥ 90%	≥ 90%
	15	85–94.9%	≥ 90%	≥ 90%
	16	≥ 95%	≥ 95%	≥ 95%

[18] For instance, many applications that involve temperature and corrosive dust or gases had been previously handled by using wet scrubbers. However, as emission requirements become more stringent, the use of scrubbers must diminish.

A filter fabric becomes more efficient, or achieves a higher MERV rating, by its ability to capture particles by *interception*, *impaction*, *diffusion*, and *electrostatic charge*. Distinctions among these capture processes are listed below.

- Interception occurs with smaller-sized particles that follow the air stream flow lines and come within one particle radius of a fabric fiber. The particles then adhere to the fabric.
- Impaction occurs with larger particles that are not able to stay on air stream flow contours, traveling through the filter media and then embedding into one of the fibers directly. The amount of impaction increases with higher airflow velocities and with decreasing distances between the fibers.
- Diffusion occurs when the smallest dust particles collide with gas molecules, especially those smaller than 0.1 µm, and then alter their flow path so that they are captured by either interception or impaction.
- With electrostatic collection, the filter fabric is made from a fabric material or media that is able to sustain an electrical charge. Because dust particles also have an electrical charge, as they pass through the filter fabric, they are attracted to and adhere to the fabric material.

Filter fabrics are constructed of either natural or man-made fibrous material and are either woven or nonwoven. Woven fabrics are normally identified by a weight per unit area as well as a thread count. Nonwoven fabrics are also identified by the weight per unit area, but typically include a filter thickness classification. Nonwoven material is usually more efficient than woven fabric of the same thickness because the open areas or pores are smaller. It is important to note that, from a dust collection standpoint, any type of filter fabric can be made more efficient or be given a higher MERV rating simply by the use of smaller fiber diameters, the inclusion of a greater weight of fibers per unit area, or by the fibers being packed more tightly.

With any filter fabric, the efficiency or MERV rating improves as the filter forms a filter dust cake. After the initial collection by one of the methods described above, as particle collection continues, a layer of dust particles forms on the fabric material, and this layer then becomes the principal collection medium. As more dust particles continue to impinge on the previously collected particles, this dust filter cake continues to grow. Over a period of time, this dust filter cake will grow to such an extent that it will become increasingly difficult for the air molecules to pass through the fabric material, and this is evidenced by an increasing pressure differential across the filter. Once this pressure reaches a certain level, the dust filter cake needs to be removed from the filter fabric by some type of mechanical process (such as by a shaker, reverse air, or pulse jet process, as described earlier).

Particulate Collection of Fabrics

There are two methods for collecting particulate on fabrics. The first is *depth loading*. This means that the fabric depends on a filter cake to optimize collection efficiencies. The second is *surface loading*, meaning that the fabric does not depend on a filter cake to obtain maximum collection efficiencies.

Felted fabrics are depth loaded. Polyesters, polypropylene, aramids, and similar fabrics rely on the ability of the dust collection system to develop and maintain a dust cake or filter cake at all times. When considering the depth of loading onto felted fabrics, the filter bag is actually acting as a support for the dust cake. Dust is allowed to penetrate into the fabric to form a layer of dust on the bag. Thus, the dust creates a “porous” cake with much smaller air passages, allowing the dust to filter itself. Without this cake, the filter would bleed through and never obtain acceptable outlet emissions. Therefore, in the design and operation of a baghouse using felted media, it is important to use appropriate air to cloth ratios, cleaning cycles, and cleaning pressures, and to pre-load the filter bags with pre-cake or dust. The optimum collector operation maintains a constant pressure drop of 3–6 inches wg and minimizes cleaning cycles and compressed air usage. This does not mean that a system running higher than a 6-inch pressure drop is not operating satisfactorily. Some systems can operate effectively at higher pressure drops. The system is operating correctly as long as the pressure drop is constant and the required air volume is being achieved.

Surface-loaded media do not require a dust cake to achieve optimum performance. As the name implies, the dust is collected on the very surface of the fabric. Some surface-loaded media use membranes composed of a very thin layer (1 mil) of PTFE (polytetrafluoroethylene) material that is laminated to a substrate. This substrate material is a conventional felt. The laminate is applied in a special process that controls the size of the pore openings; thereby the collection efficiency is predictable. These pore openings are so small that they will only allow extremely small submicron particles to pass, making these fabrics extremely efficient.

Dust collectors using felted media typically run higher pressure drops than those operating with surface-loaded media because the filter or dust cake adds resistance to the system. As previously mentioned, the pressure drop tends to range from 3 to 6 inches wg, while surface-loaded media operating without a filter cake typically run in the 2–4 inches wg range.

The standard fabrics used in shaker collectors are woven cotton and polyester sateens and lightweight felts. Pulse jet and reverse air collectors use felts ranging in weight from 14 to as heavy as 22 ounces. Woven fabrics are not used in the last two types of collectors because the cleaning system is much more aggressive than shaking. Pulsing woven fabrics opens up the weave and causes leakage and undesirable emission levels. Cartridge filters typically use cellulose/synthetic blends and spun-bonded polyester media.

When matching fabric choice to dust collection needs, the basic criteria are temperature, inlet loading, particle size distribution, gas composition, abrasion, static charge, release, and efficiency requirements. The following are some basic guidelines for each criterion.

- *Temperature*. Inlet gas temperature should be matched with a fabric capable of continuous operation at or above the maximum temperature the system might experience.
- *Inlet loading*. Inlet grain loading, which is normally expressed in grains per dry standard cubic feet (gr/dscf), is especially important when the loading is very light. Light loadings can make it difficult for the media to operate with sufficient dust cake.
- *Particle size distribution*. Finer particle size distributions often require using higher-efficiency media.
- *Gas composition.* The designer must make sure that if corrosive compounds or hydrocarbons are present in the air stream, then the media selected will be able to withstand that environment.

- *Abrasion.* When the dust is abrasive, the designer should consider using heavier felt or adding wear cuffs to the bottom of the filter bags on hopper entry inlets.
- *Static charge*. Explosive dusts and gases or dusts that can develop a static charge in the duct system require some type of static grounding. This can come in the form of a braided grounding wire sewn into the filter bag and attached to the tubesheet. Grounding can also be accomplished through the bag material by way of epitropic fibers (using carbon fibers, graphite fibers, or 3–4 percent stainless steel fibers throughout the bag). In these cases, it is important to make sure the bag collar (in top-loaded bags) is fabricated out of the same material so that there is conductivity to ground.
- *Release*. A properly designed dust collector has two functions: the first is to collect the dust; the second is to release the dust off of the filter bag after it is collected. In the case where the dust is oily or sticky, the fabric may require a treatment to the filtering surface in order to aid in the release. This can take the form of modifying the surface with treatments such as singeing or glazing. The filtering surface can also be treated with a coating such as a PTFE bath or even a membrane. There are also specialty fabrics that treat the fiber before the felting process, providing a longer-lasting surface than typical coatings.
- *Efficiency*. Expressed as a ratio of a mass loading (gr/dscf of baghouse outlet air to gr/dscf of baghouse inlet air), the required collection efficiency is determined based on EPA, state, or regional regulations that correspond to the particular plant's allowable discharges to the atmosphere.

DESIGNING MINE/PLANT DUST COLLECTION SYSTEMS

Applying the above principles presented in this chapter for simple systems provides the foundation for designing more complex exhaust ventilation systems. In reality, a complex exhaust ventilation system is actually a number of simple systems combined and pieced together (Figure 2.26). When designing a complex system, the following basic approach should be taken:

1. Consider the layout of the building, equipment, supports, etc.
2. Begin the design at the hood farthest away from the fan.
3. Create a line sketch of the proposed duct system layout (including plan and elevation dimensions), fan location, collector location, and equipment locations, with each branch and section of main on the line sketch numbered or lettered for convenience.
4. Select from an existing design or design an exhaust hood tailored to suit the operation and determine its airflow rate specifications.
5. Create a rough sketch design of the desired hood for each piece of equipment, including orientation and elevation of the outlet.

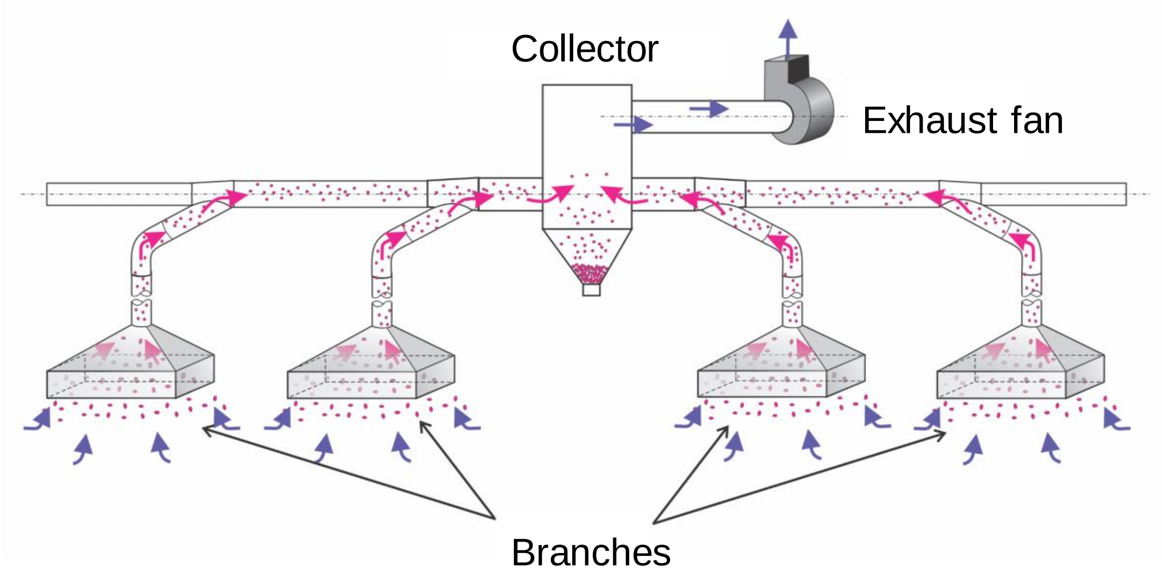


Figure 2.26. Illustration of how a complex exhaust system is a combination of branches linking simple exhaust systems [adapted from ACGIH 2010].

To begin designing a dust control system, the following are some basic preliminary considerations:

- The amount of dust emissions to be collected by a system may be the most important design consideration. Different collector systems possess different capabilities at removing particulate.
- The overall system pressure (total head) helps to determine the type of collector to use. Most fugitive dust applications will have inlet static pressures below 20 inches wg. Standard baghouses and cartridge filters are capable of handling this pressure.
- Some applications require higher system pressures (in some cases, pressures exceed 40 inches wg), and therefore the equipment must be reinforced.
- In most LEVs, square or rectangular dust collector housing designs are adequate; however, in high-pressure systems (> 40 inches wg), cylindrical housings, which are inherently stronger, are used.

Once the entire system is laid out including all the hoods, ductwork, and dust collectors, this information is then used to determine the required fan capacity for the system. Many times, fan manufacturers will provide information and assistance with determining the correct fan and settings.

Clay Application

Particular caution should be exercised in designing a system for any product that contains clay dust. Typically, clay products are dried to 10 percent moisture compared to silica products, which are dried to 0.5 percent moisture or less. The higher moisture content of the clay becomes a significant factor if the conveying air temperature approaches dew point temperature. This will usually occur at the wall of the ductwork or baghouse. The surface of clay particles will become sticky and adhere to any surface contacted. Over a period of time, plugging or blinding will occur. Therefore, additional measures may be required to prevent material buildup, such as insulating additional equipment, installing duct heaters, locating equipment indoors, etc.

FANS

Fans are a critical feature in the design of ventilation systems for dust control. They are used to move the air through the ventilation system, whether to create an exhausting or blowing ventilation system. In an exhausting system, the fan is located at the end or discharge of the ventilation system and is used to “pull” air through the entire system. In a blowing system, the fan is located at the inlet of the ventilation system and is used to “push” air through the entire system [Hartman et al. 1997].

There are different types of fans used in ventilation systems, with their selection being dependent upon their operating characteristics. Several basics of fan operation need to be understood in order to properly select a fan for a ventilation system.

Fan Operating Characteristics

The operating characteristics of the fan are provided by the manufacturer. This information can be in the format of fan performance tables and/or fan performance curves. Fan performance tables provide only the minimum information, i.e., static pressure, airflow, and brake horsepower (BHP) required for selecting a fan [Greenheck Fan Corporation 1999]. Static pressure is based upon the amount of pressure required to overcome the friction loss of the entire ventilation system. Airflow is the amount of air required for the ventilation system. BHP is the horsepower required of the motor to operate the fan at the desired static pressure and airflow.

Fan curves, or performance curves, are graphs that also describe the performance characteristics of the fan. The fan performance curve is provided for a particular model of fan at a given revolutions per minute (RPM). There can be a series of fan performance curves to cover the performance of a selected fan, with each graph representing a different RPM. A typical fan performance curve is in the format shown in Figure 2.27, with static pressure on the y-axis and airflow on the x-axis. Additionally, BHP curves for the fan can be included on the graph, with the BHP scale on a separate scaled y-axis. Information about mechanical efficiency and noise is sometimes included if the manufacturer provides this information [Hartman et al. 1997].

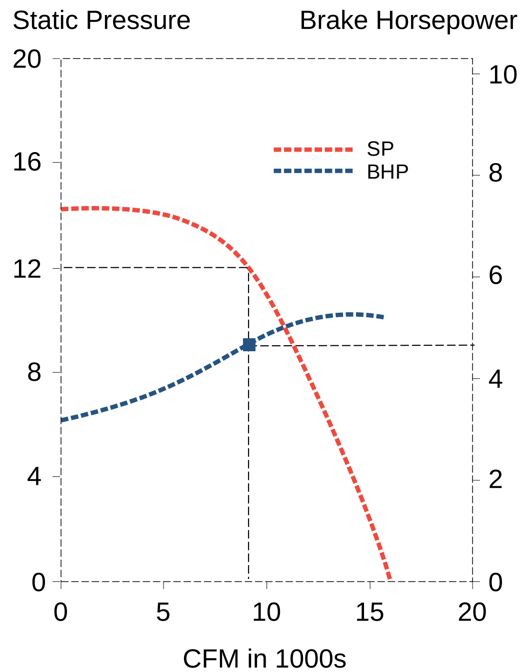


Figure 2.27. Graph of a typical fan performance curve. Each fan curve is associated with a certain fan model at a selected RPM.

Fans are selected based upon the required static pressure and airflow of the ventilation system. It is important that the static pressure and airflow be located in the operating range of the fan curve—*not* in the stalling range of the curve. Figure 2.28 shows a graph presenting the operating and stalling ranges for the fan curve.

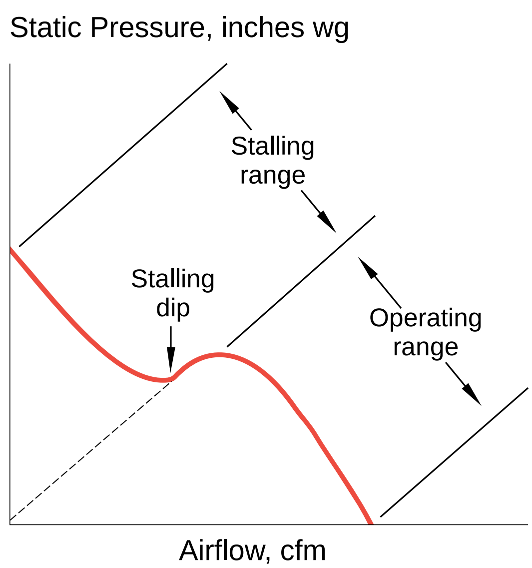


Figure 2.28. Graph of a fan performance curve showing stalling and operating ranges.

When the fan operates in the operating range, the airflow passes through the blades smoothly and quietly without any eddies. Once the static pressure and airflow are located in the operating range of the fan curve, the BHP of the motor required to operate the fan at this condition can be determined from the graph. If the static pressure and airflow are located in the stalling range of the fan, it will not operate correctly, operating in a condition known as aerodynamic stall. Stall occurs when the airflow and resulting air velocity become so low that the airflow is not able to follow the designed contours of the fan blade. The blades throw the approaching inlet air outward to produce high static pressures with low airflows, which creates high turbulence and eddies. Thus, the fan will operate noisily and with low efficiency due to the air turbulence and eddies caused by this condition [Bleier 1998].

Fan Laws

Several equations can be used to determine the effects to airflow, static pressure, and BHP from changes in RPM. These simplified equations are the general fan laws and are applicable as long as fan diameter and air density are constant [Bleier 1998]. The laws are represented in the following way.

$$\frac{CFM_2}{CFM_1} = \frac{RPM_2}{RPM_1} \tag{2.9}$$

$$\frac{SP_2}{SP_1} = \left(\frac{RPM_2}{RPM_1}\right)^2 \tag{2.10}$$

$$\frac{BHP_2}{BHP_1} = \left(\frac{RPM_2}{RPM_1}\right)^3 \tag{2.11}$$

$$N_2 - N_1 = 50 \log_{10} \frac{BHP_2}{BHP_1} \tag{2.12}$$

where *RPM* = speed of fan, revolutions per minute;
CFM = airflow, cfm;
SP = static pressure (this can be for total, velocity, or static pressure as long as the pressures used are consistent—i.e., all total, all velocity, or all static pressure);
BHP = horsepower (this can be for air, total horsepower, or brake horsepower as long as the horsepower used is consistent); and
N = noise level, decibels.

The subscripts represent the different fan characteristics—i.e., 1 for the original fan characteristics and 2 for the new/modified characteristics. There are also equations that can account for changes in fan diameter and air density, but these are beyond the scope of this chapter [Hartman et al. 1997]. Further information on changes in fan diameter and air density can be found by reviewing the references Bleier [1998] and Hartman et al. [1997].

Fan Types

There are two basic types of fans: axial-flow fans and centrifugal fans. There are also other fan designs that use or combine the concepts of axial or centrifugal flow; these are axial-centrifugal fans and roof ventilators. Again, the selection of the fan type is based upon the requirements of the ventilation system design.

Axial-Flow Fans

The axial-flow fan category includes propeller fans, tubeaxial fans, vaneaxial fans, and two-stage axial-flow fans. Axial-flow fans move the air in a direction that is "axial," or parallel, to the axis of rotation of the fan. Propeller fans are the most common type. They are generally mounted in the wall of the building near a heat source to exhaust the hot air into the outside atmosphere (Figure 2.29). They can have different drive configurations, being either direct drive or belt drive. The wall-mounted fans can also be constructed with shutters that close when the fan is turned off. The fans for this purpose can be either wall-mounted or pedestal-mounted. Propeller fans are designed to move large volumes of air at low static pressures [Bleier 1998].

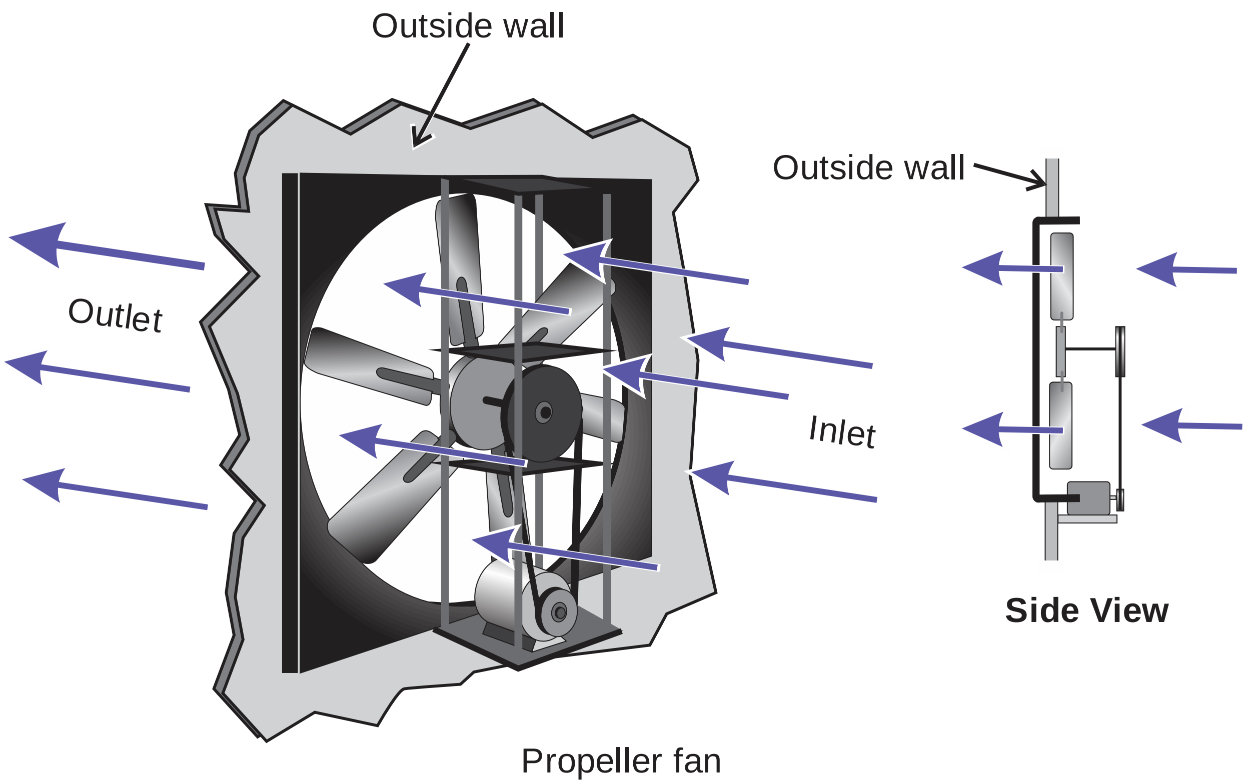


Figure 2.29. Illustration of a wall-mounted propeller fan.

Tubeaxial fans are used for exhausting air from an inlet duct (Figure 2.30, left). They consist of a fan with many blades in a cylindrical housing. The blades are generally shaped as an airfoil to help with air movement. The hub diameter can be 30 to 50 percent of the blade outside diameter [Bleier 1998]. The housing is connected to the inlet duct and also contains the motor support. These fans are used in conditions that require moderate static pressures (higher than those required for propeller fans).

Vaneaxial fans are similar to tubeaxial fans. The vaneaxial fan has a housing that contains guide vanes that are oriented parallel to the airflow (Figure 2.30, right). These vanes are used to recover the tangential airflow velocity from the fan blade to convert it into static pressure. This tangential airflow velocity is not recovered as static pressure in propeller or tubeaxial fans (this component is lost energy). The hub diameter of a vaneaxial fan is much larger, being 50 to 80 percent of the blade outside diameter [Bleier 1998]. The vaneaxial fan is used for conditions involving high static pressure.

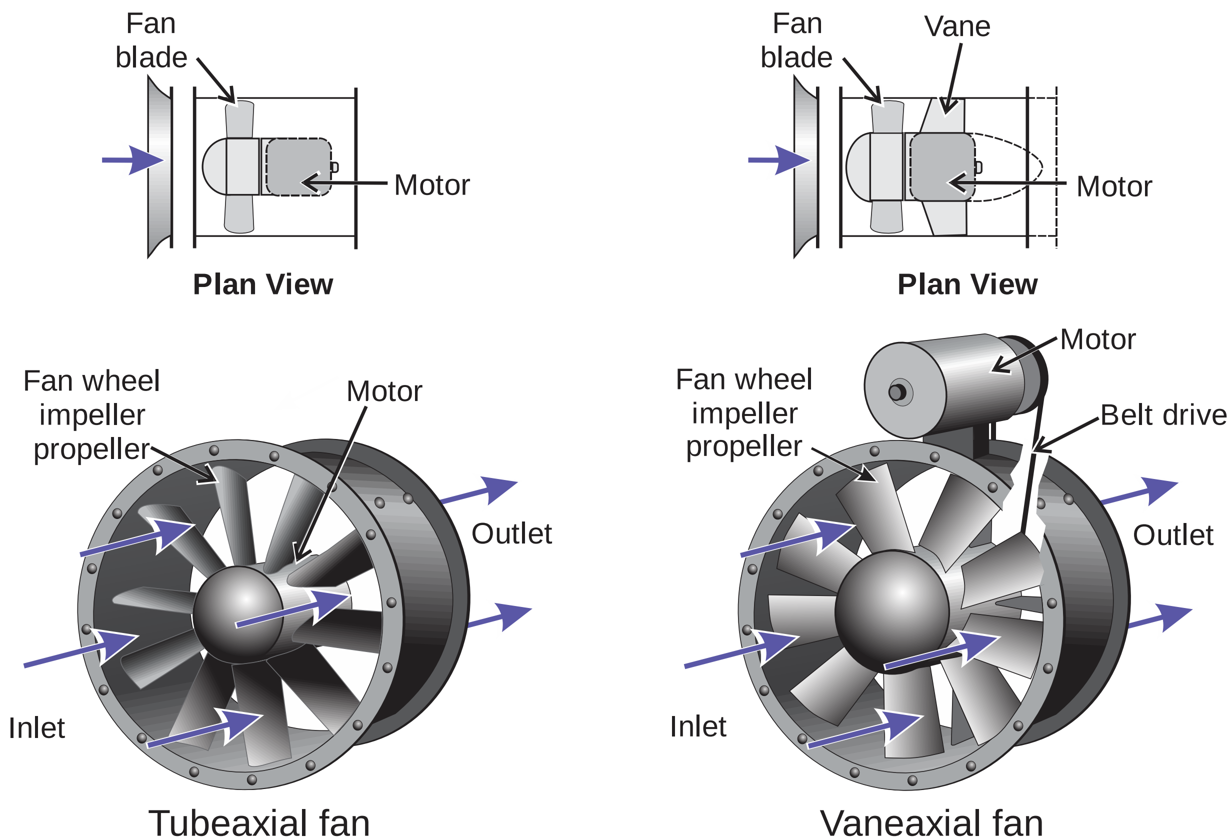


Figure 2.30. Illustration of a typical tubeaxial fan (left) and vaneaxial fan (right).

Two-stage axial-flow fans are basically two axial-flow fans configured in series. This configuration allows for operation in conditions involving high static pressure, as each fan's operating pressure is added together when in series. This fan can be designed to have each fan rotate in the same direction with guide vanes located between each of the fans, or the fans may counter-rotate.

Centrifugal Fans

The airflow for a centrifugal fan is different from that of axial-flow fans. For a centrifugal fan, the airflow is drawn into a rotating impeller and discharged radially from the fan blade into a housing. The resulting flow of air is perpendicular to the axial rotation, or parallel to blade motion [Hartman et al.1997], and the housing is used to direct the airflow to the desired location (Figure 2.31).

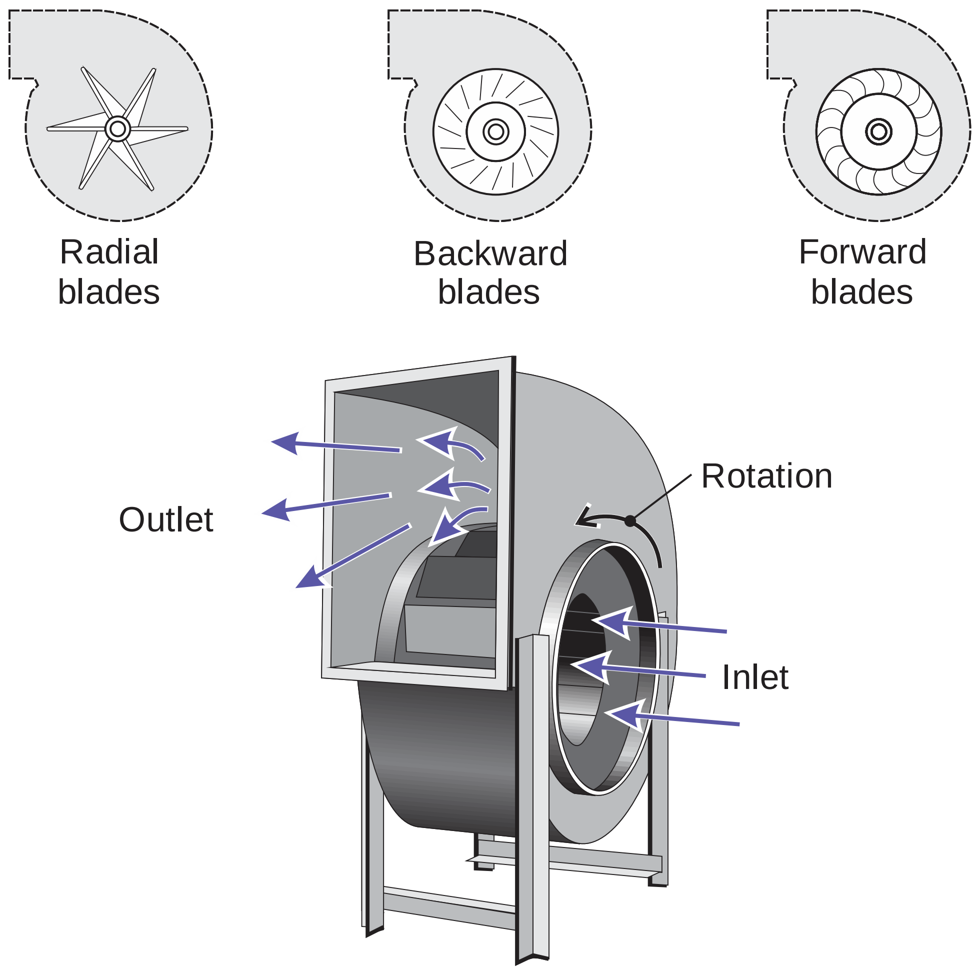


Figure 2.31. Illustration of a typical centrifugal fan.

There are numerous types of centrifugal fans. The flow through the fan is basically the same for all types, the difference being in the configuration of the blades. Each blade type has its advantages for different applications, as detailed below.

- *Airfoil blades* have the best mechanical efficiency and lowest noise level.
- *Backward curved blades* have slightly lower efficiencies compared to airfoil blades. These blades are better suited to handle contaminated air because they are single thickness and can be made of heavier material that can resist the effects of contaminated air on the fan blades.
- *Backward inclined blades* have lower structural strength and efficiencies. They are easier to produce due to the elimination of the blade curvature.

- *Radial tip blades* are curved at the tips. These types are used mainly in large diameters (30 to 60 inches) under severe conditions of high temperatures with minimal air contamination [Bleier 1998].
- *Forward curved blades* produce airflow rates higher than other centrifugal fans of the same size and speed. This allows for the fan to be more compact than other types of centrifugal fans. These fans are often used in furnaces, air conditioners, and electronic equipment cooling.
- *Radial blades* are rugged and self-cleaning but have low efficiencies. They are suited for airflows containing corrosive fumes and abrasive material from grinding operations.

Other Fan Types

Axial-centrifugal fans, also called tubular centrifugal or in-line centrifugal fans, use a centrifugal fan to move air in an in-line configuration. To accomplish this, the air flows into the inlet and makes a 90-degree turn at the fan blade, travels radially along the blade, and makes another 90-degree turn at the tip in order to flow out the outlet (Figure 2.32). These fans are easily installed in-line with the ductwork, and they produce more static pressure than vaneaxial fans of the same fan diameter and speed. However, their mechanical efficiency is lower than that of vaneaxial fans due to the two 90-degree turns required of the airflow.

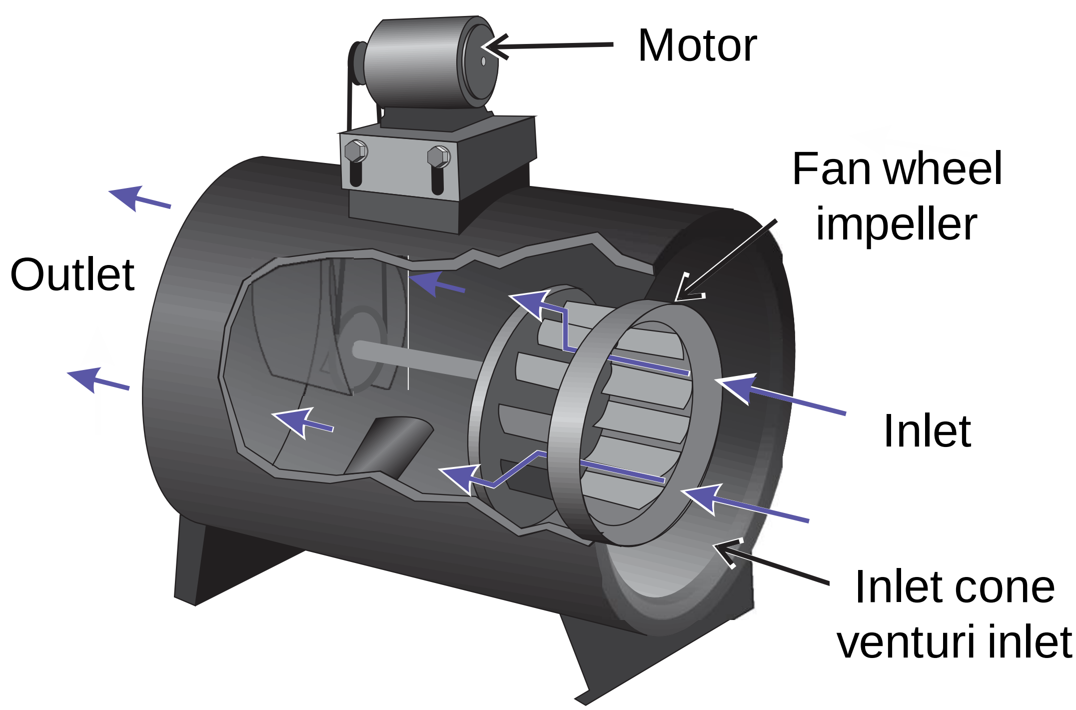


Figure 2.32. Illustration of an axial centrifugal fan showing airflow [adapted from Bleier 1998].

Roof Ventilators

Roof ventilators use either axial or centrifugal fans in their configuration (Figure 2.33). They are generally installed in the roof of the building and are an integral part of total structure ventilation design, as described in Chapter 9—Controls for Secondary Sources. Most roof ventilators are used for exhausting air from the building, creating an updraft throughout the building. However, they can also be used for supplying clean air by blowing it down into the building by creating a downdraft if required by the ventilation design. The exhaust discharge can be radial or upblast, with upblast used mainly for air laden with oil/grease or dust. Roof ventilators using axial fans generally do not require ductwork. However, those using centrifugal fans in their units may require some ductwork.

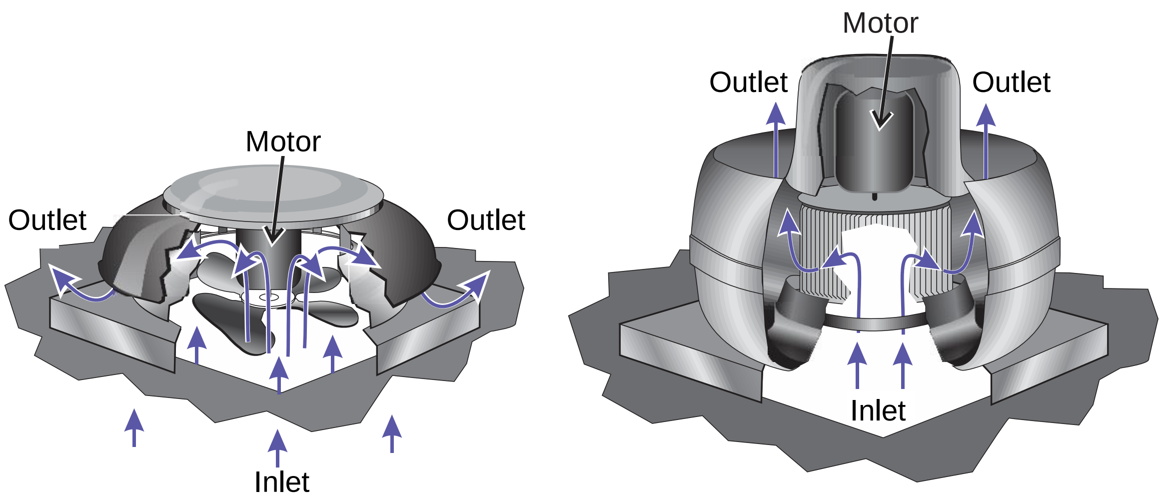


Figure 2.33. Illustration of typical roof ventilators using axial fans (left) and centrifugal fans (right).

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Chapter 3: Wet Spray Systems

CHAPTER 3: WET SPRAY SYSTEMS

Probably the oldest and most often used method of dust control at mining and mineral processing operations is the use of wet spray systems. In essence, as the fines are wetted each dust particle's weight increases, thus decreasing its ability to become airborne. As groups of particles become heavier, it becomes more difficult for the surrounding air to carry them off. The keys to effective wet spray dust control are proper application of moisture, careful nozzle location, controlling droplet size, choosing the best spray pattern and spray nozzle type, and proper maintenance of equipment. Another secondary benefit in some engineering control applications is the ability of wet sprays to also move air via the air induction principle and act as fans to move the dust-laden air in a specific direction away from workers or the work environment.

In the vast majority of cases for mining and mineral processing operations, the wet spray system uses water sprays. Wet spray systems can also use other sprayed liquids, such as surfactant solutions to reduce the surface tension of the liquid droplets, solutions containing anti-freezing agents for applications in extremely cold environments, and more viscous liquid solutions that dry to create a film over dust-laden surfaces to prevent dust from becoming airborne. However, the majority of wet spray systems discussed in this chapter use water as the sprayed media.

Although the use of water sprays is a very simple technique, a number of factors should be evaluated to determine the most effective design for a particular application. The following two methods are used to control dust using wet sprays at mining and mineral processing operations.

- Airborne dust prevention, achieved by direct spraying of the ore to prevent dust from becoming airborne. The goal is to increase the moisture content of the ore, typically while it is being conveyed, in an effort to prevent airborne dust generation as the ore is transferred to another conveyor, stockpile, or transport vessel or vehicle.
- Airborne dust suppression, which involves knocking down dust already airborne by spraying the dust cloud with like-sized droplets at the point of dust generation. This causes the particles to collide, agglomerate, and fall out from the air because of their increased mass. Dust suppression is designed to only wet the airborne dust and not the ore.

Most operations will use a combination of both of these methods at various application points in the overall dust control plan.

PRINCIPLES OF WET SPRAY SYSTEMS

To use wet sprays effectively, it must be remembered that each ore type and application point is unique and needs to be evaluated separately to achieve the optimal design. For example, wet sprays cannot be used with all ores, especially those that have higher concentrations of clay or shale. These minerals tend to cause screens to blind and chutes to clog, even at low moisture percentages. Also, water cannot be used at all times throughout the year in various climates where low temperatures may cause freezing.

Water Application

When water sprays are used to control dust, the water has only a limited residual effect due to evaporation and will need to be reapplied at various points throughout the process to remain effective. Overapplication in the amount/volume of moisture can be a problem in all operations and may impact the equipment as well as the total process and transportability of the final product if shipped in bulk. In most cases, a properly designed suppression spray system using finely atomized water sprays will not exceed 0.1 percent moisture application [USBM 1987]; however, in systems that address prevention over larger areas with plain water, larger droplet sprays may add up to 5 percent moisture to the process [Swinderman et al. 2009]. These types of systems use a greater amount of water because they are designed to increase the moisture content of the ore by spraying water directly onto the ore, typically while it is being conveyed, in an effort to prevent airborne dust generation as the ore is transferred to another conveyor, stockpile or transport vessel or vehicle. Figure 3.1 illustrates these water consumption extremes and the effect of using foam and/or surfactants (discussed in later sections) as opposed to plain water.

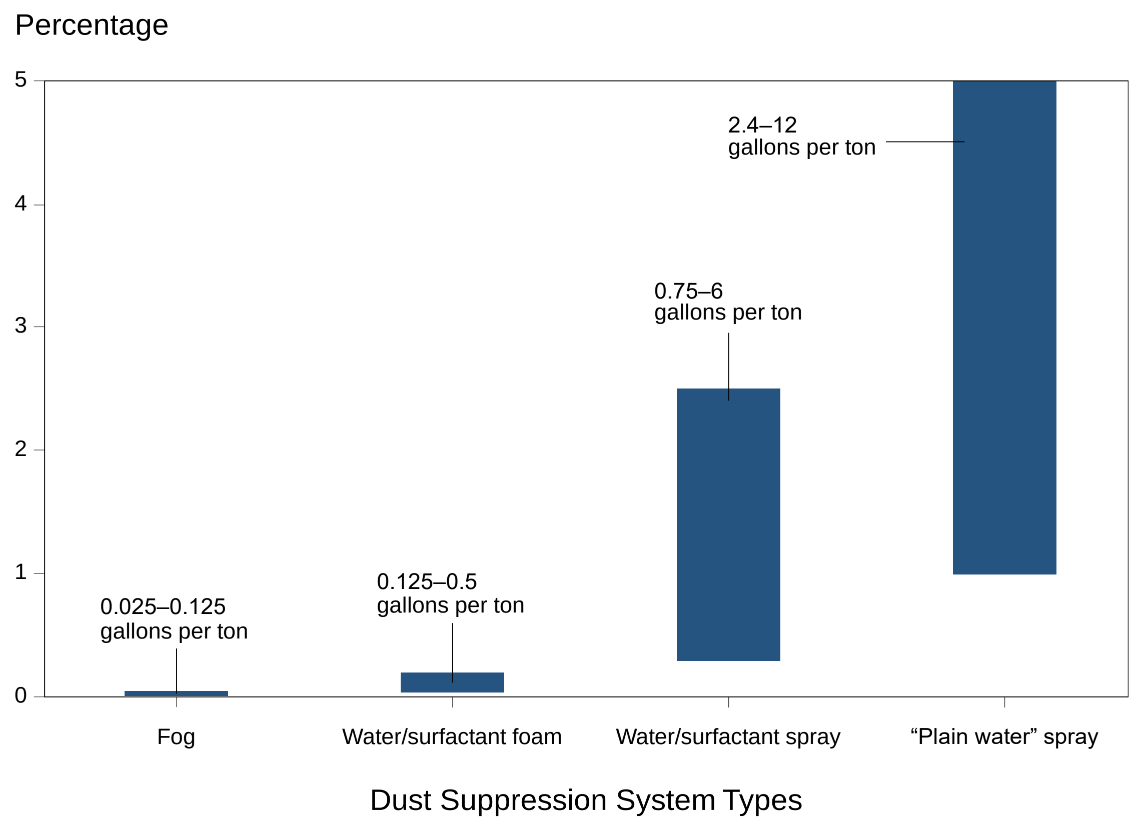


Figure 3.1. Typical rates of moisture addition for various dust suppression systems [adapted from Swinderman et al. 2009].

The vast majority of dust particles created during crushing are not released into the air, but stay attached to the surface of the broken material. The degree to which dust is produced depends on the type of crusher that is being used. Therefore, adequate wetting is extremely important because it ensures that the dust particles stay attached to the broken material. Uniformity of wetting is also an important issue for an effective system. By far the best dust reductions can be achieved by spraying the ore with water before and after crushing and then mechanically mixing the ore and water together to achieve a uniformity of wetting.

Ideally, the spray system should be automated so that sprays are only activated when ore is actually being processed. For dust knockdown, or suppression, a photo eye activation system with a delay timer may be incorporated into some applications to allow the spray system to operate for a short time period after a dust-producing event.

Nozzle Location

Due to the unique characteristics of each application, there are no hard and fast rules for specifically locating spray nozzles in dust control applications; however, the following guidelines will contribute to spray system efficiency.

- For wet dust prevention systems, nozzles should be located upstream of the transfer point where dust emissions, in most cases, are being created, with care taken to locate nozzles for the best mixing of material and water [Blazek 2003].
- Additional nozzles should be located at the transfer points to wet as much of the surface area of the ore as possible.
- For airborne dust prevention, the nozzles should be located at an optimum target distance from the material—far enough to provide the coverage required but close enough so that air currents do not carry the droplets away from their intended target [Blazek 2003].
- Droplet size also needs to be considered when setting the correct target distance.
- Transfer points should be enclosed as much as possible to prevent the dust and water droplets or fog from escaping the transfer points before the agglomeration process is complete.
- For airborne dust suppression, nozzles should be located to provide maximum time for the water droplets to interact with the airborne dust.

Figure 3.2 illustrates a common dust control application at a conveyor dump point into a bin. In this dust suppression application, spray nozzles are positioned in a manner that allows the spray patterns of the individual nozzles to properly interact with the dust particles and at a distance where the droplets will not be carried off by air currents.

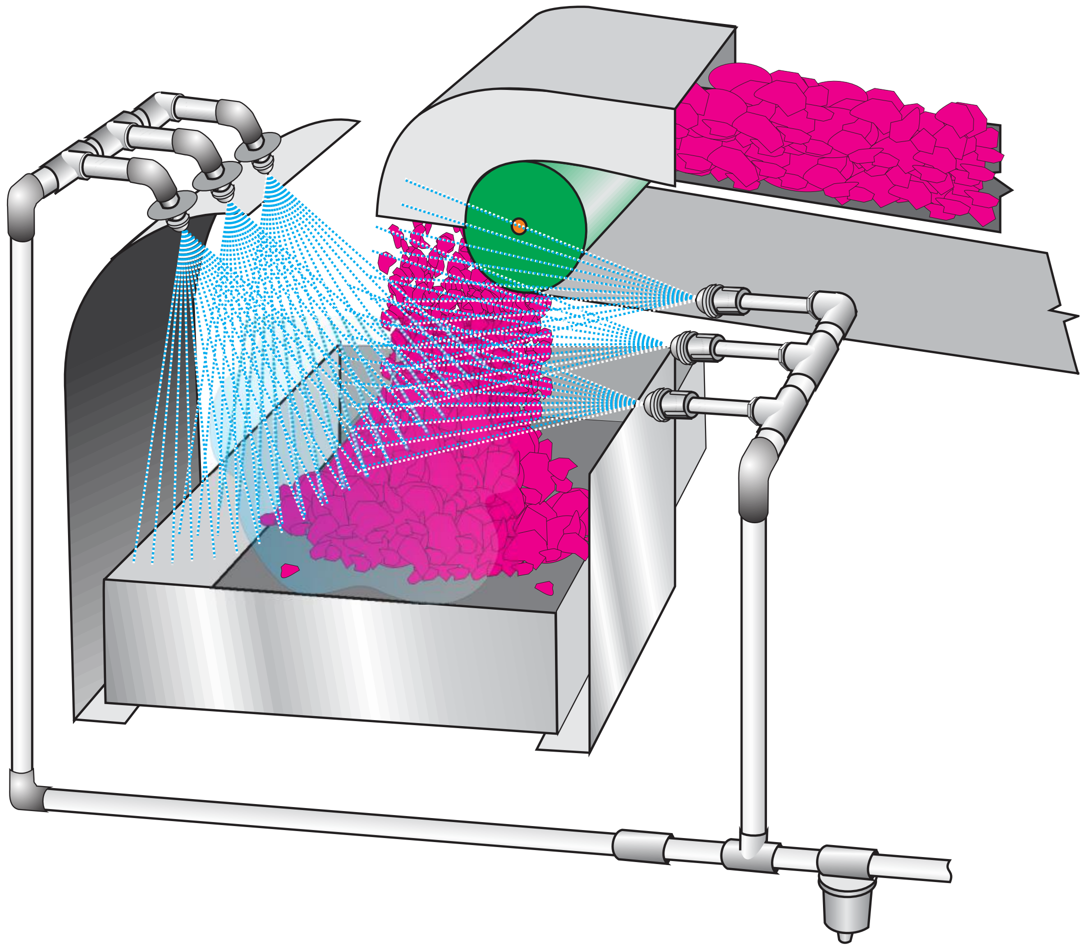


Figure 3.2. Common dust control application illustrating nozzle positioning.

Controlling Droplet Size

When wetting the bulk ore to achieve dust prevention, the goal is to wet the ore to the point where dust does not become airborne. In these applications, droplet sizes above 100 micrometers (µm) (preferably 200 to 500 µm) should be used.

In contrast, for airborne dust suppression, where the goal is to knock down existing dust in the air, the water droplets should be in similar size ranges to the dust particles. The intent is to have the droplets collide and attach themselves (agglomerate) to the dust particles, causing them to fall from the air. To achieve this goal, droplets in the range of 2 to 20 µm have been shown to be most effective. If the droplet diameter is much greater than the diameter of the dust particle, the dust particle simply follows the air stream lines around the droplet. If the water droplet is of a size comparable to that of the dust particle, contact occurs as the dust particle follows the stream lines and collides with the droplet (Figure 3.3). For optimal agglomeration, the particle and water droplet sizes should be roughly equivalent. The probability of impaction also increases as the size of the water spray droplets decreases, because as the size of the droplets decreases, the number of droplets increases [Rocha 2005a].

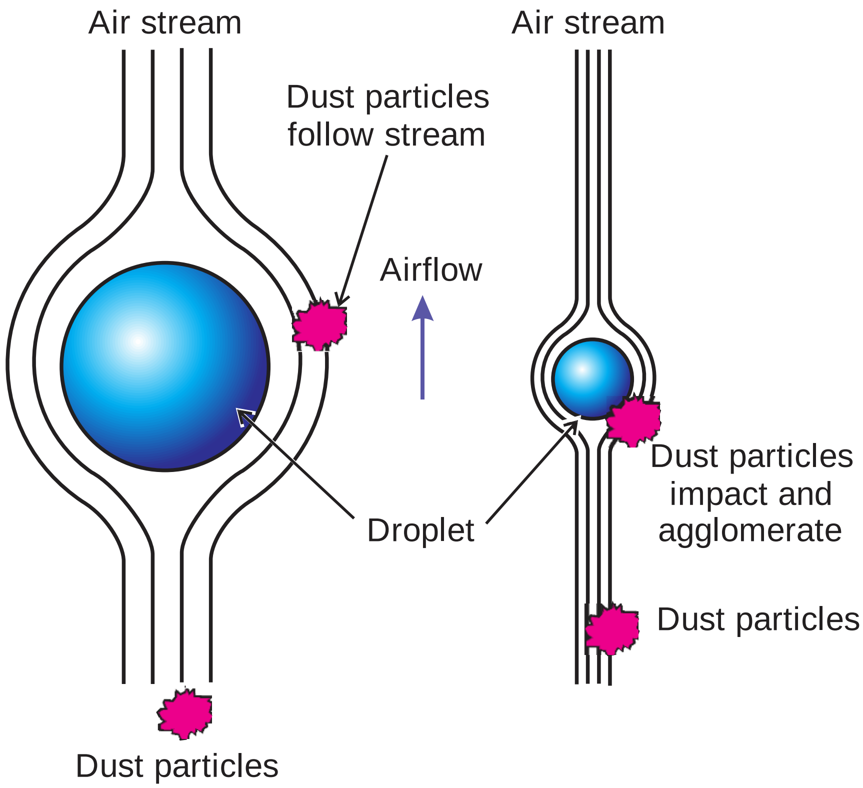


Figure 3.3. Illustration of the effect of droplet size on dust particle impingement.

Table 3.1 relates the size range of dust particles that may be produced in a mining operation to the size range of common precipitation droplets. The table also includes the length of time that it takes for each droplet size class to fall a distance of 10 feet in order to give the reader an estimate of how long various sized droplets will remain airborne.

Table 3.1. Particle size in comparison to common precipitation droplet size [adapted from Bartell and Jett 2005]

Dust particle size in micrometers (µm)	**Reference precipitation droplet size**	**Seconds for particle/droplet to fall 10 feet**
5,000 to 2,000	Heavy rain	0.85 to 0.90
2,000 to 1,000	Intense rain	0.9 to 1.1
1,000 to 500	Moderate rain	1.1 to 1.6
500 to 100	Light rain	1.6 to 11
100 to 50	Mist	11 to 40
50 to 10	Thick fog	40 to 1,020
10 to 2	Thin fog	1,020 to 25,400

Methods of Atomization

Atomization is the process of generating droplets by forcing liquid through a nozzle, which is accomplished by one of the following methods.

- *Hydraulic* or *airless atomization* controls droplet size by forcing the liquid through a known orifice diameter at a specific pressure. Generally, the higher the liquid pressure, the smaller the droplet size. This method utilizes high liquid pressures and produces relatively small- to medium-sized droplets in uniformly distributed fan, full cone, or hollow cone spray patterns. Hydraulic fine spray nozzles are preferred in most areas because operating costs are lower since compressed air is not required.
- *Air atomizing* controls droplet size by forcing the liquid through an orifice at lower pressures than the hydraulic atomizing method, and using compressed air to break the liquid into small droplets. This method produces very small droplets and uniform distribution in a variety of spray patterns. However, it is more complex and expensive because it requires compressed air. In most cases, air atomizing nozzles are effective in locations where dust particles are extremely small and the nozzles can be located in close proximity to the dust source, although some applications require large-capacity air atomizing nozzles to throw their sprays long distances to reach the dust.
- *Dry fogging* controls droplet size by utilizing a nozzle design that passes water through high-frequency sound waves produced by a highly accelerated mixture of water and compressed air. The speed of the compressed air and water mixture hitting a small cup in front of the nozzle reflects the energy back into itself and creates a sonic shock wave that produces very small droplets in a cloud dispersion. Like air atomizing nozzles, dry fog systems require compressed air. The very small droplets produced make dry fog nozzles particularly effective at knocking down respirable airborne dust.

Chemical Additives to Control Droplets

Surfactants are sometimes used in wet spray applications because they lower the surface tension of the water solution, which has the following effects:

- a reduced droplet diameter;
- an increase in the number of droplets for a given volume of water; and
- a decrease in the contact angle [Blazek 2003], defined as the angle at which a liquid meets a solid surface (θ, as shown in Figure 3.4).

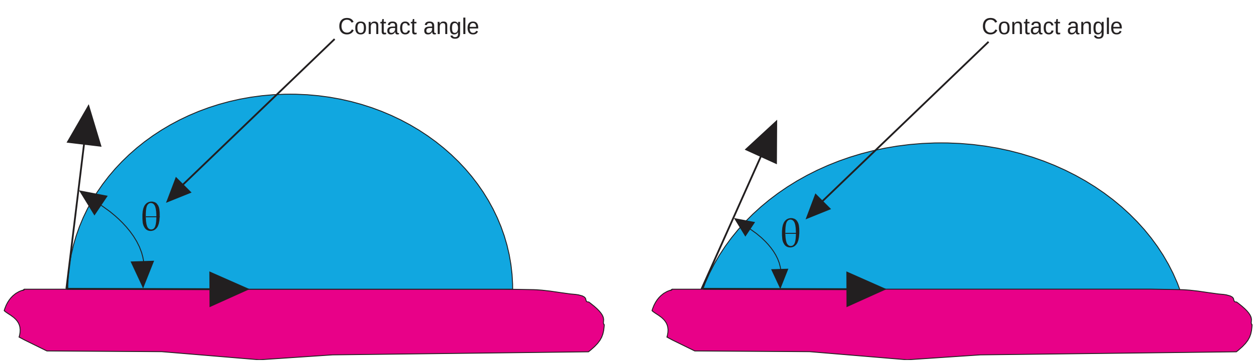


Figure 3.4. Illustration of contact angle resulting from a liquid meeting a solid surface. The left image shows a non-treated water droplet with a greater contact angle. The right image shows a surfactant-treated water droplet with a lesser contact angle [adapted from NDT 2018].

The use of surfactants increases the rate at which the droplets are able to wet or coat dust particles; thus, less moisture is used to produce the same effects as a typical water application. Small amounts of surfactants can be injected into the spray water, typically in a dilution range of 1:700 to 1:1500, to improve the wetting and subsequent control of dust particles [Swinderman et al. 2009]. Despite the effectiveness of chemical additives, it must be noted that they are not often used in the metal/nonmetal mining industry based upon several limitations, as described below.

- Surfactants are significantly more expensive than a typical water application.
- They can alter the properties of the mineral or material being processed.
- They can damage some equipment, such as conveyor belts and seals.
- Surfactant systems require more upkeep and maintenance than typical water systems.
- Surfactants have limited usefulness in the metal/nonmetal mining industry as opposed to in the coal industry, since ore or stone are much easier to wet than coal due to its hydrophobic nature [NIOSH 2003].

The effectiveness of chemical additives depends on the following issues [Rocha 2005b]:

- the type of wetting agent used,
- the hydrophobic nature of the mineral particles,
- dust particle size,
- dust concentration,
- water pH,
- minerals present in the water used, and
- the goal of applying the additive (suppression vs. prevention).

As noted above, the coal industry has been the primary area of application for surfactants, and research conducted for coal applications has shown a wide variation in reported effectiveness [Organiscak 2013]. Selection of a particular surfactant for a particular coal seam and surfactant concentration were key factors impacting effectiveness. A controlled laboratory study of three different surfactants for reducing airborne respirable coal dust demonstrated minimal improvement over plain water [Organiscak 2013]. However, this research noted that only suppression was tested, and the potential benefit of prevention resulting from surfactant application was not evaluated.

NOZZLE TYPES AND SPRAY PATTERNS

Spray nozzles are categorized by the type of atomization method used and by the spray patterns and the sizes of the droplets they produce. The most commonly used spray nozzles produce full cone, hollow cone, round, or flat fan patterns. Air atomizing nozzles (which utilize compressed air) are typically used to produce round or flat fan spray patterns, while hydraulically atomizing nozzles are typically used to produce full or hollow cone spray patterns; however, some hydraulically atomizing nozzles can also produce flat fan spray patterns. Dry fog ultrasonic nozzles (which also utilize compressed air) produce a plume of very small low-mass droplets.

Air Atomizing Nozzles

Air atomizing nozzles are sometimes called two-fluid nozzles because they inject compressed air into the liquid stream to achieve atomization. Figure 3.5 depicts two styles of air atomizing nozzles known as internal mix and external mix. Internal mix nozzles use an air cap that mixes the liquid and air streams internally to produce a completely atomized spray, and external mix nozzles use an air cap that mixes the liquid and air streams outside of the nozzle. With an internal mix nozzle, the atomization air pressure acts against the liquid pressure to provide additional liquid flow rate control. With an external mix nozzle, the liquid pressure is unaffected by the atomization air pressure.

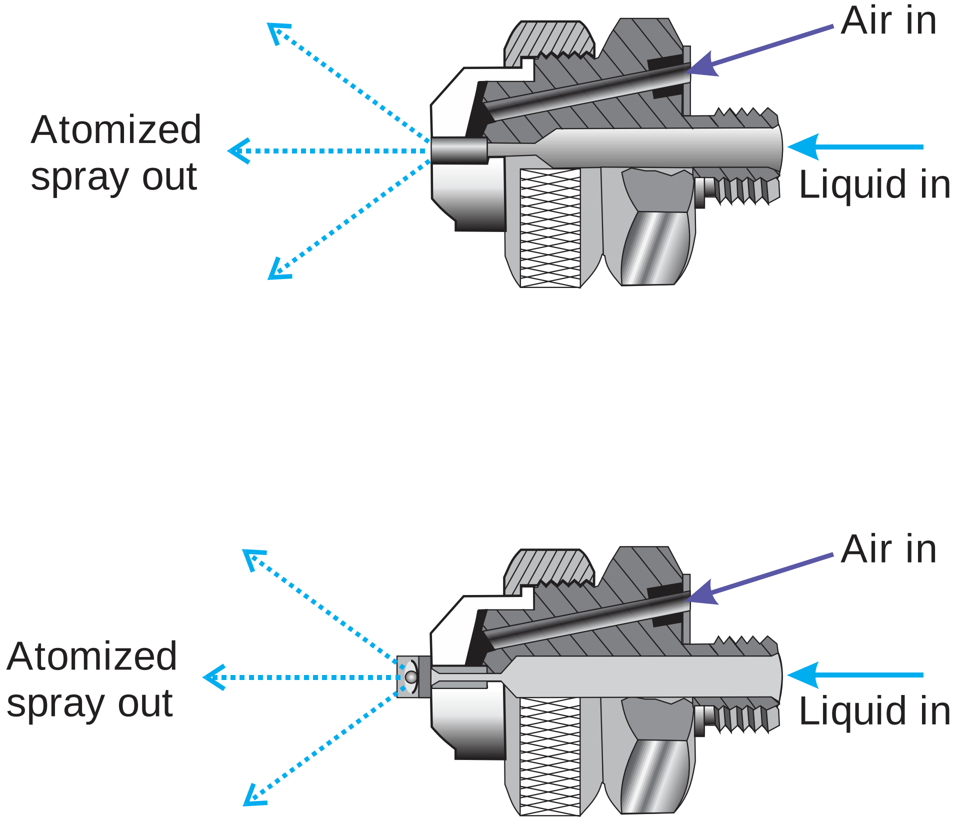


Figure 3.5. Two styles of air atomizing nozzles. The top illustration shows a typical internal mix nozzle. The bottom illustration shows a typical external mix nozzle [adapted from SSCO 2018].

As illustrated in Figure 3.6, internal mix nozzles can produce either round or flat spray patterns, and external mix nozzles produce flat spray patterns.

Air atomizing nozzles generally produce smaller droplets than hydraulically atomizing nozzles and, for this reason, are more often used in airborne dust suppression applications. Air atomizing nozzles impart greater energy to the sprayed droplets and are better suited in enclosed applications where overspray is contained.

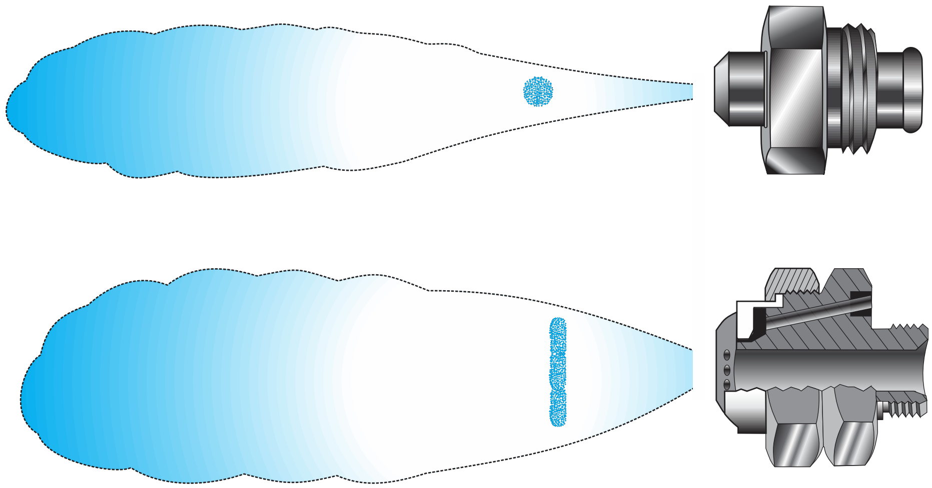


Figure 3.6. Two types of nozzle spray patterns. The top illustration shows a typical air atomizing nozzle round spray pattern. The bottom illustration shows a typical fan spray pattern [adapted from SSCO 2018].

Hydraulically atomizing nozzles force liquid through a fixed orifice at high pressures to achieve atomization into droplets. The orifice geometry produces various spray patterns and droplet sizes.

Hydraulic Full Cone Nozzles

Hydraulic full cone nozzles produce a solid cone-shaped spray pattern with a round impact area that provides high velocity over a distance (Figure 3.7). They produce medium to large droplet sizes over a wide range of pressures and flows. They are normally used when the sprays need to be located further away from the dust source [Bartell and Jett 2005].

Because of their generally larger droplet sizes, hydraulic full cone nozzles are more commonly used in dust prevention applications where the ore is wetted to prevent dust from becoming airborne.

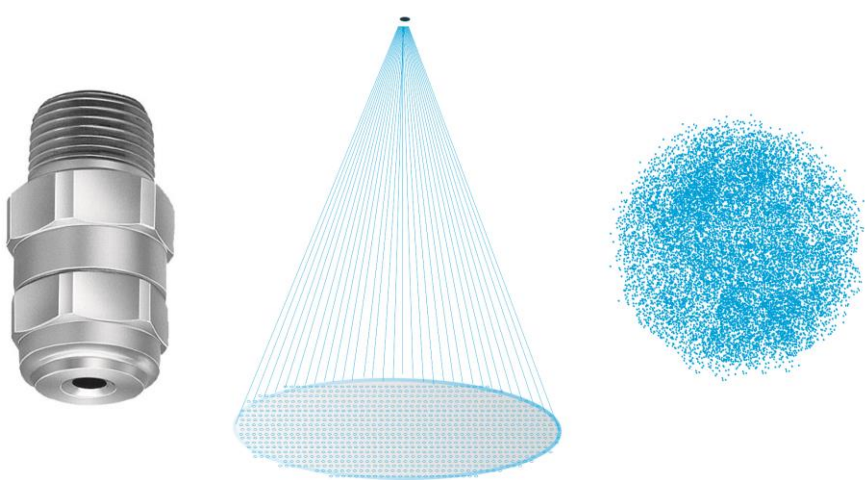


Photo by SSCO

Figure 3.7. Typical full cone nozzle and spray pattern [adapted from Schick 2008].

Hydraulic Hollow Cone Nozzles

Hydraulic hollow cone nozzles produce a circular ring spray pattern and typically produce smaller drops than other hydraulic nozzle types of the same flow rate (Figure 3.8). They also have larger orifices, which results in reduced nozzle clogging. Hollow cone nozzles are normally useful for operations where airborne dust is widely dispersed and are available in two different designs: whirl chamber and spiral sprays. In most whirl chambers, the spray pattern is at a right angle to the liquid inlet; however, in-line designs are also available. Both produce a more uniform pattern with smaller droplets (Figure 3.8). Spiral sprays are used when greater water flow is needed, resulting in less clogging due to the large orifices. There is also less pattern uniformity, and therefore larger droplets are created (Figure 3.9) [Bartell and Jett 2005].

Hydraulic hollow cone whirl spray nozzles are typically used in airborne suppression applications because of their smaller droplets, and hydraulic hollow cone spiral spray nozzles are typically used in prevention applications because of their larger droplets, greater flow rates, and ability to cover large areas.

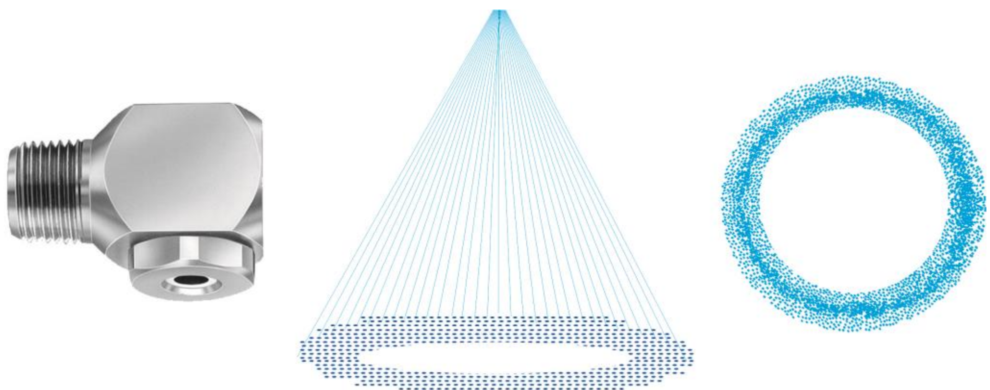


Photo by SSCO

Figure 3.8. Typical hollow cone whirl chamber nozzle and spray pattern. A right angle design is shown [adapted from Schick 2008].

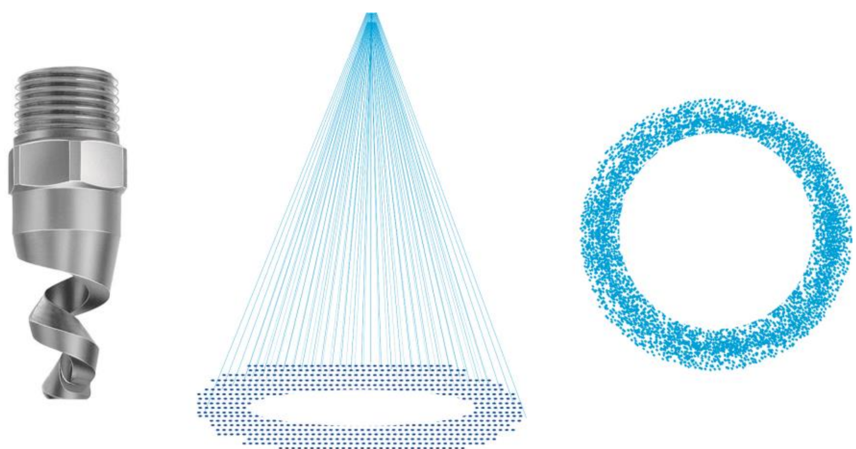


Photo by SSCO

Figure 3.9. Typical hollow cone spiral nozzle and spray pattern [adapted from Schick 2008].

Hydraulic Flat Fan Nozzles

Hydraulic flat fan nozzles produce relatively large droplets over a wide range of flows, and the nozzle spray angles and are normally located in narrow enclosed spaces (Figure 3.10). These nozzles are useful for wet dust prevention systems because of their large droplets. Flat fan nozzles are available in three different designs: tapered, even, and deflected [Bartell and Jett 2005].

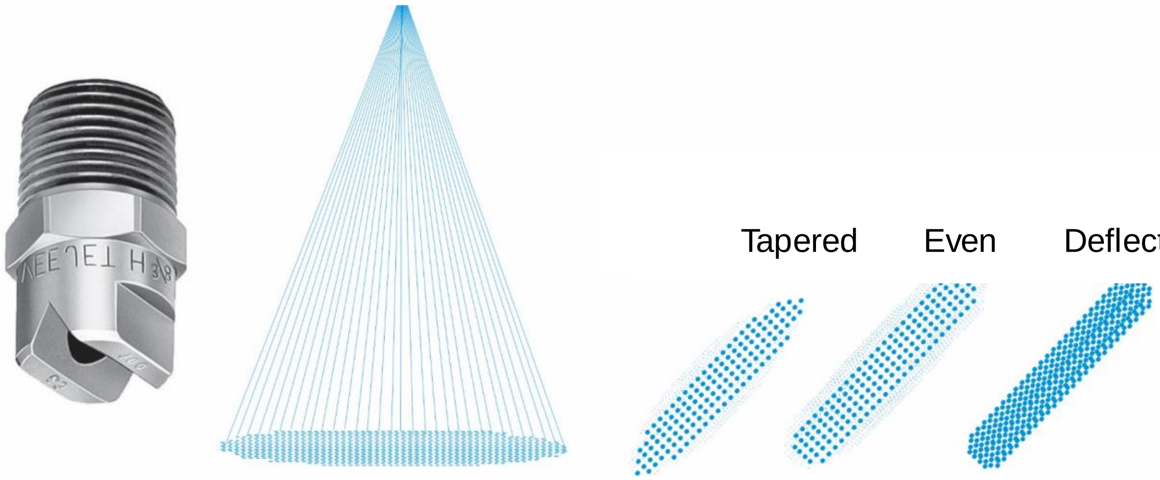


Photo by SSCO

Figure 3.10. Typical flat fan nozzle and spray patterns [adapted from Schick 2008].

Figure 3.11 shows the airborne suppression performance of the different spray nozzles performing at different operating pressures. As shown, atomizing sprays are the most efficient for dust knockdown or suppression, followed by the hollow cone sprays. Hollow cone sprays are a good choice for many applications in mining and mineral processing operations because significant coverage or wetting of the ore occurs, even at low moisture percentages. Full cone sprays would be most applicable in the early stages of the process where the quantity of moisture added is not as critical. Flat fan sprays are most appropriate for spraying into a narrow rectangular space because less water is wasted by spraying against an adjacent rock or metal surface.

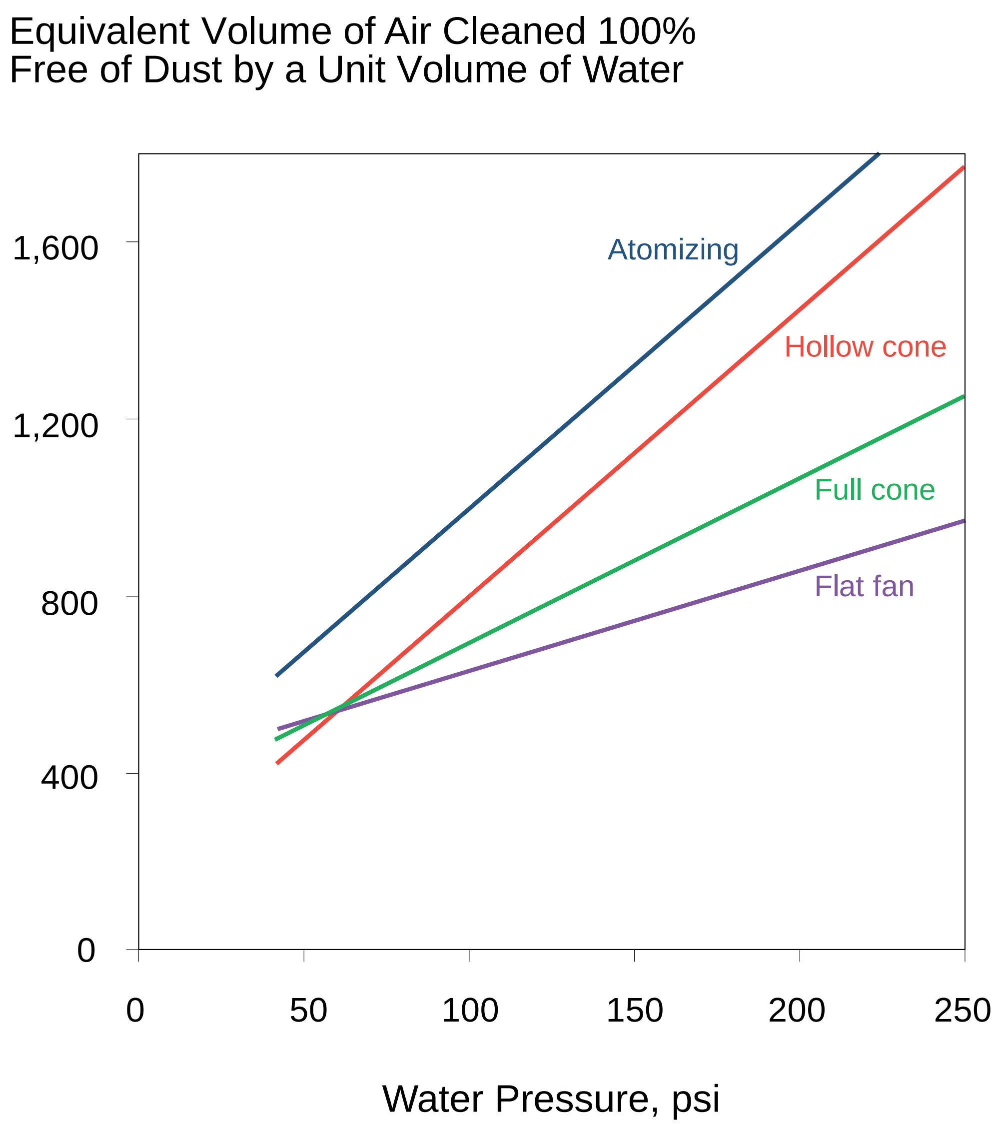


Figure 3.11. Airborne suppression performance of four types of spray nozzles. The atomizing nozzle is air atomizing. The hollow cone, full cone, and flat fan spray nozzles are hydraulically atomizing [adapted from NIOSH 2003].

Ultrasonic Dry Fog Nozzles

Ultrasonic dry fog nozzles (Figure 3.12) are used primarily in airborne dust suppression applications to knock down dust that is already airborne. These nozzles produce very small droplets uniformly distributed in a plume-shaped cloud. Each nozzle is an air-driven acoustic oscillator that creates fog by passing liquid through a field of high-frequency sound waves inside the nozzle. Compressed air enters the nozzle at very high speed, creating a sonic shock wave that explodes the water droplets into thousands of micron-size droplets. The air then escapes around the resonating chamber and the droplets emerge from the nozzle in a soft, low-velocity fog (Figure 3.13). Droplets produced by these nozzles have very low mass, so they stay suspended in air for a greater length of time, dependent on relative humidity, which results in more opportunities for the dust particles and droplets to interact.

Photo by Dust Solutions

Figure 3.12. Ultrasonic dry fog nozzle.

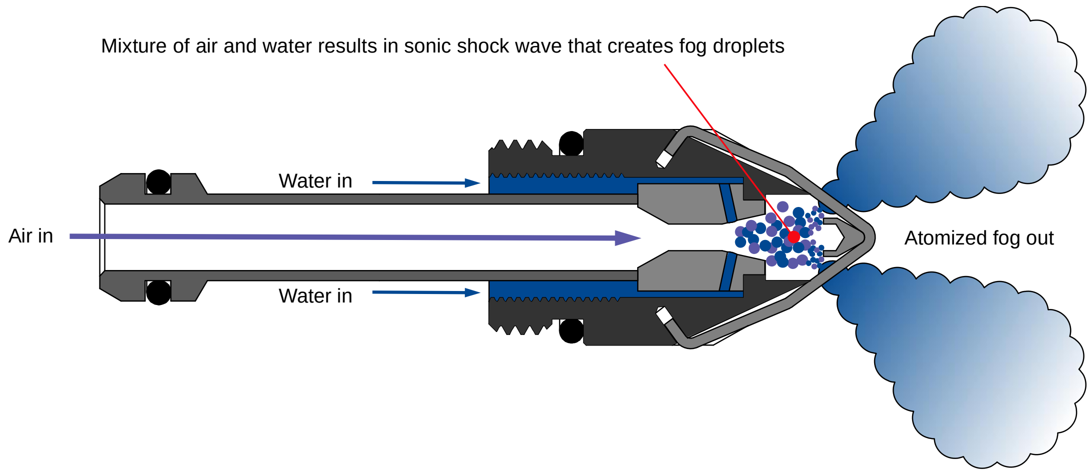


Figure 3.13. Illustration of an ultrasonic dry fog nozzle principle of operation [adapted from Dust Solutions 2018].

The small-sized droplets produced by ultrasonic dry fog nozzles do not require surfactants to attach to and penetrate the dust particles in the air. The surface tension of the material is not a factor as dry fog is not designed to impact the material, but to only wet the airborne dust so it will stick to other slightly wetted dust particles (agglomerate). The increased mass of the agglomerated particles makes them fall out of the air and back into the process.

Since very small droplets can be easily carried by wind currents, dry fog nozzles are typically used in enclosed transfer point locations or in areas protected from wind by a suitable wind fence; curtain arrangement; or, in some cases, the application itself, such as a large hopper or ship hold (Figure 3.14). Figure 3.15 illustrates the typical spray patterns produced by these nozzles.

Photos by Dust Solutions

Figure 3.14. Typical wind fence installations. The left photo shows a porous windbreak material around a stockpile drop. The right photo shows the material being used at the top of a loadout hopper.

Photos by Dust Solutions

Figure 3.15. Typical dry fog nozzle spray patterns. The left photo shows sprays mounted above a grizzly at a railcar dumper. The right photo shows a primary crusher with nozzle manifolds.

Table 3.2 lists some common dust control application areas and the type of spray nozzle typically used for that application, with liquid and air pressures expressed in pounds-force per square inch gauge (psig).

Table 3.2. Typical applications by spray nozzle type

	Air Atomizing	Hydraulic Full Cone	Hydraulic Hollow Cone	Hydraulic Flat Fan	Ultrasonic Dry Fog
Typical liquid pressures	10–60 psig	10–300 psig	5–1000 psig	10–500 psig	7–17 psig
Typical air pressures	10–70 psig	N/A	N/A	N/A	70–80 psig
Jaw crushers	✓		✓		✓
Loading terminals	✓		✓		✓
Primary dump hoppers	✓		✓		✓
Transfer points	✓		✓		✓
Stackers					✓
Stackers, reclaimers		✓			✓
Stockpiles				✓	
Transfer points		✓	✓		
Transport areas/roads			✓		

Figure 3.16 illustrates a typical dump application with both dust suppression and prevention spray nozzles. In this case, dumping action produces airborne dust in the upper level of the enclosure, and the impact of the falling material with the material already in the enclosure causes additional dust to become airborne. The dust suppression spray nozzles in the headers at the top of the enclosure would be either air atomizing or hydraulic fine spray hollow cone nozzles because of the smaller droplet sizes they produce. The dust prevention spray nozzles at the lower level of the enclosure would be hydraulic atomizing full cone nozzles because of their larger droplet sizes and full cone spray pattern for large surface area coverage.

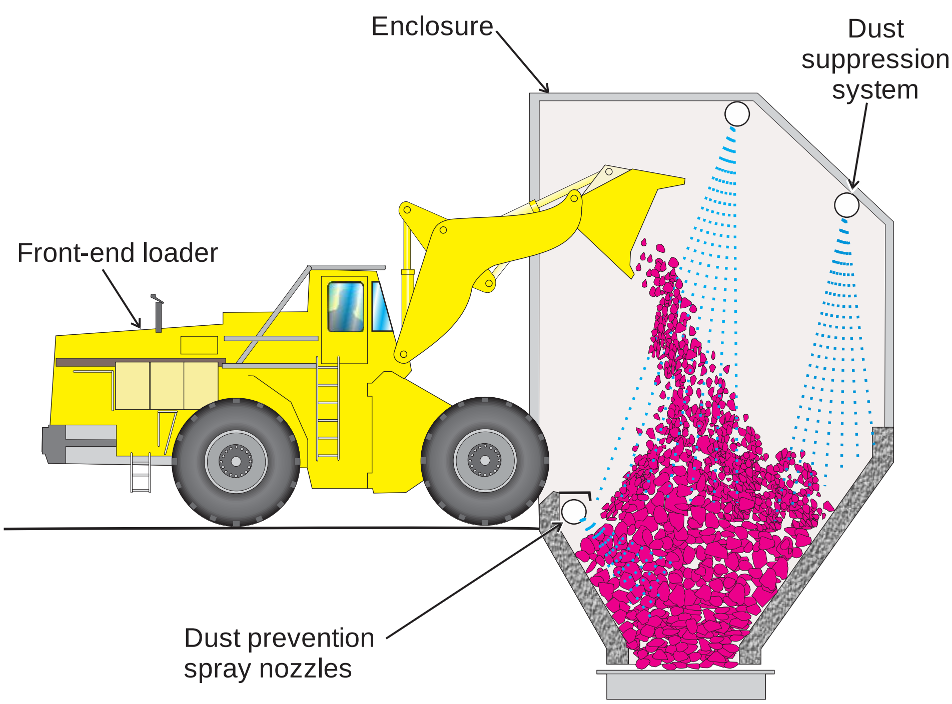


Figure 3.16. Illustration of a typical loader dump dust control application.

Figure 3.17 illustrates a typical conveyor application with both dust suppression and prevention spray nozzles. In this case, dust prevention spray nozzles are positioned above the moving conveyor to prevent dust on the material from becoming airborne. Dust suppression nozzles are positioned at the discharge end transfer point to control airborne dust.

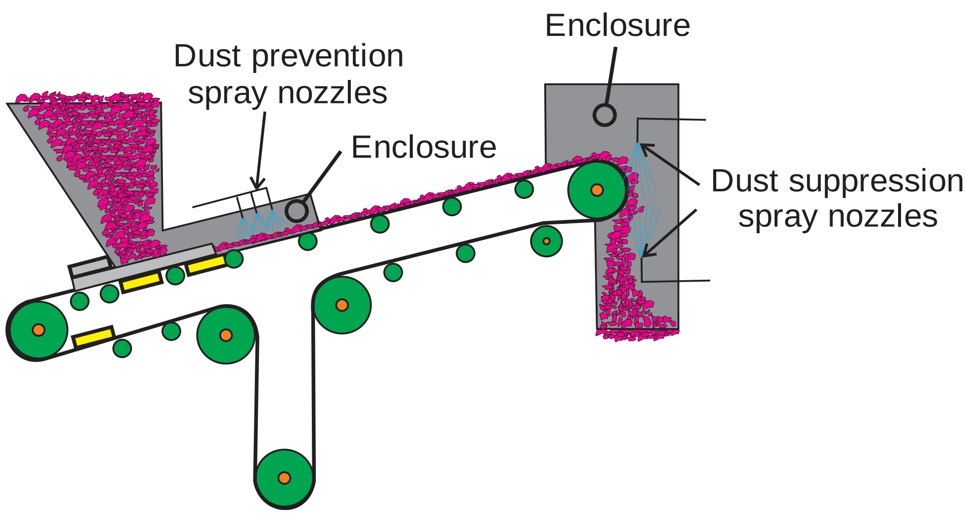


Figure 3.17. Illustration of a typical conveyor dust control application [adapted from Swinderman et al. 2009].

SPRAY CONTROLS AND OPTIMIZATION

Methods for controlling wet spray systems can range from simple manual valves, which turn on and off liquid flow, to sophisticated automated equipment systems that monitor environmental conditions and make automatic adjustments without operator intervention. In designing a wet spray dust control system, the degree of automation required is determined by the analysis of the following factors:

- *Need for operators in the production area.* Operators can monitor dust conditions and manually actuate spray equipment when needed. However, the analysis of the need for an operator includes a determination of both the accessibility and safety of the area where operators would need to access and monitor the equipment and activate the system.
- *Need for intermittent or continuous spraying*. Applications such as truck dumps benefit from automatic sensing of the dump, whereas a continuous application such as a conveyor transfer may be adequately served by a system that can be manually actuated to operate continuously throughout the day and then be manually shut down.
- *Variations in the severity of the dust problem*. Applications where the quantity of dust produced is inconsistent benefit from a system that can automatically sense the dust quantity and automatically adjust the amount of liquid sprayed.
- *Training level of operators.* Manually controlled systems require less training to operate than automated systems, which require a higher level of training and competence.
- *Relative cost of a simple versus a more sophisticated control system*. As expected, simple manual controls are less expensive than sophisticated automation; however, cost should not be the only consideration where health and safety issues are involved.

Manual Valve Control

Manual valve control is the simplest method of controlling the spray nozzles. This method uses pressure regulators and manual ball valves for liquid and atomizing air, if applicable, to turn the liquid on or off and to atomize air to the spray nozzles (Figure 3.18). The regulators and valves are typically open or in-line plumbed but may be enclosure-mounted, as illustrated, for protection.

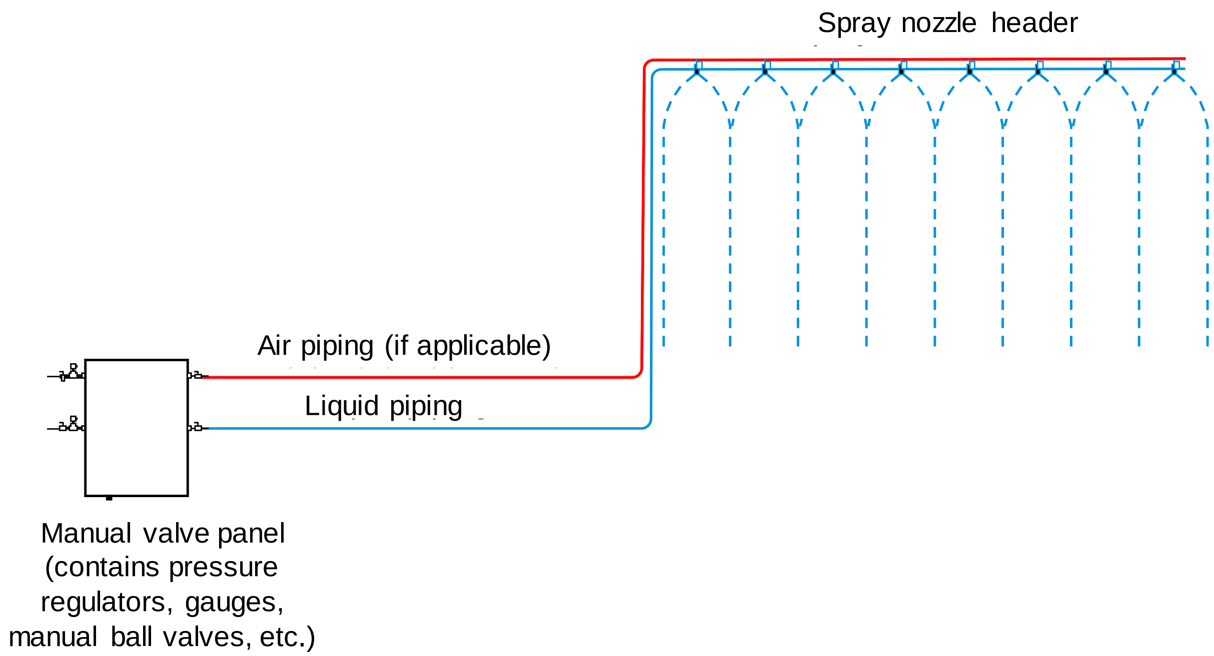


Figure 3.18. Illustration of a typical manual valve control system schematic.

Automated Control Systems

Automated control systems vary in their type and in their degree of automation. They typically provide more precise spraying by consistently controlling the liquid spray volume and liquid pressure. Spray volume ensures proper wetting in dust prevention applications, and liquid pressure controls the droplet size to more accurately match the dust particle size in dust suppression applications.

Figure 3.19 illustrates the basic components of an automated control system, as described below.

- Input devices that collect environmental or system performance data and feed the data to a system controller. Environmental data are generated from inputs such as particulate sensors that read the dust concentration in the air and photo eyes that detect the presence of rock on a conveyor, a dump truck, etc. System performance data are generated from inputs such as liquid flow sensors that read the actual liquid flow to the spray nozzles and liquid pressure sensors that read the actual pressure of liquid to the spray nozzles.
- A spray controller that receives and processes the sensor data and then outputs commands to the spray nozzles such as trigger on/off, liquid pressure settings, and atomizing air pressure settings.
- Spray nozzles that atomize and spray the liquid onto the substrate or into the dust cloud.

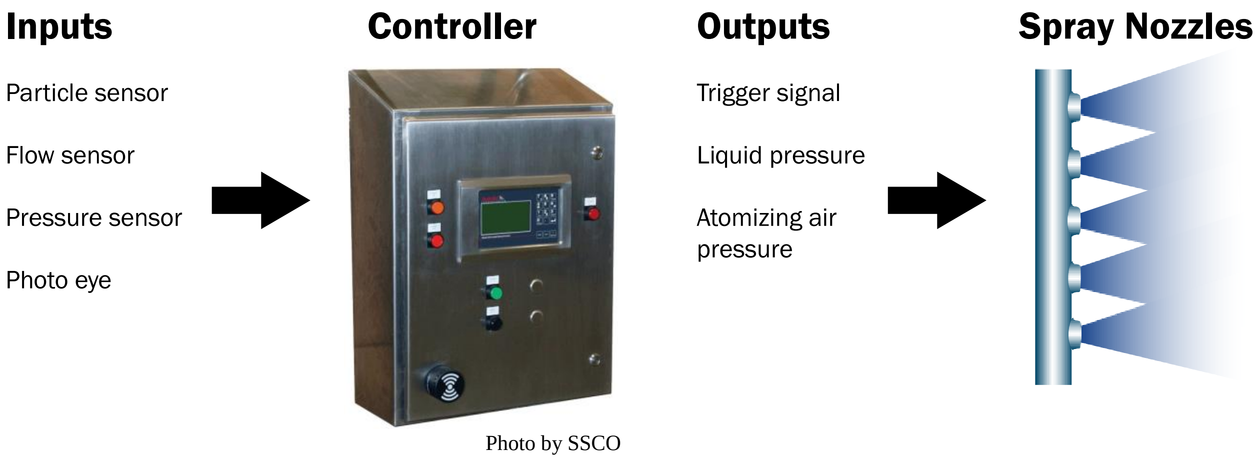


Figure 3.19. Components of a typical automated control system. Arrows indicate flow of the system logic. Inputs feed into the controller and the controller feeds outputs to affect the operation of the nozzles [adapted from SSCO 2018].

Spray System Optimization

Spray system optimization involves designing the spray system in such a manner as to achieve the maximum desired dust control performance. For complex dust control applications, the optimum spray nozzle positioning, liquid flow rates, and droplet sizes can be more accurately determined by using computational modeling to simulate the existing dust problem and the effect that a proposed spray system may have on controlling the dust. Computational fluid dynamics (CFD) is a fluid flow simulation tool that utilizes specific information about the motion of air, spray droplets, and the dust-producing environment. CFD can be used to create a simulation that is manipulated to determine the design parameters of an optimum solution for that specific dust problem. The process requires extensive data gathering, user time commitment, and computational resources to complete the simulation; however, the resultant information gained can significantly reduce or eliminate field trial and error and aid in designing a highly efficient dust control solution.

MAINTENANCE ISSUES WITH WET SPRAY SYSTEMS

Water Quality

A fundamental consideration with any wet spray control system is the quality of the water being sprayed, with water hardness and cleanliness being of greatest concern. If the available water supply contains a high level of minerals, nozzle wear can be accelerated. The user should consider nozzles fabricated in stainless steel if this condition is present. A high level of minerals in the supply water can also introduce caking, which is a buildup of carbonates on the nozzle, and can increase the amount of maintenance required. Although it may not be possible to modify the hardness of the water being sprayed, a properly designed and applied maintenance program can help to minimize the adverse effects of high levels of minerals in the available water supply.

If spray nozzles become plugged with sediment or debris, they render the spray system ineffective. Since the water to be used for spray systems at most mining and mineral processing operations is drawn from settling ponds, water purity is a concern. It is recommended to use a water filtering system to eliminate the possibility of sediment and debris clogging the water sprays. Most spraying companies offer filtering systems for this purpose.

An effective method of supplying water to the system is to use a self-contained water delivery system specifically designed for the application. Such a system includes a water pump selected to provide water at the specific flow and pressure required for the application. Also included are a manual inlet valve, an inlet strainer, a flow switch to prevent the pump from operating without any water supply, pressure indicators, a bypass circuit to allow manual adjustment of water flow, a manual outlet valve, and a manual or timer-based control panel. In some cases, a system with a protective enclosure is advantageous to protect the system from the elements. A typical unenclosed water delivery system is illustrated in Figure 3.20.

Water supply systems can be as simple as one that delivers a fixed water flow rate or one that can adjust the water flow rate in reaction to the needs of an application. Today's electronic technology offers the ability to sense factors such as the dust loading and automatically adjust the liquid flow rate and pressure to optimize the dust control system performance.

Photo by SSCO

Figure 3.20. Typical self-contained water delivery system.

In applications where water quality is poor and where the water contains excessive amounts of particulate, such as water drawn from settling ponds, additional filtration should be provided. In these cases, it is recommended that a duplex basket strainer be used prior to the water delivery system inlet. These units provide two basket strainers and a manual valve, which allows the operator to switch from one strainer to the other to allow the inactive strainer to be removed and cleaned. The strainer mesh should be selected based on the particulate size present in the water supply. The function of the strainer is to stop particles that could ultimately clog the spray nozzle orifice. For this reason, the strainer mesh should be such that it will stop solid particles that are larger in diameter than the orifice of the spray nozzles in the system. A typical duplex basket strainer is shown in Figure 3.21.

Photo by SSCO

Figure 3.21. Typical duplex basket strainer.

Another method of filtering water is to use a permanent media (screen) mechanical strainer with an automatic flushing function and then a smaller micron-rated disposable cartridge filter downstream (Figure 3.22). This arrangement can reduce the frequency of filter changes while still eliminating particulate that can plug the nozzle.

Photo by SSCO

Figure 3.22. Typical screen mechanical strainer with automatic self-cleaning [from SSCO 2008].

Nozzle Maintenance

Nozzles require maintenance, regular inspection, cleaning, and even replacement to preserve final production quality and to maintain production processes on a cost-efficient basis. The type and frequency of the maintenance schedule depends on the particular application. In some operations, nozzles can spray usefully after hundreds of hours of operation; in others, nozzles require daily attention. Most nozzle applications fall between these extremes. At a minimum, nozzles should be visually surveyed for damage on a regular basis. Additional maintenance will depend on application specifications, the water quality used, and nozzle material.

Erosion and Wear

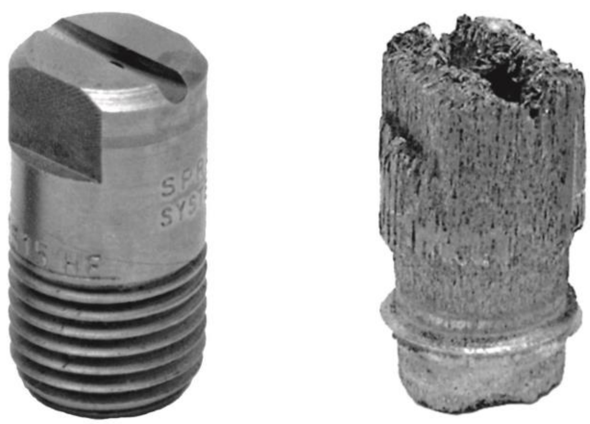
The gradual removal of material from the surfaces of the nozzle orifice and internal flow passages causes them to become larger and/or distorted (Figure 3.23), which can affect flow, pressure, and spray pattern.

Photos by SSCO

Figure 3.23. Nozzle erosion—new versus used [adapted from SSCO 2013].

Corrosion

The chemical action of sprayed material or the environment causes corrosion breakdown of the nozzle material (Figure 3.24).



Photos by SSCO

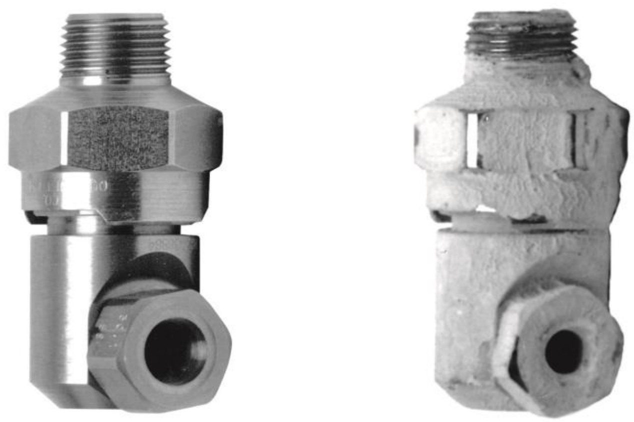
Figure 3.24. Nozzle corrosion—new versus used [adapted from SSCO 2013].

Clogging

Unwanted dirt or other contaminants blocking the inside of the orifice can restrict the flow and disturb spray pattern uniformity.

Caking

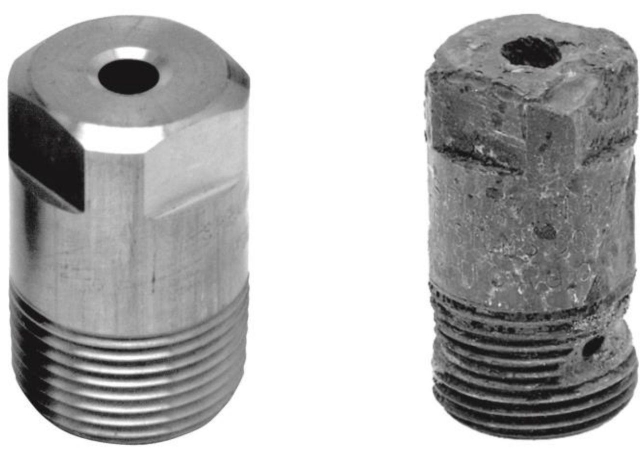
Overspraying, misting, or chemical buildup of material on the inside or outer edges of the orifice from evaporation of liquid can leave a layer of dried solids and obstruct the orifice or internal flow passages (Figure 3.25).



Photos by SSCO

Figure 3.25. Nozzle caking—new versus used [adapted from SSCO 2013].

Heat may have an adverse effect on nozzle materials not intended for high-temperature applications (Figure 3.26).



Photos by SSCO

Figure 3.26. Temperature damage—new versus used [adapted from SSCO 2013].

Improper Reassembly

Misaligned gaskets, overtightening, or other repositioning problems can result in leakage as well as poor spray performance.

Accidental Damage

Inadvertent harm to an orifice can be caused by scratching through the use of improper tools during installation or cleaning (Figure 3.27).

Photos by SSCO

Figure 3.27. Nozzle damage—new versus used [adapted from SSCO 2013].

Checking Spray Nozzle Performance

Visual nozzle inspections alone will not always indicate whether the nozzle is performing to specifications. The spray tips pictured in Figures 3.28 and 3.29 illustrate that factors that affect performance, such as wear, are not always obvious.

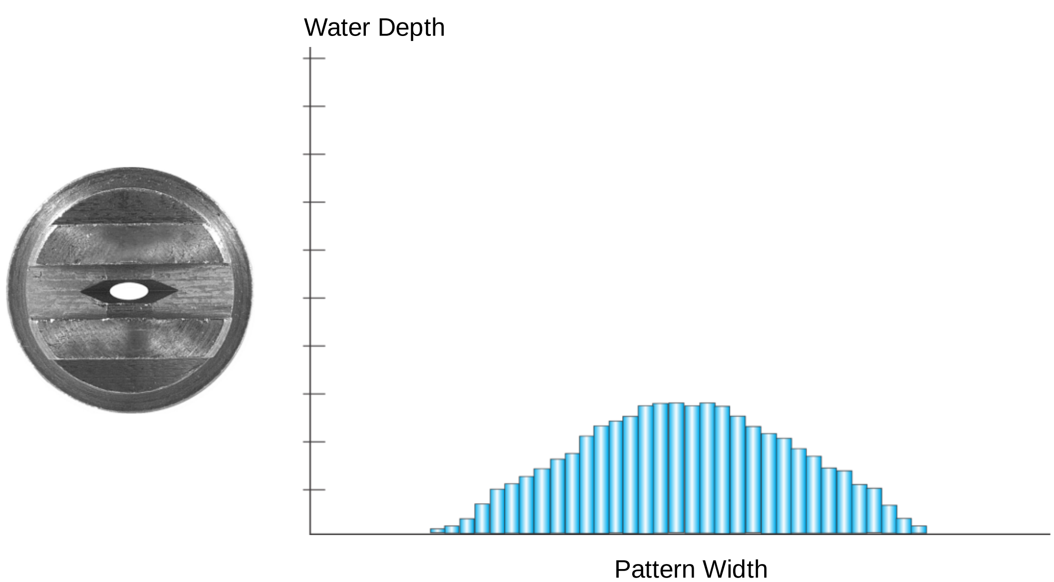


Photo by SSCO

Figure 3.28. Good spray tip showing pattern and distribution graph. Bar height indicates distribution of water over pattern width and shows relatively uniform flow over the width of the pattern [adapted from SSCO 2013].

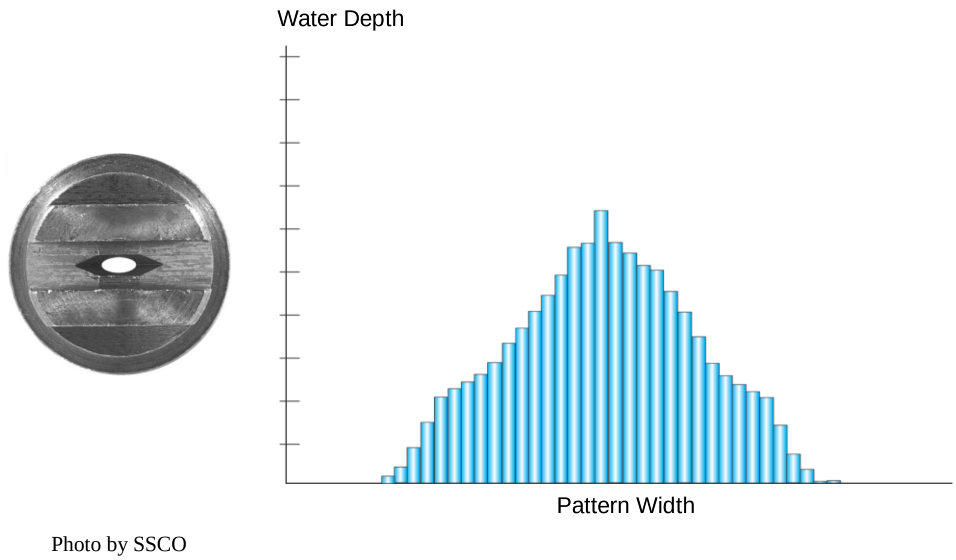


Figure 3.29. Worn spray tip showing pattern and distribution graph. Bar height indicates distribution of water over pattern width and shows an increase of and excessive flow in the center of the pattern due to orifice wear [adapted from SSCO 2013].

Performance Testing of Equipment

Due to the number of possible maintenance issues, performance testing should be done regularly to monitor the condition of spray equipment, considering numerous factors, as described below.

- *Application-specific analysis or measurements*. The dust content of the air should be surveyed and checked either visually, to determine the effectiveness of the spray at removing dust, or by using dust monitoring equipment that measures dust content in air. Visual inspection consists of simply observing the dust-producing area to determine if the spray system is effectively controlling the dust condition. Because this method of monitoring does not quantify the dust loading and is subject to operator interpretation, it does not specifically measure the efficiency of the spray system. Dust particle monitoring equipment is available that will quantify the dust loading in the problem area and provide a more accurate assessment of the system efficiency.
- *Flow rate*. The eye cannot necessarily detect increased flow, so the flow rate of each nozzle should be checked periodically by reading the flow meter or collecting the spray in a container. The results should be compared to specifications or to the performance of new nozzles.
- *Spray pressure*. Pressure in the nozzle manifold should be checked using a properly calibrated pressure gauge.
- *Spray pattern*. In many instances, visual inspection is adequate for monitoring pattern uniformity. Changes caused by orifice damage, clogging, or caking are usually noticeable. However, to detect gradual orifice wear, special measuring equipment will be required. A flow meter may be used to compare the flow of a new nozzle at a specific liquid pressure to the flow of a used nozzle at the same pressure. Nozzle wear causes the flow to increase, so the flow meter reading is a quantifiable indicator of the degree of orifice wear.

- *Nozzle alignment*. To provide uniform coverage, nozzles should be oriented correctly in relation to one another so that all like patterns are parallel.

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Chapter 4: Drilling and Blasting

CHAPTER 4: DRILLING AND BLASTING

The drilling process is used in both surface and underground mines for blasting operations that are conducted to fragment the rock. While the drilling process is similar for both types of mines, the different operating environments require specialized techniques to accomplish the same task. Drilling operations are notorious sources of respirable dust, which can lead to high exposure levels for the drill operator, drill helper, and other personnel in the local vicinity during operation. Therefore, dust controls on drills are necessary and involve both wet and dry methods.

Operator cabs are increasingly becoming an acceptable method for protecting the drill operator from respirable dust generated by the drilling operation, and the use of cabs is fully discussed in Chapter 10— Filtration and Pressurization Systems for Environmental Enclosures. Enclosing the operator in an environmentally enclosed cab is extremely effective. However, the protection provided, is only available to the personnel inside the cab. Other personnel working in the vicinity of the drilling operations, the drill helper, shotfirer, mechanics, etc., cannot be protected in this manner. They can attempt to maintain a work location upwind of the drill to avoid respirable dust, but this is not always practical. Therefore, methods for dust control on drilling operations are still required.

There are two basic methods for controlling dust on drills: either a wet suppression system or a dry cyclone/filter collector. Wet systems operate by spraying water into the bailing air as it enters the drill stem. Dust particles are conglomerated as the drill cuttings are bailed out of the hole. Dry collectors operate by withdrawing air from a shroud or enclosure surrounding the area where the drill stem enters the ground. The air is filtered and exhausted to the atmosphere. When dust controls are implemented effectively at drilling operations, both wet suppression and dry collection systems can achieve good dust control efficiency.

This chapter reviews methods for efficient and effective dust control for both underground and surface drilling operations. Much of the research for dust control has been conducted throughout the past century. The timeline for underground dust control research was during the 1920–1950 time period, when there was a significant program undertaken by the U.S. Bureau of Mines to prevent silicosis in underground miners [Reed et al. 2008]. Although this research could seem outdated, the principles still apply today and are confirmed to be still effective by practices in the field. Additionally, many of the results from underground research form the basis for dust controls developed for surface mine drilling. Surface mine dust control research began around 1980, when it was recognized that surface drillers were also susceptible to silicosis. Research continues today to discover new methods for dust control for both surface and underground drilling.

SURFACE DRILLING DUST CONTROL

Surface mine drilling is accomplished using both rotary and percussion drilling methods. Rotary drilling achieves penetration through rock by a combination of rotation and high down-pressures on a column of drill pipe with a roller drill bit attached to its end. Percussion drilling also achieves rock penetration through rotation and down-pressure, but with a pneumatic drill, which contains a piston that delivers hammer blows to the drill column or the drill bit, depending upon the location of the drill (top hammer or down-the-hole hammer). Percussion drilling eliminates the need for the high down-pressures required in rotary drilling.

Typical holes can be any size up to 15 inches in diameter, with the larger hole diameters commonly produced using rotary drill bits. Generally, these holes are oriented vertically, although some operations do use angled holes in their blast design, and the holes are drilled in a pattern where they are aligned in rows. The type of drilling equipment can range from small surface crawler rigs to truck-mounted drills to large track-mounted drill rigs, as seen in Figure 4.1.

Dust control methods for surface drilling use wet drilling or dry drilling with dust collection systems. There are variations to these methods due to the operating environment of the surface drilling operation and the type of equipment used, but the principles of dust control presented in this chapter are generally applicable to all types of surface drilling, including small crawler, truck-mounted, and large track-mounted drills.

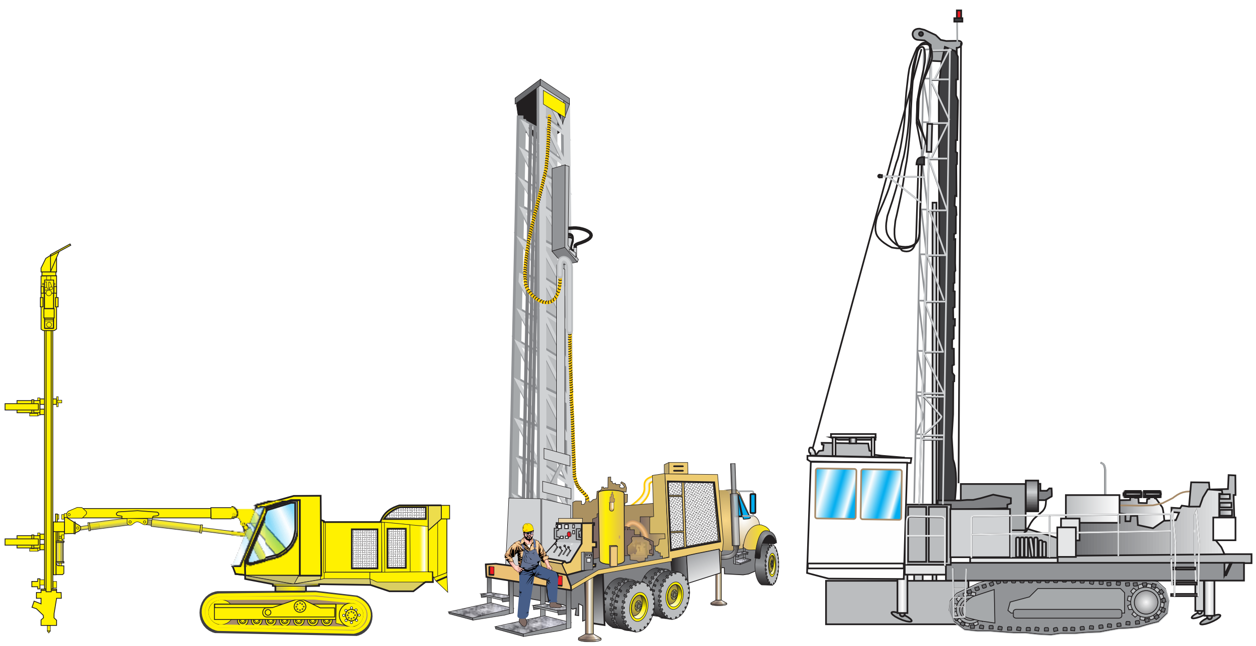

Figure 4.1. Illustrations depicting three types of rigs. A small surface crawler drill rig is on the left, a truck-mounted drill rig is in the center, and a large track-mounted drill rig is on the right.

Wet Drilling

An effective method for dust control in surface drilling is to use wet drilling techniques. Wet drilling injects water along with the air to flush the cuttings out of the hole, as shown in Figure 4.2. Testing has shown that this technique can provide dust control efficiencies up to 96 percent [USBM 1987].

Water injection requires monitoring by the drill operator to efficiently control dust. The amount of water required for dust control is not large. Typical water flow rates in wet drilling systems generally range from 0.1 to 2.0 gallons per minute (gpm), but this varies based on the drill type, geology, and moisture level of the material being drilled. For example, testing at a surface mine site showed that dust control efficiencies greatly increased when water flow was raised from 0.2 to 0.6 gpm. The dust control efficiencies then leveled off above this flow rate. However, once the flow rate approached 1.0 gpm at this site, operational problems were encountered such as the drill bit plugging and the drill steel rotation binding due to the water causing the drill cuttings to become too heavy to be removed by the bailing air [USBM 1987]. Therefore, too little water reduces dust control efficiency while too much water creates operational problems. The amount of water needed depends upon the surface drill type and the material being drilled.

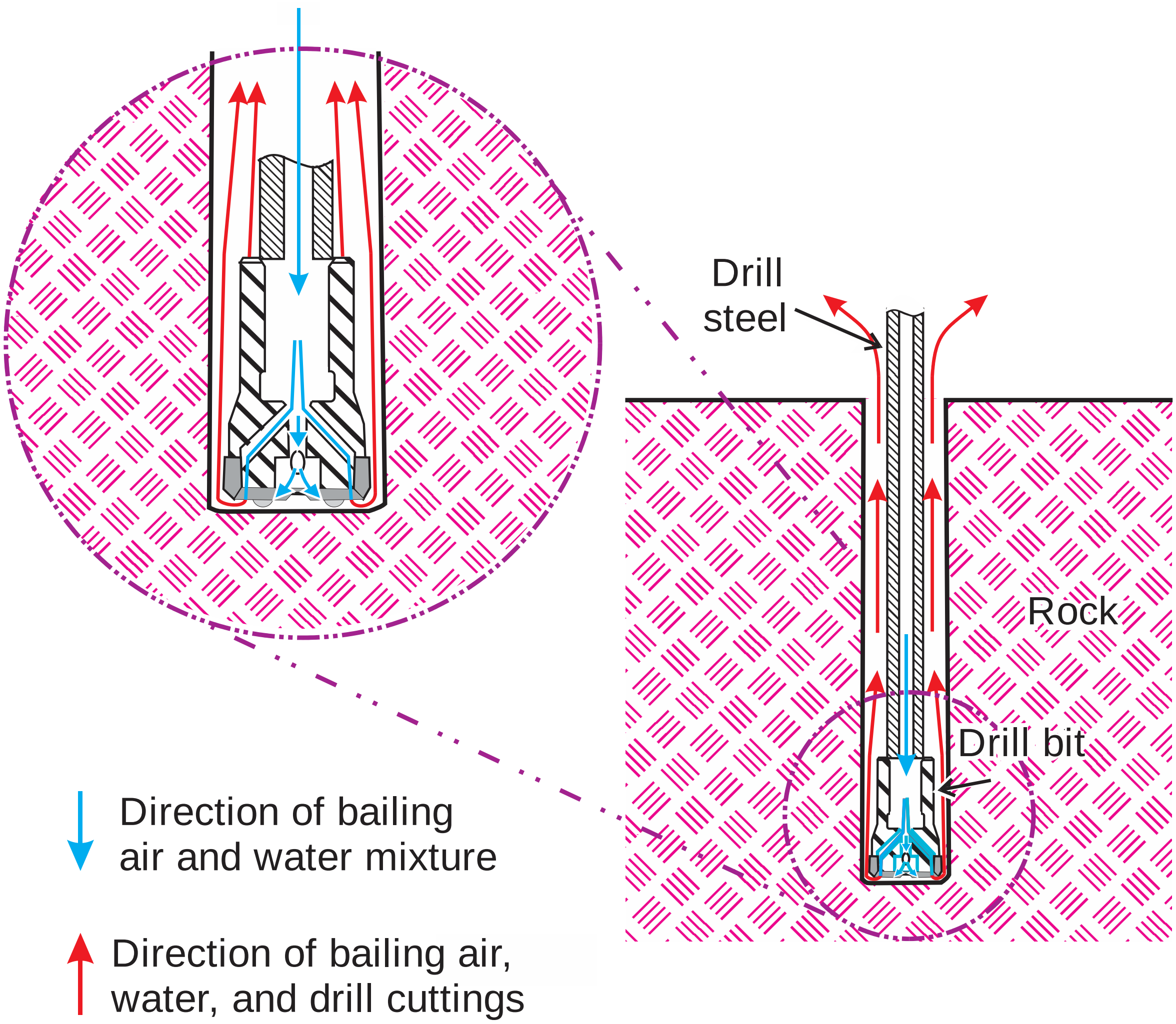

Figure 4.2. Illustration of air and water flow during drilling to demonstrate water flushing of the drill cuttings. The water flows through the center of the drill steel and out the end of the drill bit to remove the cuttings from the drill hole.

To provide for wet drilling, a water tank mounted on the drill is used to pump water into the bailing air, and the water droplets trap dust particles as they migrate up the annular space of the drilled hole (the annulus is the open area of the drill hole between the drill steel and the wall of the drill hole), thus controlling the dust as the air bails the cuttings. The drill operator controls the water flow from the cab, and some cabs are equipped with a meter to indicate water flow rate.

Advantages to Wet Drilling

A potential advantage to the use of water in percussion drilling operations, besides better dust control, is that the use of water may improve the penetration rate of percussion drilling for surface mining. There is very little information on wet drilling effects on penetration rate, but sources have shown that the use of water while percussion drilling in underground mining can produce an increase in the penetration rate of the drilling operation [Hustrulid 1982; USBM 1995]. Since this is applicable for underground mining, it may also correlate to increased penetration rates in surface mining situations. Further testing would be required to definitively assert that wet drilling would increase penetration rates of surface percussion drilling operations.

Recommendations for Proper Wet Drilling

Based on testing results and observational best practices, the following recommendations apply to surface drilling using wet drilling techniques.

- In order to operate at close to the optimum water flow rate, the operator should slowly increase the amount of water just to the point where visible dust emissions are abated. Addition of more water beyond this point will not provide any significant improvement in dust control but will most likely create operational problems, such as bit degradation (when using tri-cone bits) and possible seizing of the drill stem. Using less water will give poor dust control.
- It is important that the water be increased slowly to account for the lag time as the air/water/dust mixture travels from the bottom to the top of the hole.
- Continuous monitoring of the water flow during drilling is necessary to provide optimum dust control and prevent drill steel binding.
- The water used in the wet drilling system should be filtered to prevent debris from plugging the drill's wet drilling system.
- When using a wet suppression system in outside temperatures below freezing, the system must be heated when the drill is in operation, and during downtimes the system must be drained. For most drilling machines the proximity of the water tank and lines to the engine and hydraulic lines is sufficient to prevent freezing during operation (except in extreme cold weather situations). The water tank and lines must be drained when the drill is not in operation.

Disadvantages to Wet Drilling

While wet drilling may be an advantage when percussion drilling, there is a disadvantage to wet drilling when rotary drilling. The use of water degrades the tri-cone roller drill bits and shortens their lives by 50 percent or more [Page 1991]. This is due to rapid bearing material degradation through hydrogen embrittlement and accelerated bit wear. The bit wear is a result of operating in the abrasive rock dust-water slurry environment.

There is a solution to the disadvantage of short bit lives when wet drilling. In order to obtain acceptable drill bit life, the water must not reach the drill bit. This can be achieved through effective water optimization and water separation. Data gathered by the Bureau of Mines (BOM) from a mine where drilling occurred in monzonite, sandstone, limestone, and iron ore over a 14-

year period showed that drill bit life averaged 1,938 ft/bit when wet drilling without water separation. With water separation, the drill bit life increased over 450 percent to an average of approximately 9,000 ft/bit [USBM 1988].

Water Separator Sub

Water separation can be achieved through the use of a water separator sub. A water separator sub uses inertia to remove the injected water from the bailing air. A sub is a short length of a drill collar assembly which is placed between the drill bit and the drill steel. This assembly has male threads on one end to accommodate the drill steel and female threads on the other for the drill bit. It generally incorporates stabilizer wear bars affixed on its circumference which are used to center the drill bit in the drill hole.

Water separation is accomplished by forcing the bailing air stream to make a sharp turn or turns within its course just above the bit (Figure 4.3). Basically, the air/water mixture flows down through the center of the drill steel, past the standpipe, and makes a u-turn at the water reservoir. The airflow then flows up the outside of the stand pipe and through the slots, at which point the flow turns down the inside center of the standpipe, exiting through the nozzles in the drill bit. Due to the much higher inertia of the water, it cannot negotiate the turns and thus separates from the air. Since the drill stem interior is under positive air pressure, the accumulated water ejects through weep holes. These holes are in the separator perimeter above the bit, and the water ejects into the drill stem annulus. All drill cuttings cleared by the airflow travel through this annulus and are wetted. This prevents water from reaching the drill bit and inhibits the formation of slurry at the bit/rock interface.

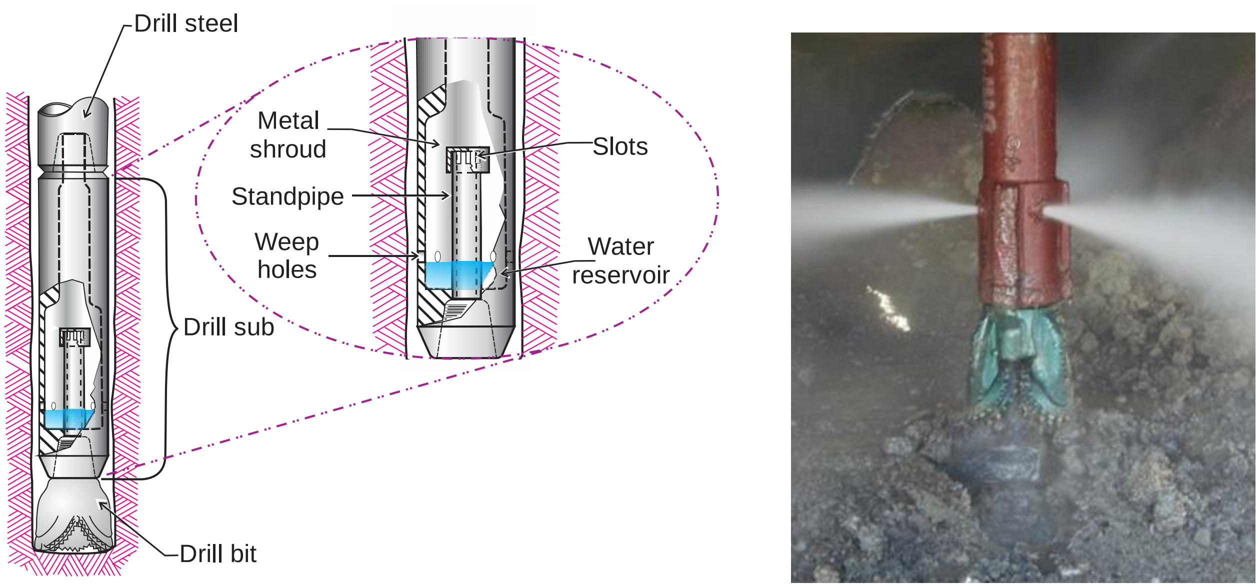

Photo by NIOSH

Figure 4.3. Illustration of the internal workings of a water separator sub. The photo on the right shows water being ejected from the weep holes.

Testing has demonstrated that dust control efficiencies of up to 98 percent can be obtained using the water separator sub, while dust control efficiencies of wet drilling without the water separator sub were 96 percent [Page 1991]. Most importantly, the use of the water separator sub increased bit life.

Dry Drilling

Dry drilling is accomplished without the use of water for dust control. Dust control is accomplished using a fan-powered dust collection system mounted on the drill. These systems have the ability to operate in various climates, i.e., they are not subject to freezing at lower temperatures as with the use of water, and they can be up to 99 percent efficient if properly maintained [USBM 1987]. There are different types of dust collector configurations used, dependent upon the size of the drill.

Medium- to Large-Diameter Drill Dust Collection Systems

Figure 4.4 shows a typical dry dust collection system on a medium- to large-diameter drill. Drill dust is generated by the bailing air, which is compressed air that is forced through the drill steel out the end of the drill bit and is used to flush the cuttings from the hole (Figure 4.2 depicts a similar scenario, but includes water). In a properly operating collection system, these cuttings are contained by the drill deck and shroud located over and around the drilling area, respectively. This dusty air from underneath the shrouded drill deck is removed by the dust collection system. The collector is composed of an exhaust fan, which transports the air from underneath the shroud area to filters located in the collector. The collector is generally self-cleaning, using compressed air to backflush through the filters at timed intervals to clean them and prevent clogging. The filtered fine-sized material then drops out the bottom of the collector to the collector dump, where it is then discharged to the ground. As shown in the figure, some dust can escape during the process around the drill deck, shroud, and collector dump.

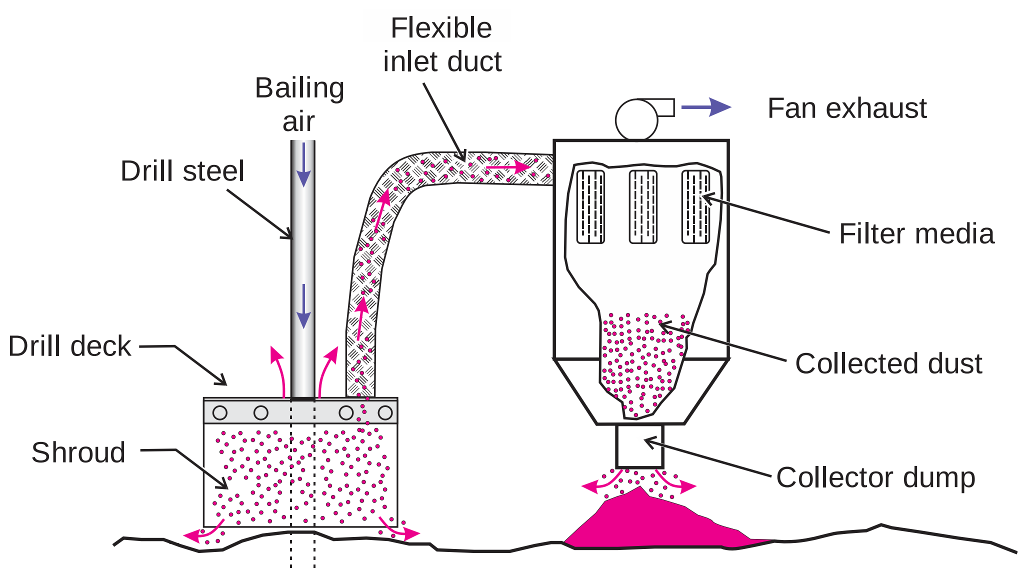

Figure 4.4. Illustration of a basic dry dust collector system on a drill.

Sources of Dust Emissions from Collection Systems

Damaged, nonfunctional, or missing dust collector filters are generally the root cause of dusty exhaust air from the collector. Other emission sources in the collection system can be caused by damaged or worn collector system enclosure components or operational conditions impeding the enclosure components from containing and capturing dust.

The integrity of the drill deck shroud and its sealing capability to the ground are critical factors in the effectiveness of a dry collection system for medium- to large-diameter drills. Over half of the dry dust collector emissions are from shroud and drill stem bushing leakage [USBM 1985]. Openings or gaps greater than six inches between the drill deck shroud and ground can significantly diminish the dust collector’s inlet capture effectiveness [USBM 1986; Zimmer et al. 1987]. Three areas of vulnerability related to dry dust collection have been identified:

- deck shroud leakage,
- collector dump discharge, and
- drill stem/deck leakage.

Deck Shroud Leakage Solutions

With the exception of air track drills, most rock drills have the same basic configuration and collector airflow volumes. The only parameter that varies is the shroud leakage area, and such variances obviously change the capture efficiency. Some of the most common shroud enclosure openings are between the bottom of the shroud and the ground, caused by uneven or sloping drill bench surfaces and at the corners of the drill deck.

Rectangular Shroud

Some shrouds have gaps at the corners of the front side of the shroud, which can be hydraulically lifted up so that drill cuttings are not dragged over the hole when the drill moves with its boom up. Because most deck shrouds are rectangular and constructed from four separate pieces of rubber belting attached to the deck, leakage can also occur as the seams separate from one another. To combat this problem, corner flaps can be added, attached with brackets, to help preserve the integrity of the shroud (Figure 4.5), or the shroud can be constructed with a single piece of material (rubber belting) encompassing the drill deck perimeter and overlapping itself at the seam.

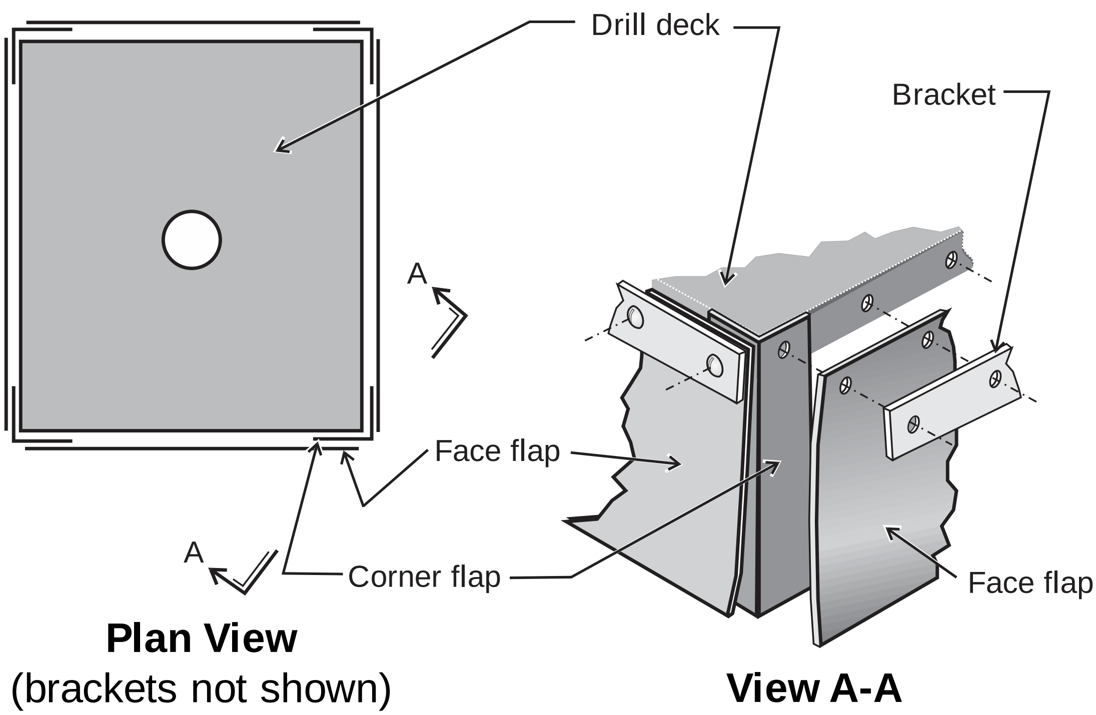

Figure 4.5. Illustration of reinforcing flaps added to each corner of a rectangular deck shroud to reduce leakage.

Circular Shroud

In contrast to the use of a typical rectangular shroud, a specialized circular deck shroud can be used to effectively accomplish dust capture during dry collection. A circular deck shroud is slightly conical in design with no open seams, and steel banding is used to attach the shroud to the bottom of the drill deck. The shroud can be hydraulically raised to the drill deck and lowered to make contact with the ground. A steel band is also attached to the bottom of the shroud to help maintain its shape and provide weight for lowering it to the ground, and guide wires are attached to the bottom of the steel band and a hydraulic cylinder (Figure 4.6). A thin sheet rubber material is used on the shroud to give it flexibility, and the shroud has a small trap door, operated manually so that the cuttings can be shoveled from inside the shroud without compromising capture efficiency.

During drilling, a large amount of cuttings may be generated and it is frequently necessary to raise the circular drill shroud to prevent the cuttings from falling back into the hole. As a result, there are times when it is unavoidable to have a broken seal between the shroud and the ground or cuttings. Therefore, it is important that the driller make a conscientious effort to keep the leakage area to a minimum. This may involve making frequent inspections underneath the shroud by raising the drill shroud to visually assess the circumstances.

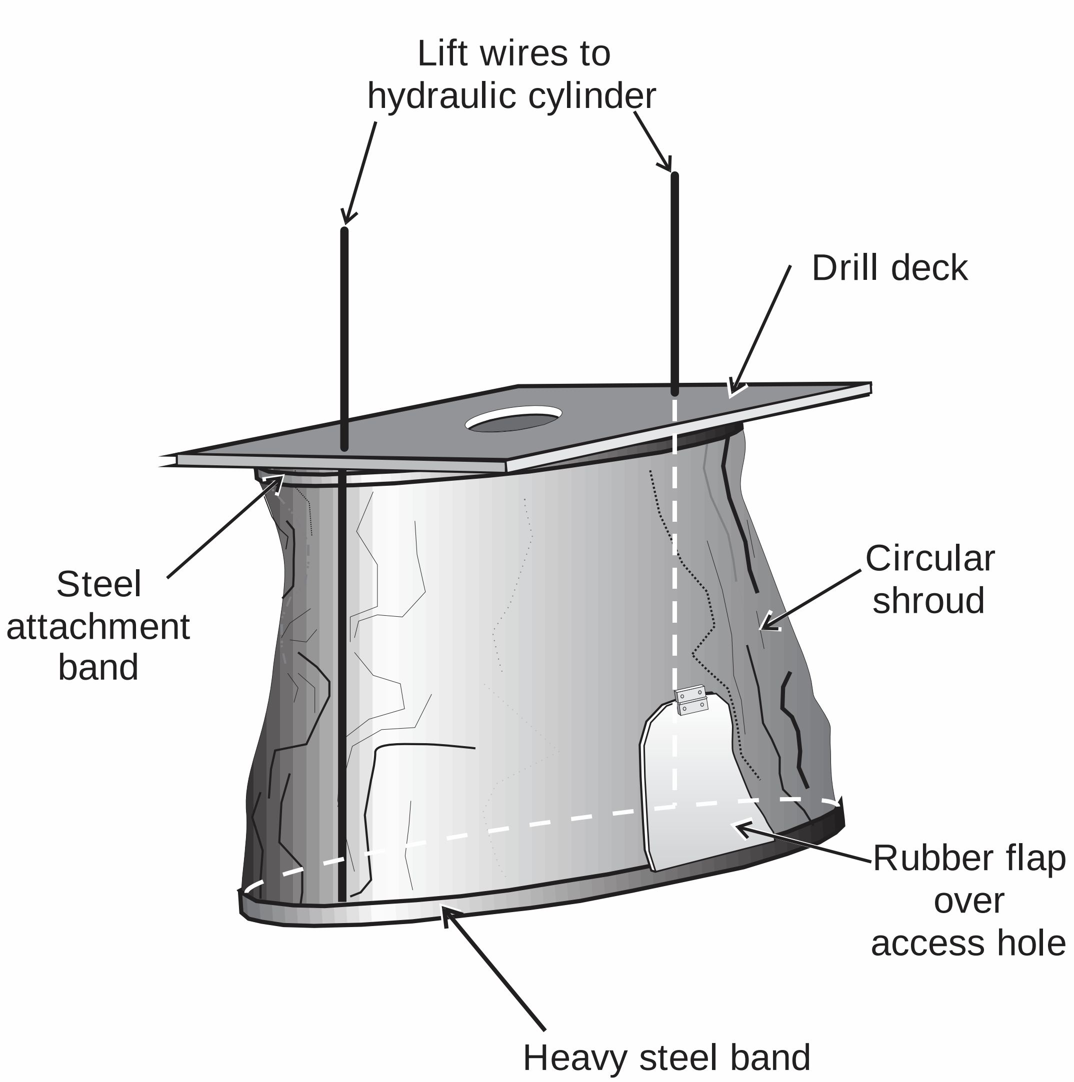

Figure 4.6. Illustration of a circular shroud design.

Collector to Bailing Airflow Ratio

Dry collection can be performed most efficiently by maintaining an appropriate collector to bailing airflow ratio. This ratio, which can be represented by Q_C/Q_B, has been found to be an important indicator of dust collection performance. Dust collector airflow (Q_C) in standard cubic feet per minute (scfm) is the quantity of airflow generated by the dust collector fan, which pulls the air from underneath the drill shroud. Bailing airflow (Q_B) in scfm is the quantity of compressed air blown down the drill stem through the bit in order to flush the cuttings out of the hole.

Bailing airflow (Q_B) can be obtained from the drill manufacturer as the quantity airflow rating of the drill's compressor, which has units in scfm, while measurements of the collector airflow (Q_C) can be reasonably made by using a hot wire anemometer, vane anemometer, or pitot tube at the collector exhaust. More accurate measurements can be obtained by attaching a short (4-foot) duct extension to the collector exhaust and inserting the hot wire or pitot tube, to measure the airflow in cubic feet per minute (cfm), into a hole made at the halfway point in the duct. This extension can be simply made from cardboard and fitted to the outside of the collector exhaust duct. The collector airflow can be converted to scfm, but this is not necessary as the corrections from the ambient conditions generally have a small effect on the measurement. Also, due to the changes in the pressure drop across the filters caused by dust buildup, the quantity of air from the dust collector can vary by an amount that is much more significant than changes from standard atmospheric conditions.

Common collector to bailing airflow ratios on operating drilling rigs were found to be as high as 3:1 in the field. However, 2:1 ratios were more typical of operating collectors with normal filter loading [Page and Organiscak 2004]. Poorly operating collectors were found to operate at ratios of 1:1 or lower. Testing has shown a notable reduction in dust concentrations escaping through the bottom of the deck shroud gap by increasing the collector to bailing airflow ratio [NIOSH 2006; Organiscak and Page 2005]. Figure 4.7 shows the results of changing the collector to bailing airflow ratio at various drill deck shroud gap heights from the ground. As shown, the largest decrease in dust levels is observed when the collector to bailing airflow ratio is increased from 2:1 to 3:1, with further decreases in dust levels as the ratio is increased to 4:1.

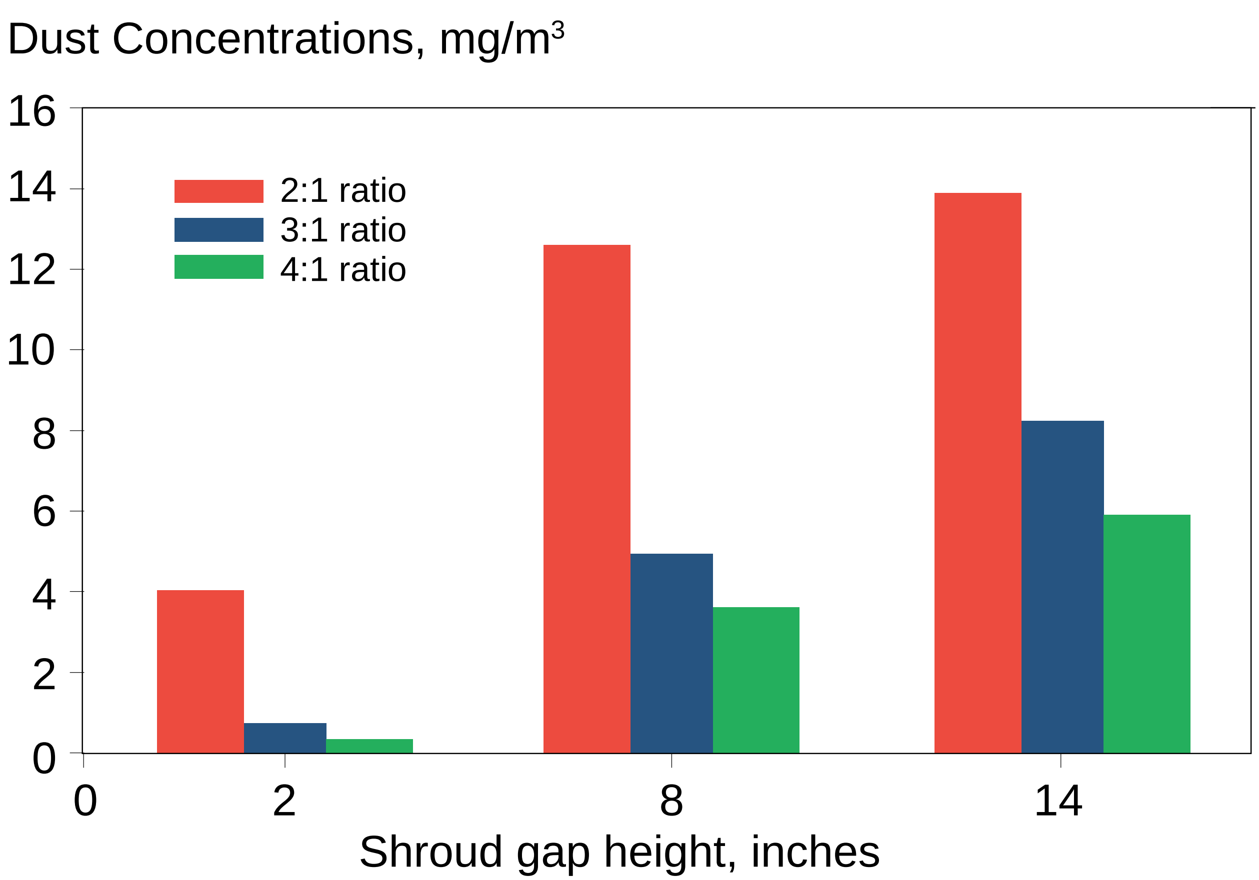

Figure 4.7. Results of changing the collector to bailing airflow ratio at various shroud gap heights.

Airflow Maintenance for Dust Control

The collector and bailing airflows need to be maintained to sustain the high collector to bailing airflow ratios that prevent high dust emissions. The bailing airflow from the drill's compressor is the maximum rated airflow and generally does not vary much over the life of the drill. Therefore, its impact on the collector to bailing airflow ratio is minor compared to the impact of the dust collector airflow. Performing the normal maintenance on the compressor as required by the manufacturer will keep it in proper operating condition.

The dust collector airflow has a more substantial impact on the ratio due to the many components that make up the collector. The dust collector airflow can decrease over time due to damaged components and neglected maintenance. Therefore, proper maintenance of the collector to maintain maximum airflow is required. Collector maintenance involves five actions by the operator:

- ensuring that filter backflushing is operating properly and within specifications,
- verifying that the intake duct and collector housing are tightly sealed and free of holes,
- changing filters at recommended intervals or when damaged,
- ensuring that the tubing and inlet to the collector are free of obstructions, and
- ensuring that the collector fan is operating properly and within its specified speed.

Use of Collector to Bailing Airflow Ratios for Dust Control

The collector to bailing airflow ratios are useful in that they form the basis of a model to predict the relative severity of the drill dust emissions and to estimate how much of a reduction is possible by measuring several basic parameters of the drilling operation. The parameters needed are: dust collector airflow (Q_C), bailing airflow (Q_B), drill deck shroud cross-sectional area (A_S), and shroud leakage area (A_L) or an approximate estimate for the leakage area [Page et al. 2008a,b].

The model depicted as a graph in Figure 4.8 (top) shows the relative reductions possible by reducing the leakage area [Page et al. 2008a,b]. To demonstrate how the graph can be used, the following example is given.

> An operator has a drill rig with drill deck dimensions of 4 feet by 5 feet. The rated compressor Q_B is 260 scfm and Q_C was measured at 530 scfm which represents a collector to bailing airflow ratio Q_C/Q_B of approximately 2. The area of the shroud is calculated by multiplying the width by the length resulting in $A_S = 20\ ft^2$. A_L is calculated by multiplying the leakage height (LH) in feet by the perimeter of the shroud which results in A_L = LH x 18 ft. Therefore, the ratio $A_S/A_L = 20\ ft^2/(LH \times 18\ ft)$ and can be calculated by estimating LH.
>
> Since $Q_C/Q_B = 2$, the top graph in Figure 4.8 can be used to show how reducing the leakage gap between the shroud and the ground will reduce the severity of the dust concentrations. A gap of 14 inches corresponds to $A_S/A_L = 0.95$, showing a relative airborne respirable dust concentration of approximately 16 mg/m^3, while a gap of 2 inches corresponds to $A_S/A_L = 6.7$, resulting in a relative airborne respirable dust concentration of approximately 5 mg/m^3. This example demonstrates that reducing

the leakage height of the drilling operation will result in a substantial improvement in dust reductions.

It should be noted that any leakage area due to vertical shroud seam gaps should also be included by estimating the area for vertical leakage and adding this value to the shroud leakage area (A_L), but many times, vertical leakage may not be significant. Graphs for Q_C/Q_B greater than 2 are similar, with the difference being that airborne respirable dust values at any value of A_S/A_L will become smaller as Q_C/Q_B increases [Page et al. 2008b], as demonstrated in the comparison of the two graphs in Figure 4.8.

It is important to keep in mind that the calculated value of airborne respirable dust is a relative value only and is not as important as the estimated value of A_S/A_L. The key considerations are where on the curve the drill operates, as determined by A_S/A_L, and which curve is applicable (i.e., what value is Q_C). These determinations will indicate the long-term average improvement that can be expected from either increasing the collector airflow (installing clean filters or a larger collector) or reducing the amount of shroud leakage.

To demonstrate, a drill currently operating on the left side of the curves in Figure 4.8 can readily make significant airborne respirable dust reductions. A drill operating on the right side of the curves indicates that only minimal reductions are achievable. However, operation on the right side of the curves also usually indicates a drill that has good operating dust controls [Page et al. 2008b]. As stated previously, typical values of Q_C/Q_B in actual operation with dirty filters are on the order of 2. Therefore, on surface blasthole drill rigs it is important to maintain collector to bailing airflow ratios greater than 2, with ratios of 3 or more being more desirable.

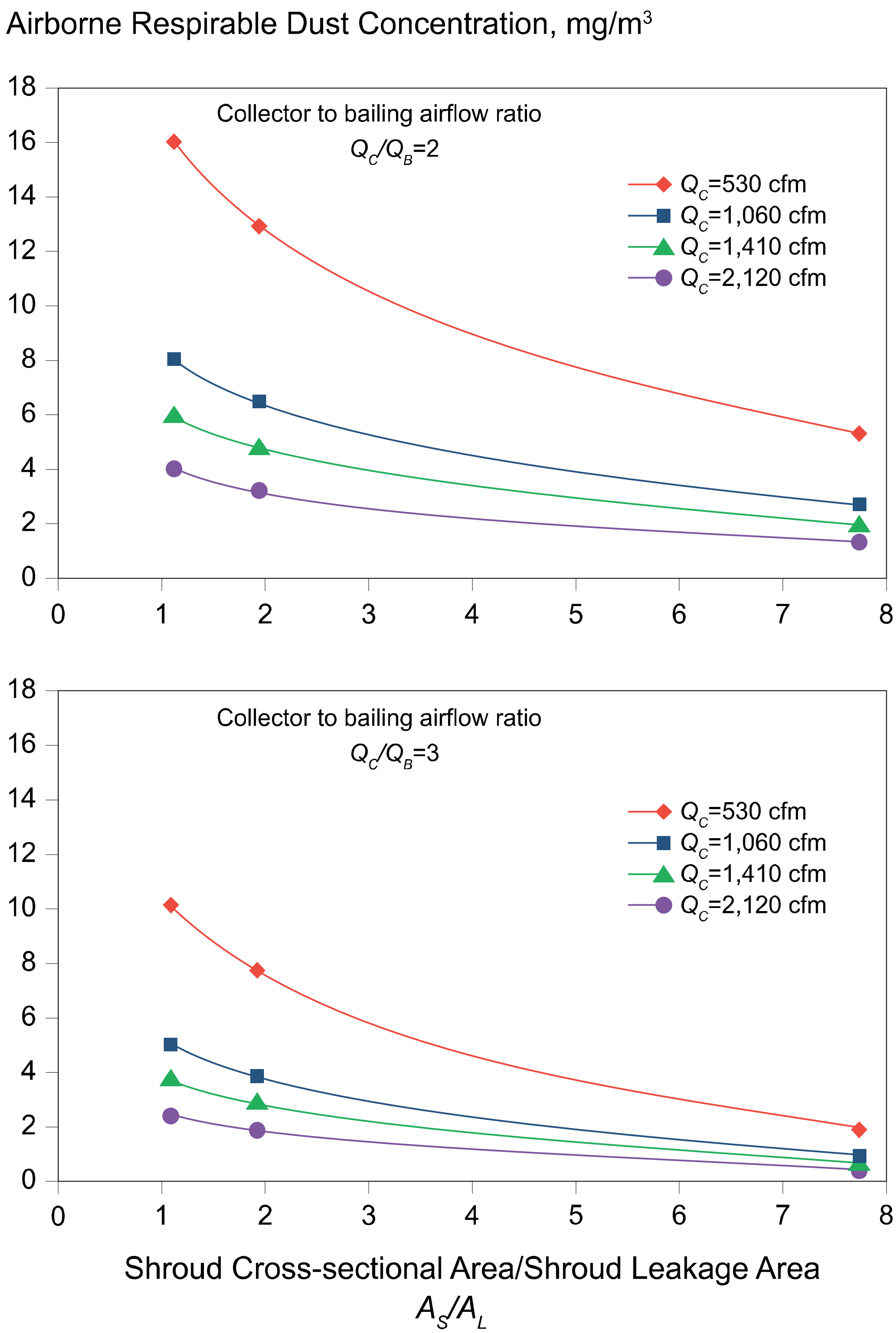

Figure 4.8. Graphs of the model representing the severity of dust emissions based upon collector to bailing airflow ratios. The graphs show that the respirable dust concentrations become lower as the collector to bailing airflow ratio increases.

Air-blocking Shelf

The air-blocking shelf is a dust control that has been found to be effective for medium- to large-sized track-mounted blasthole drills. However, it would be effective for any drill with a large-sized drill shroud with approximate minimum dimensions of 4 feet by 4 feet. A 6-inch-wide shelf is placed underneath the drill shroud along the inside perimeter of the shroud. Its purpose is to reduce dust emissions from the drill shroud while the drill is operating. It was developed by observing the airflow patterns underneath the drill shroud at a drill shroud test facility [Potts and Reed 2008; Reed and Potts 2009].

Normally during drilling, the airflow pattern occurs as shown in Figure 4.9 (left) and consists of the bailing air exiting the drill hole along with an influence from the dust collector. The bailing air travels from the drill hole through the middle of the shrouded area, maintaining its course along the drill steel to the underneath side of the drill table, where it exhibits a coanda effect (a moving fluid's tendency to be attracted to a nearby surface) as it fans out across the bottom of the drill table and continues down the sides of the shroud. All of this occurs at a high velocity. Dust emissions at the ground surface occur when the air strikes the ground and fans out from underneath the shroud enclosure. The 6-inch-wide shelf is placed along the inside perimeter of the shroud, where it disrupts the downward airflow along the shroud (Figure 4.9, right).

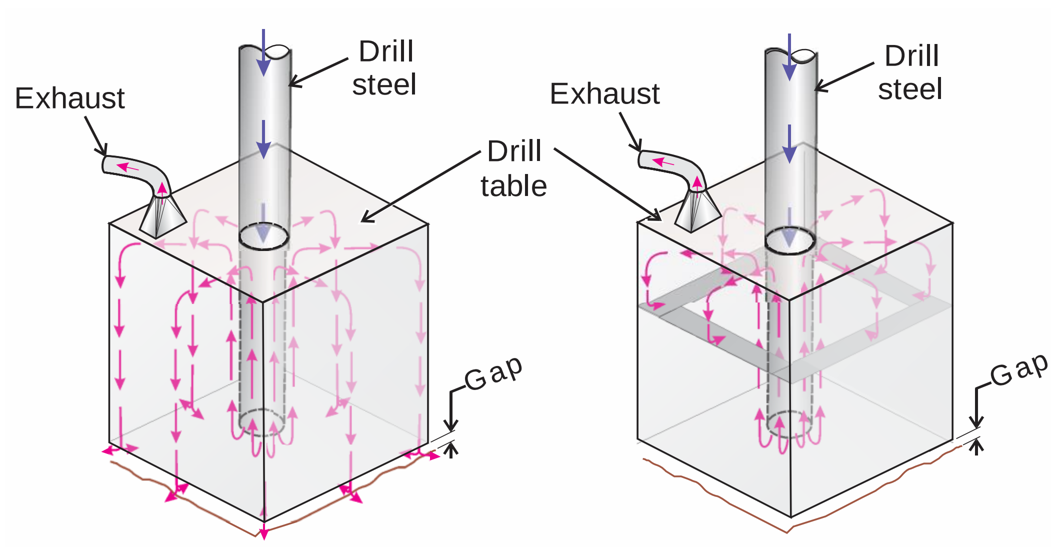

Figure 4.9. Qualitative models of airflow patterns underneath the shroud. The left illustration shows the airflow pattern without the air-blocking shelf. The right illustration shows the airflow pattern with the air-blocking shelf.

Using computational fluid dynamics (CFD) software, the downward airflows are shown to be redirected inward toward the center of the enclosure. At the ground surface, the downward airflow is pulled back into the flow of upward moving air from the blasthole. This prevents the downward contaminated airflow from leaving the shroud at the ground-to-shroud gap interface [Potts and Reed 2008; Reed and Potts 2009; Zheng et al. 2016; Zheng et al. 2018]. For an illustration of this process by way of CFD modeling software, see Figures 4.10 and 4.11. Both figures depict airflows resulting from a 500 cfm bailing airflow and 2:1 collector to bailing airflow ratios.

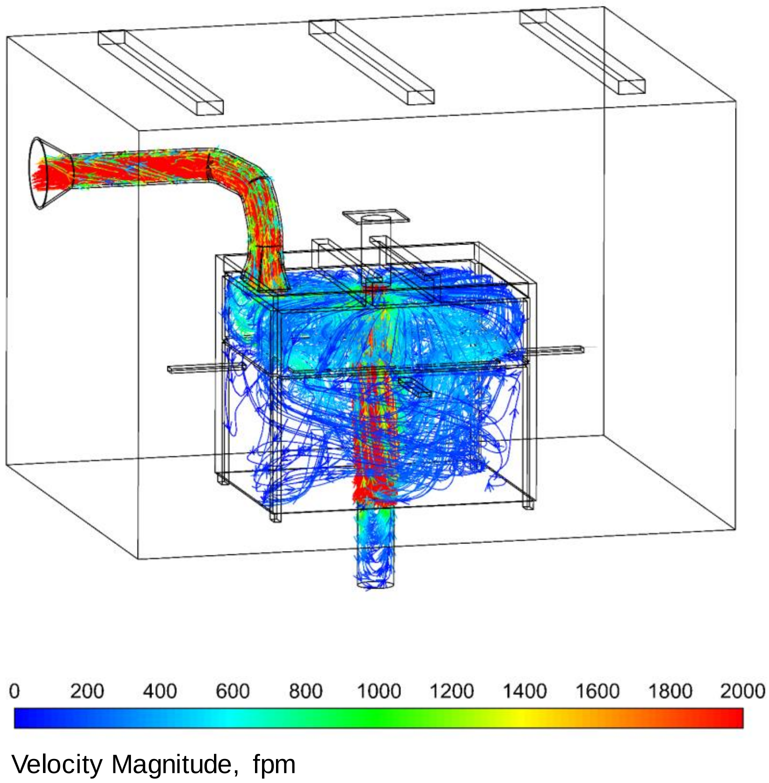

Figure 4.10. The pathline of bailing airflow colored by a velocity magnitude of 0 to 2,000 feet per minute (fpm) with a 6-inch-wide shelf.

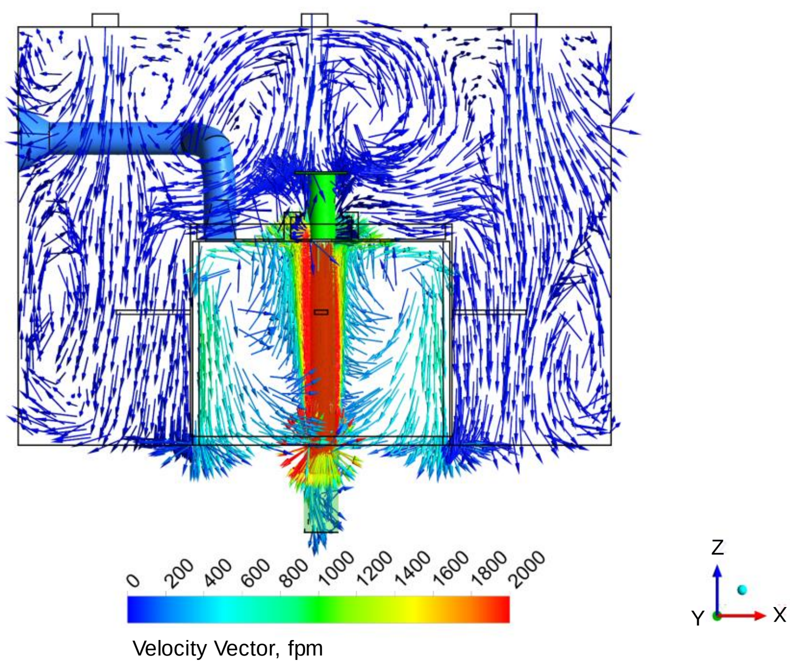

Figure 4.11. Velocity vectors for a cross-sectional plane (shroud without air-blocking shelves) with a detailed view underneath the table.

Figure 4.12 shows a shelf installed on a blasthole drill during testing. The shelf was constructed of 6-inch conveyor belting material that was bolted to 2-inch light-gauge angle iron. The angle iron was then bolted to the inside perimeter of the shroud. A section of shelf (not pictured) was added to the door flap of the shroud to ensure complete coverage of the parametric cross section. The shelf was installed at a location that is approximately halfway between the top of the shroud and the ground surface. Laboratory testing demonstrated that the individual shelf pieces, which were located on each side of the shroud, did not have to be installed on the same horizontal plane in order to be effective. Rather, coverage of the parametric cross section of the shroud seemed to be the important design criterion (i.e., no gaps should be allowed at the corners or along the length of the shelf). Installation was simple, with two persons able to assemble the shelf in less than an hour [Potts and Reed 2008].

Once installed, the air-blocking shelf requires no maintenance unless it is damaged during tramming from hole to hole. Field testing of the air-blocking shelf on blasthole drills has shown dust reductions from the shroud ranging from 66–81 percent [Potts and Reed 2011], with the differences being attributable to differing wind directions and rock type drilled. However, it should be noted that when the dust levels from drilling operations are very low (< 0.5 mg/m^3), the effectiveness of the air-blocking shelf is reduced. This is due to the effect of the many other dust sources (dust collector, table bushing, other mining operations, etc.) surrounding the drill, which can impact the dust levels [Potts and Reed 2011].

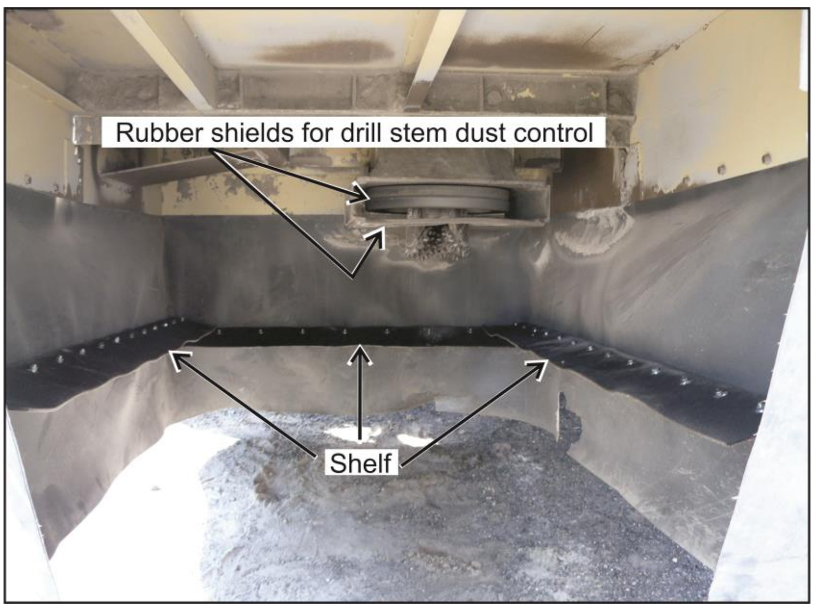

Photo by NIOSH

Figure 4.12. Air-blocking shelf installed on the inside perimeter of the drill shroud of a blasthole drill. Note the overlap in the rear corners to eliminate any gaps in the shelf perimeter.

A disadvantage that was found with the shelf is that material buildup from the drill cuttings can occur on the air-blocking shelf (Figure 4.13, left). This can cause significantly higher dust levels when lowering the mast due to the additional built-up material falling off the air-blocking shelf (Figure 4.13, right). Dust emissions from material falling from the shroud during drill mast lowering normally occur without the shelf. Therefore, the shelf does not create a new problem of dust emissions from mast lowering, but it does have the potential to exacerbate this existing problem. This disadvantage can be overcome by installing the shelf at a 45-degree angle from the horizontal and constructing it from different material (Figure 4.14).

Photos by NIOSH

Figure 4.13. Material buildup from drill cuttings that can occur with the use of an air-blocking shelf. The left photo shows buildup of material on the air-blocking shelf. The right photo shows the resulting dust emissions created during lowering of the drill mast.

Photo by NIOSH

Figure 4.14. Air-blocking shelf with modifications incorporated into installation. This shelf was installed in short sections in an attempt to prevent potential damage that could occur during tramming with the drill mast up. Note that each of the sections overlap, eliminating any gaps in the shelf perimeter.

When installing the shelf at a 45-degree angle, it is important that the shelf width be increased from 6 inches to 8 inches to maintain an equivalent 6-inch horizontal width. The shelf should be constructed of 1/4-inch high-density polyethylene (HDPE). The HDPE has a slippery surface, which minimizes adhesion of the dust to its surface. It can be purchased in 4-foot by 8-foot sheets and cut to the required dimensions. These modifications eliminate the buildup of material on the air-blocking shelf. Additional modifications include shortening the shelf sections to prevent possible damage during tramming, and the addition of chains to support the shelf to prevent it from sagging. When using shortened shelf sections, it is important that they overlap to eliminate any gaps that may occur in the air-blocking shelf perimeter. These modifications should not diminish the effectiveness of the air-blocking shelf.

Collector Dump Discharge

The collector dump cycle can account for as much as 40 percent of the respirable dust emissions [USBM 1985]. The dust collector dump cycle operates in one of two modes: trickle mode or batch mode. In the first mode (trickle mode), the collector filter cleaning mechanism operates at preset time intervals, e.g., every 1 minute. This allows the fine material from the collector to trickle out onto the ground. In the second mode (batch mode), the collector cleaning mechanism operates when the bailing airflow stops. This condition occurs during intervals when adding or removing drill steels, or when removing the drill bit from the hole. The batch mode creates the highest dust levels because of the longer accumulation time of fine material in the collector before dumping. During the batch mode, the dust is usually emitted into the ambient air when the fine material is dropped, which creates significant dispersion. Also, this fine material strikes the ground, producing more dust dispersion. Finally, the drill itself and service vehicles frequently drive through the dust pile formed by dumping, stirring up clouds of dust. Avoiding disturbing the collector dump piles will prevent dust from being entrained into the air.

Preventing Collector Dump Dust Entrainment

The dust collector dump point is generally anywhere from 24 to 36 inches above the drill bench. Dumping the fine material from this height causes entrainment of the respirable fraction of this material into the air. To reduce this entrainment and lower the respirable dust concentrations at the collector dump point, a piece of brattice cloth can be attached to the dust collector dump using a large hose clamp. Figure 4.15 shows the installation of the dust collector dust shroud. This dust shroud was installed over the existing rubber boot attached to the dust collector dump.

A B C

Photos by NIOSH

Figure 4.15. Installation of the dust collector dust shroud. Dust collector dump point prior to shroud installation (A). Two workers installing the shroud onto the dust collector dump point (B). The dust collector dump point after installation of the shroud (C).

This simple procedure of creating a dust collector dump shroud has been shown to be very effective in reducing the respirable dust. Respirable dust concentrations measured after installation of the dust collector shroud ranged from 0.16 to 0.24 mg/m^3. Figure 4.16 shows the reduction of the respirable dust concentrations near the collector dump point with and without the dust collector shroud. It can be seen that the respirable dust generated by the dust collector dump point can be reduced by between 63 and 88 percent using the shroud [Reed et al. 2004]. It should be noted that this reduction is highly dependent upon wind direction and wind speed. Advantages to this method of respirable dust reduction are that the material is inexpensive and requires almost no maintenance. If the shroud becomes damaged, it can easily be replaced in 10–15 minutes, requiring little if any downtime for the drill.

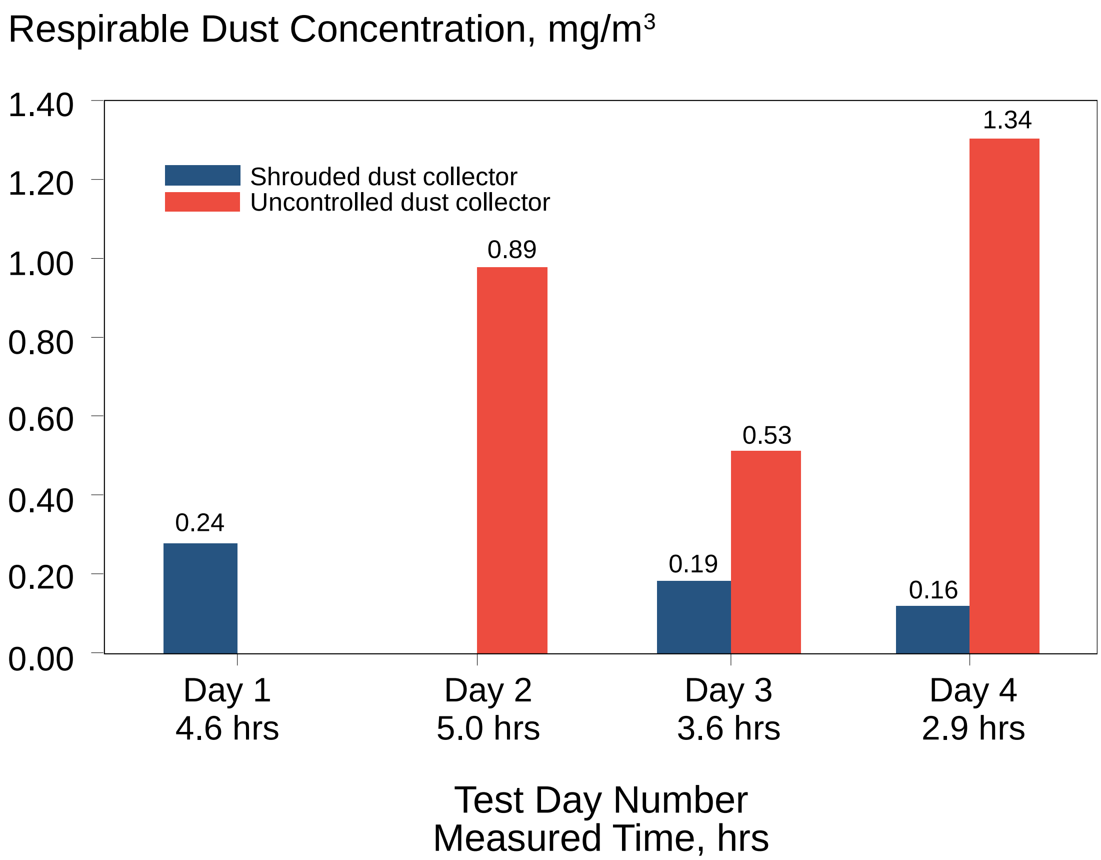

Figure 4.16. Comparison of dust concentrations of uncontrolled dust collector dump to shrouded dust collector dump.

To install the shroud, the length of brattice cloth (or similar material) should be sufficient to allow it to extend from the dust collector dump point to the ground. It should be cut so that it is only long enough to just touch the ground when the drill is lowered. When wrapping the cloth around the dust collector dump, the overlap should be placed so that it is on the outside of the dust collector dump (i.e., it should be visible as the installer looks directly at the dust collector dump, as shown in Figure 4.13C). This overlap allows the cloth to expand as fine material is dumped to the ground, while containing the entrained respirable fraction within its confines. Placement of the overlap on the outside also keeps the fine material off the drill tracks, which otherwise could cause re-entrainment of the respirable fraction of the material when the drill starts in motion.

Drill Stem/Deck Leakage

Drill cuttings and dust leaking through the drill table bushing can be a large source of respirable dust exposure to the drill operator and surrounding personnel. The table bushing, when new, generally prevents drill cuttings from coming through the drill deck. However, the table bushing is susceptible to wear during drilling operations, creating gaps between the bushing and the drill steel and deck surfaces, which can allow the drill cuttings and dust to escape from underneath the deck.

Preventing Drill Stem/Deck Leakage

In an attempt to minimize this source of dust, many drill operations install a rubber shield (generally a piece of used conveyor belting) underneath the drill deck covering the area of the table bushing. A hole is placed in this shield to allow the drill bit to pass through. This shield is also susceptible to wear and damage, and dust emissions through the drill table bushing occur over time. Figure 4.10 shows this rubber shield, which is located at the drill bit underneath the drill deck.

An innovation to help keep dust from escaping around the drill stem/deck is the air ring seal (AIRRS). The AIRRS is a nonmechanical, virtually maintenance-free system consisting of a donut-shaped compressed air header with closely spaced holes (Figure 4.17) along its inside perimeter [Page 1991]. When compressed air is supplied to the AIRRS, high-velocity air jets are produced through the holes. These jets are directed across the opening to be sealed in order to impede movement of dust particles through the opening.

The AIRRS is installed underneath the drill deck at the location where the drill steel penetrates the drill deck, positioned so that the drill bit and steel penetrate the inside diameter of the AIRRS. The diameter of the AIRRS should be as small as possible, but maintaining clearance for the drill bit and table bushing is an important consideration to minimize damage when raising the drill steel to remove the table bushing and drill bit. It is also very important that the drill’s dust collector be maintained to achieve a collector to bailing airflow ratio of at least 2:1; otherwise more dust will be generated from the shroud area when using the AIRRS.

On surface mine drills equipped with the AIRRS, it successfully and significantly reduced respirable dust levels, as well as helped to keep the drill deck clean [Page 1991]. Solid-mounting the AIRRS flush with the deck virtually eliminates all large cuttings as well as the visible dust above the deck. The amount of air supplied to the AIRRS would be limited to what is available from the drill’s compressor. An air pressure of 30 pounds-force per square inch gauge (psig) with 1/16-inch holes in the AIRRS was successful in reducing respirable dust levels [Page 1991]. However, this amount of air would be highly dependent upon the drill configuration.

In addition to using the AIRRS, installing a low-clearance deck bushing can minimize drill cuttings through the drill deck by reducing the gap size through which cuttings can escape. Replacement of the deck bushing as necessary can also enhance the performance of the air ring seal.

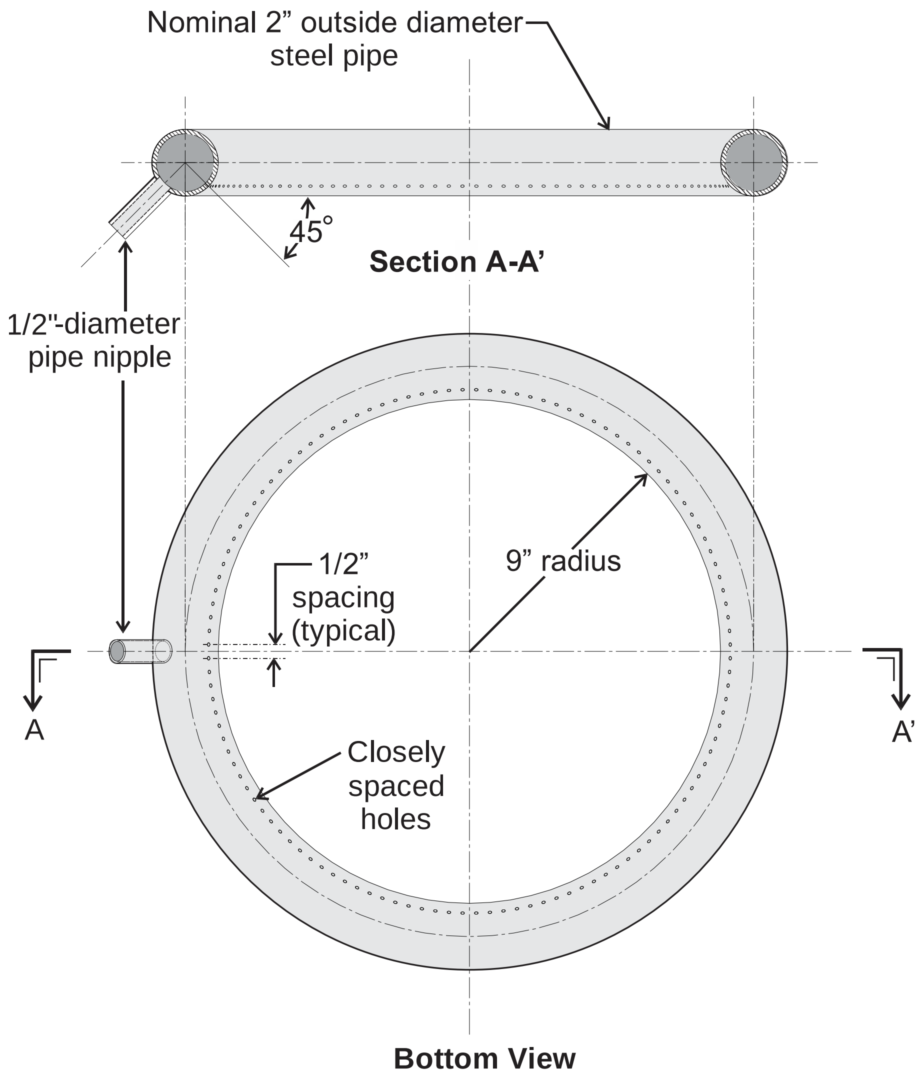

Figure 4.17. Air ring seal used to impede the movement of dust particles through an opening.

Small-Diameter Drill Dust Collection Systems

A dust collection system used for small- to medium-diameter drills and small surface crawler (or "buggy") drills is shown in Figure 4.18. A schematic shows the operation of this type of system. The difference from the large-diameter drill dust collection system is that this system collects all the drill cutting material, sends it to a large separation cyclone on the drill boom to drop out the large-diameter material, and then sends the remainder to the dust collector at the back of the drill where the fine-sized material is discharged.

Maintenance of the dust collection system is important in sustaining efficient dust control with these systems. Two important maintenance issues are as follows:

- filters should be replaced before they become clogged; and
- dust leakage from the bushing at the drill steel and the shroud device can be severe if not properly maintained (this has been shown to be even more important to dust control than the seal between the shroud device and the rock) [USBM 1956].

These drills may also contain a water misting system for dust control. This system includes a tank containing a dust suppressant mixture that is injected into the primary and fine collectors to reduce dust from their discharge [Sandvik 2005]. Monitoring the dust suppressant is important to maintain the integrity of the dust collector system.

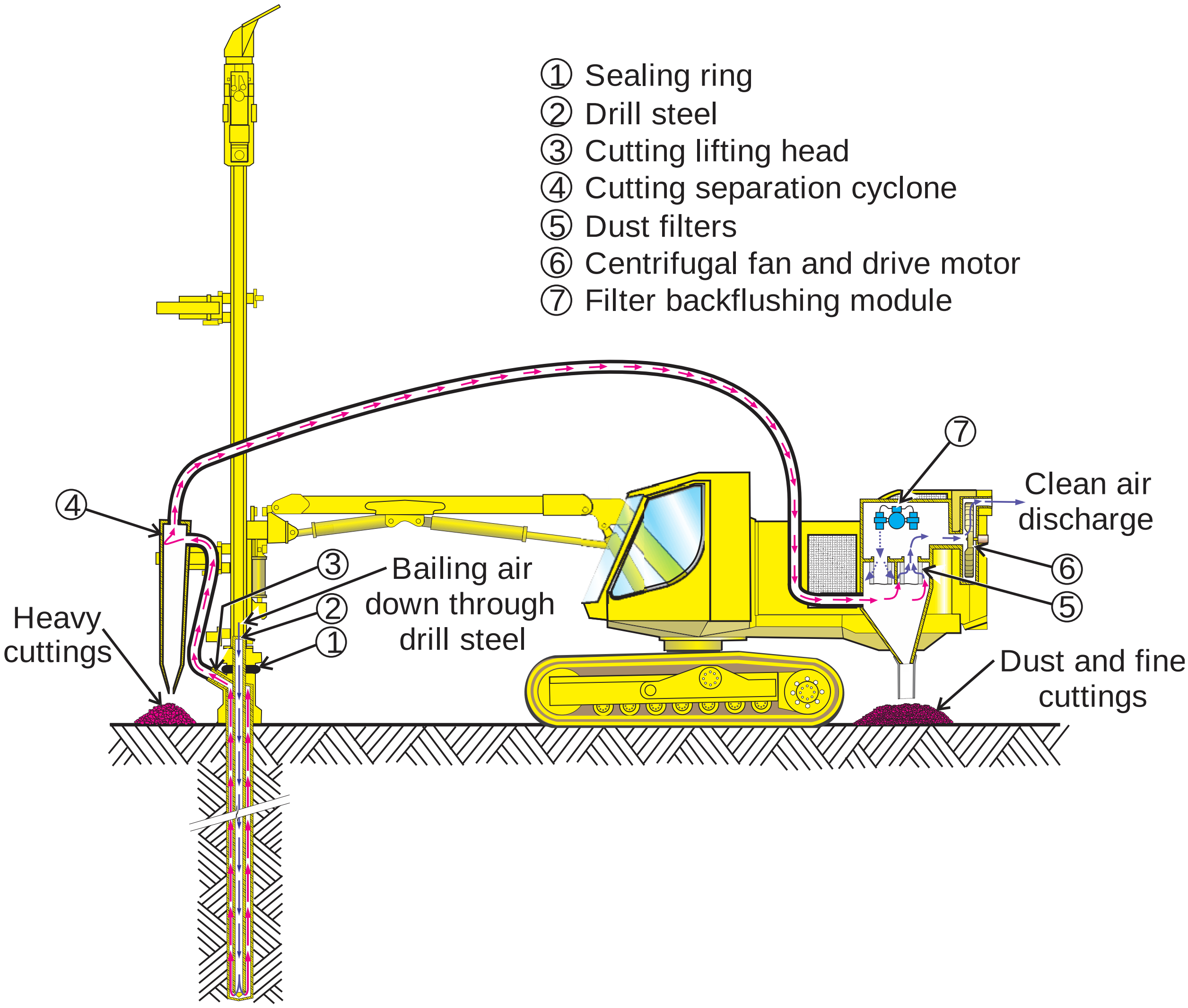

Figure 4.18. Illustration of a typical dust collector system used by small crawler (or "buggy") drills.

UNDERGROUND DRILLING DUST CONTROL

Underground drilling is generally accomplished using percussion drilling with small-diameter holes (up to three inches). Depending upon the type of underground mining method used, these holes can be oriented in almost any direction. Generally the holes for a blast are consistently oriented horizontally or vertically and are drilled in a symmetrical pattern. The type of drilling equipment used can range from jackleg drills to stopers to jumbos, which operate two to three drill booms as shown in Figure 4.19. The most common method of dust control for underground drilling is using wet drilling techniques. Dry collectors have been used in the past, but are not commonly used due to the bulkiness of the collectors and their associated maintenance issues [USBM 1951].

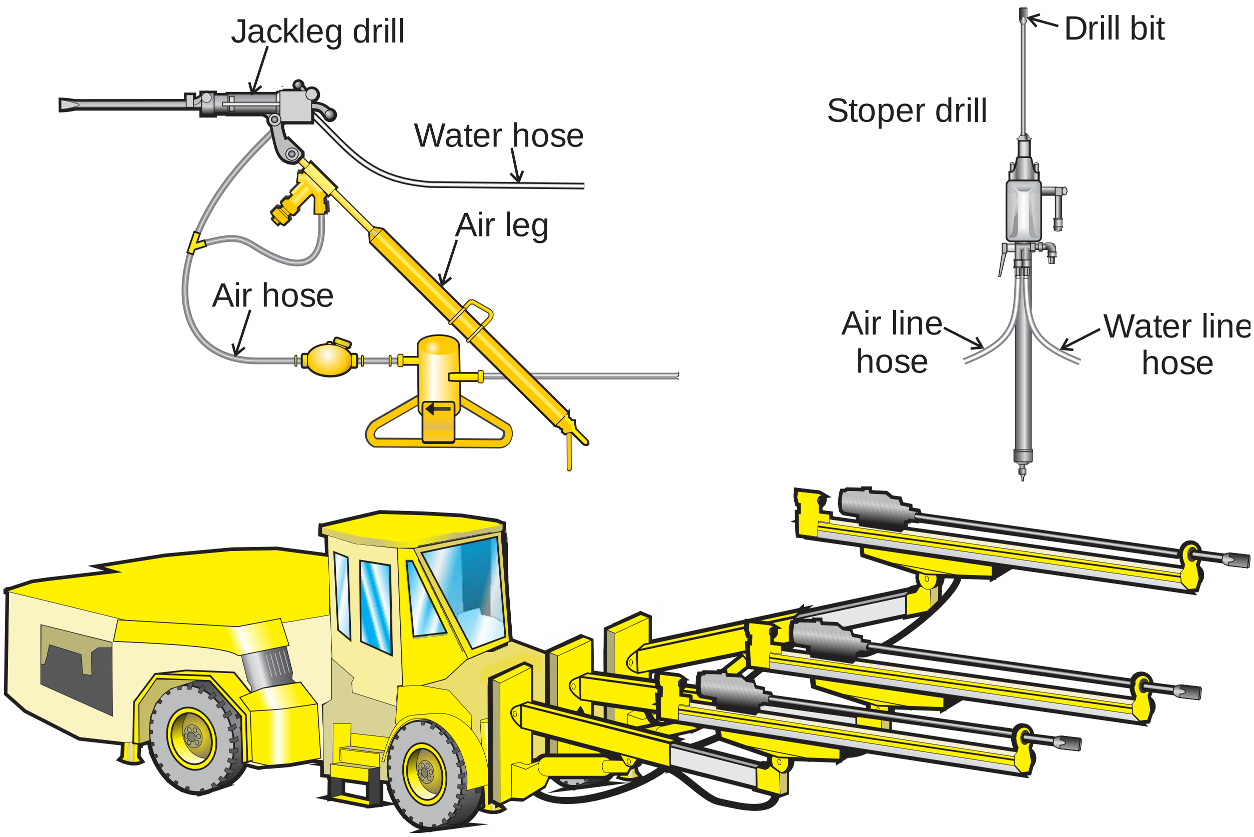

Figure 4.19. Illustrations of three types of drilling equipment. A typical jackleg drill is shown on the top left, a stoper drill on the top right, and a three-boom jumbo on the bottom.

Wet Drilling

Wet drilling uses water to flush the drill cuttings from the hole. Figure 4.20 illustrates the water being forced through the center of the drill steel, out the end of the drill bit, and back through the drill hole, forcing the cuttings out of the hole. The water pressure required to accomplish flushing of the drill hole is equal to the air pressure required for drilling or no less than 10 psig lower than the air pressure [Hustrulid 1982].

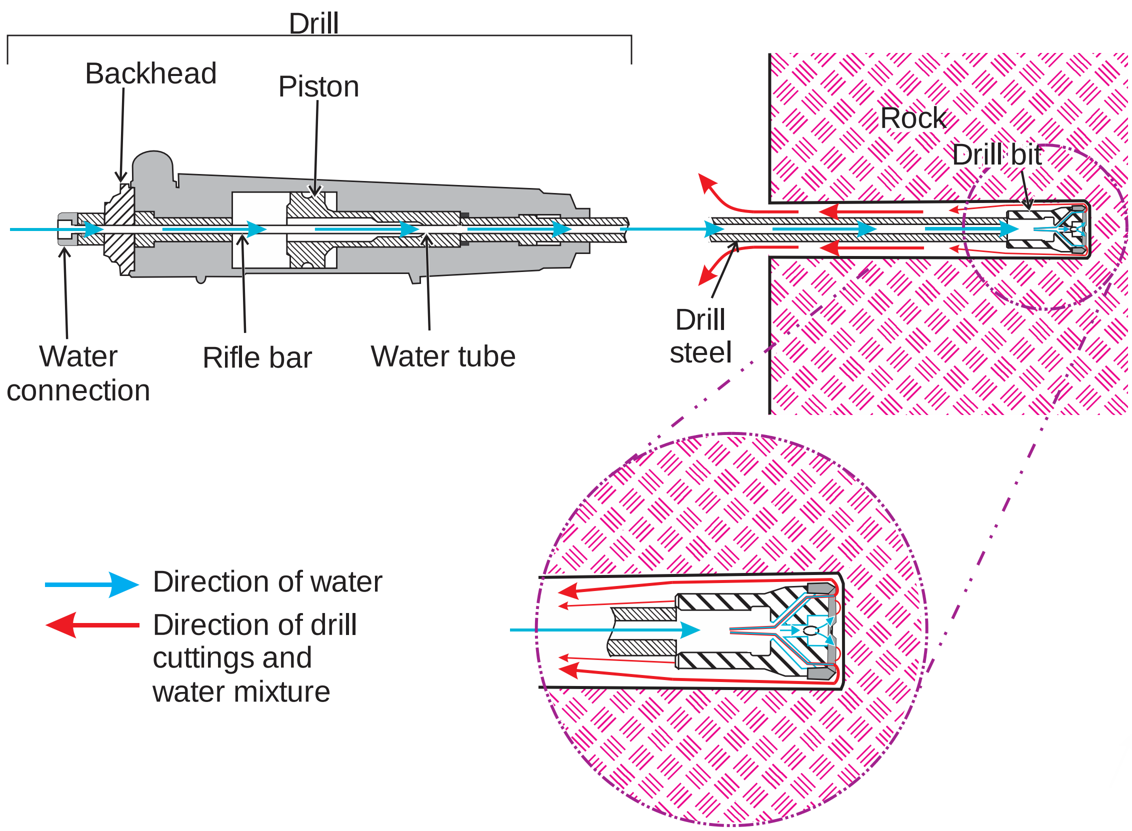

Figure 4.20. Illustration of water flow during a drilling operation to demonstrate water flushing of the drill cuttings. The water flows through the drill into the center of the drill steel and out the end of the drill bit to remove the cuttings from the drill hole.

Wet drilling has been found to be the best method of dust control, with dust reductions ranging from 86 to 97 percent depending upon the type of drilling involved [USBM 1921; USBM 1939]. The angle of the drill hole directly impacts wet drilling's effectiveness, with the amount of dust reduction being less for overhead vertical holes. Angle holes from the vertical were found to produce 50–60 percent less dust than overhead vertical holes [USBM 1938a]. The reason the overhead vertical holes produce more dust is due to the short amount of time that water contacts the drill hole face and the increase in sludge dropping through the air and running down the drill steel. The sludge running down the drill steel gets slung into the air from the rotation of the steel. Methods used to reduce dust from overhead vertical holes include the following [USBM 1938c]:

- increasing the amount of water used in wet drilling,
- creating a trap to capture the sludge from the drillhole and divert it away from the drill steel,
- designing drills that reduce the amount of air leaking from the front head along the drill steel, and
- preventing the exhaust air generated by the drill from dispersing sludge into the air.

The relationship of water flow to dust concentrations was tested in both stoper and drifter drills. For stoper drills, as the water flow increased to 1.3 gpm, it was found that the dust concentrations decreased rapidly. Above 1.3 gpm, the dust concentrations decreased at a slower rate. This phenomenon was also seen in drifter drills but at a water flow rate of 1.0 gpm. Therefore, it was recommended that the optimal water flow should be 1.3 gpm for stoper drills and 1.0 gpm for drifter drills [USBM 1938c]. Additionally, there are advantages gained through wet percussion drilling, such as less drill steel breakage and greater penetration rate with wet drilling than with dry drilling [USBM 1921].

To characterize the typical dust emissions during wet drilling, it was shown through testing that the first 1–2 feet of drill hole were the dustiest when wet drilling [USBM 1938b]. After the first 1–2 feet were completed, the dust concentrations dropped rapidly and maintained a constant level. This study also demonstrated that collaring a hole was not responsible for the high dust concentrations since the holes were precollared prior to testing [USBM 1938b].

Water Mists and Foams

Water mists, which use a mixture of compressed air and water, and foams injected through the drill steel have also been shown to reduce dust concentrations by 91–96 percent, respectively [USBM 1982a,b]. However, the limited improvement in dust reduction by comparison to wet drilling does not justify the cost involved with using these methods.

Wetting Agents

The use of "wetting" agents or additives to the water used in drilling has also been evaluated, without much success. Results showed that wetting agent solutions applied at varying flow rates provided better dust control [USBM 1943]. However, the dust control provided by wet drilling alone was so good that the additional dust reduction from the use of wetting agent solutions was insignificant. The claim that wetting agents can improve penetration rate was shown to be unsubstantiated due to the inconsistent drilling rates (ranging from -24.9 to +57.5 percent) and the dependency upon drilling circumstances [USBM 1943]. As noted in Chapter 3—Wet Spray Systems—wetting agents are primarily used in underground coal mining operations and have shown varied success.

External Water Sprays

External water sprays, depicted in Figure 4.21, have been used in the past, but for dry drilling they only produced dust reductions up to 25 percent compared with dry drilling alone—i.e., drilling without the use of any water [USBM 1921]. In an attempt to improve dust reductions, an external water spray device, a ring that contained spray holes on the inside diameter for dust control during dry drilling, was developed and tested. This device was slipped over the drill steel and sprayed water on the drill steel outside of the hole. By comparison to dry drilling, the use of the external water spray device produced variable dust reductions ranging from 75 to 88 percent [USBM 1939]. Shrouding of the drilling area was tested through the addition of a rubber shroud mounted at the end of the boom to surround the external spray and drill bit. This was shown to improve dust reduction to 53 percent [USBM 1982a]. Although these devices were an improvement over external water sprays, results showed that these devices along with external water sprays could not be used to replace wet drilling and maintain proper dust control during drilling operations. They could be used to enhance dust control in conjunction with wet drilling.

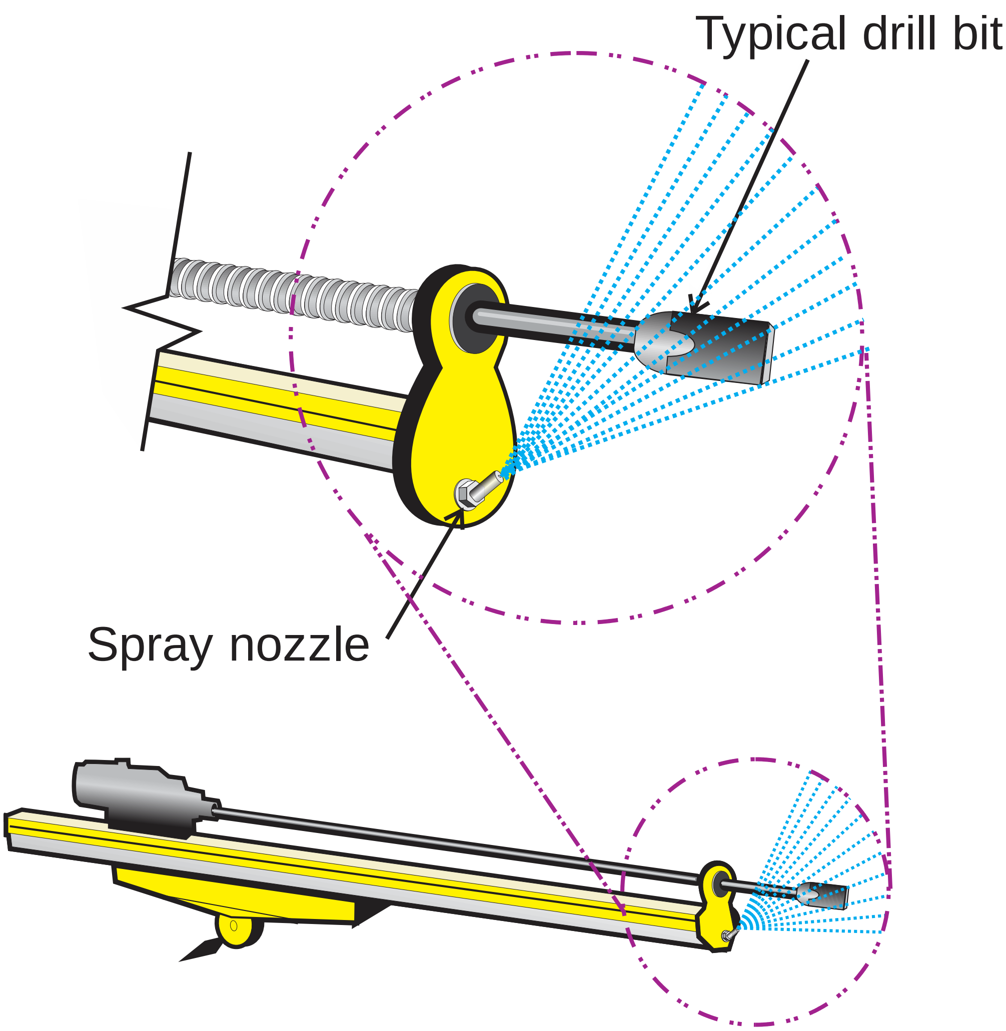

Figure 4.21. Illustration of drill boom showing external water sprays directed onto the drill steel and toward the collar of the hole.

RESPIRABLE DUST CONTROL FOR BLASTING

Blasting is a controlled operation that generally occurs intermittently at mining operations and is used to fragment the rock being mined. This is an important step in industrial mineral production as it is required to break up the mineral product, and the effectiveness of blasting may be a significant factor when optimizing the fragmentation and cost of the crushing and grinding circuit [Hustrulid 1999]. While blasting seemingly generates large amounts of dust, the operation occurs infrequently enough that it is not considered to be a significant contributor to particulate matter less than 10 micrometers (µm), or PM_{10} [EPA 1991; Richards and Brozell 2001]. Testing has been conducted to create an estimator for the amount of dust generated from surface blasting. The estimator is shown as the following equation:

$$e = 0.00050A^{1.5} \tag{4.1}$$

where e = total suspended particulate emission factor (lb/blast), and
A = area blasted (m^2) as long as hole depth does not exceed 70 feet.

To estimate the PM_{10} emissions from blasting, the following equation is used:

$$PM_{10} = e \times 0.5 \tag{4.2}$$

where PM_{10} = pounds per blast of particulate matter less than 10 µm; and
e = total suspended particulate emission factor (lb/blast).

It must be noted here that the Environmental Protection Agency (EPA) determined that this estimator should only be used for guidance. More reliable emission factors for particulate emissions should be based upon site-specific field testing in order to determine the amount of particulate matter generated from blasting [EPA 1998].

Since underground blasting emissions are contained in an enclosed volume (mine workings), no known work has been completed to create a method of predicting the amount of dust generated in underground blasts. Underground blasting can create a substantial amount of dust and introduce gases into the mine, but it is done intermittently. Drilling and loading of explosives are conducted during working shifts, but setting off the blast in underground operations generally occurs off-shift when the mine personnel have left. During the off-shift, ventilation is used to clear the mine of any dust or gases generated by the blast. Therefore, dust and gas exposure issues to personnel from blasting are not typical problems in underground mining.

Blasting Dust Control Measures

As a result of blasting being considered an insignificant dust source, there is very little documentation for dust control of blasting operations. There are five methods of dust suppression that can be used for the control of dust during blasting, many of which are effective for underground mining only [Cummins and Given 1973]:

- wetting down the entire blasting area prior to initiating the blast;
- using water cartridges alongside explosives;
- using an air-water fogger spray prior to, during, and after initiating the blast;
- using a filtration system to remove pollutants from the air after the blast; and
- dispersal and removal of the dust and gases using a well-designed ventilation system.

Wetting Down the Blasting Area

A common method of dust control for blasting operations is to wet down the entire blasting area prior to initiating the blast. This procedure minimizes dust being entrained into the air from the blasting activity by allowing it to adhere to the wet surfaces [Cummins and Given 1973]. This method has been shown to be effective for dust control during blasting in underground mines. It could also be effective for surface mining, depending upon the time interval between watering and blast initiation—with the possibility of exposure to the surface atmospheric conditions causing the moisture to quickly evaporate and rendering the watering ineffective. However, safety considerations may preclude wetting the blast area during the “tying in” phase of the blast, where all the individual hole charges are connected together prior to blasting.

Water Cartridges

Water ampoules, or cartridges inserted into the blasthole with the explosive, have been used successfully for dust reduction in past underground coal mining blasting operations [ILO 1965]. The water cartridges consist of a properly sized plastic bag that is prefilled with water or can be filled in the hole. The cartridges can be placed in front of, alongside, or behind the explosive without causing any adverse effects to fragmentation. There is another type of cartridge that can be used in place of stemming, as shown in Figure 4.22. This cartridge uses a PVC bag that is inserted into the hole after the explosive and is then filled with water to maintain a tight seal with the blasthole.

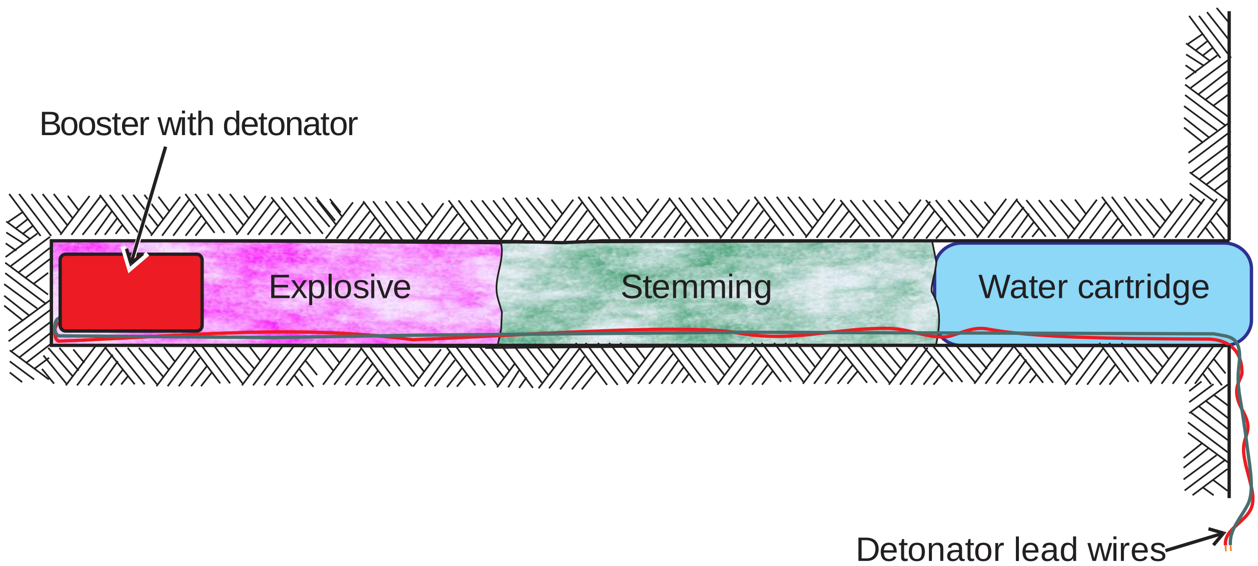

Figure 4.22. Illustration of a typical blasthole containing an explosive charge with stemming and using a water cartridge to suppress dust.

Fogger Sprays

In the past, many underground operations used a fogger type spray, also known as a water blast, in the heading where the blasting is conducted, as shown in Figure 4.23. This setup uses both compressed air and water forced through a nozzle to create a fogged-in blast area. The nozzle is located at an approximate distance of 100 feet from the face, is turned on prior to blast initiation, and remains operational for 20 to 30 minutes after the blast [ILO 1965]. While a fogger type spray is effective for underground blasting, it is not known if such a system would be viable for surface blasting.

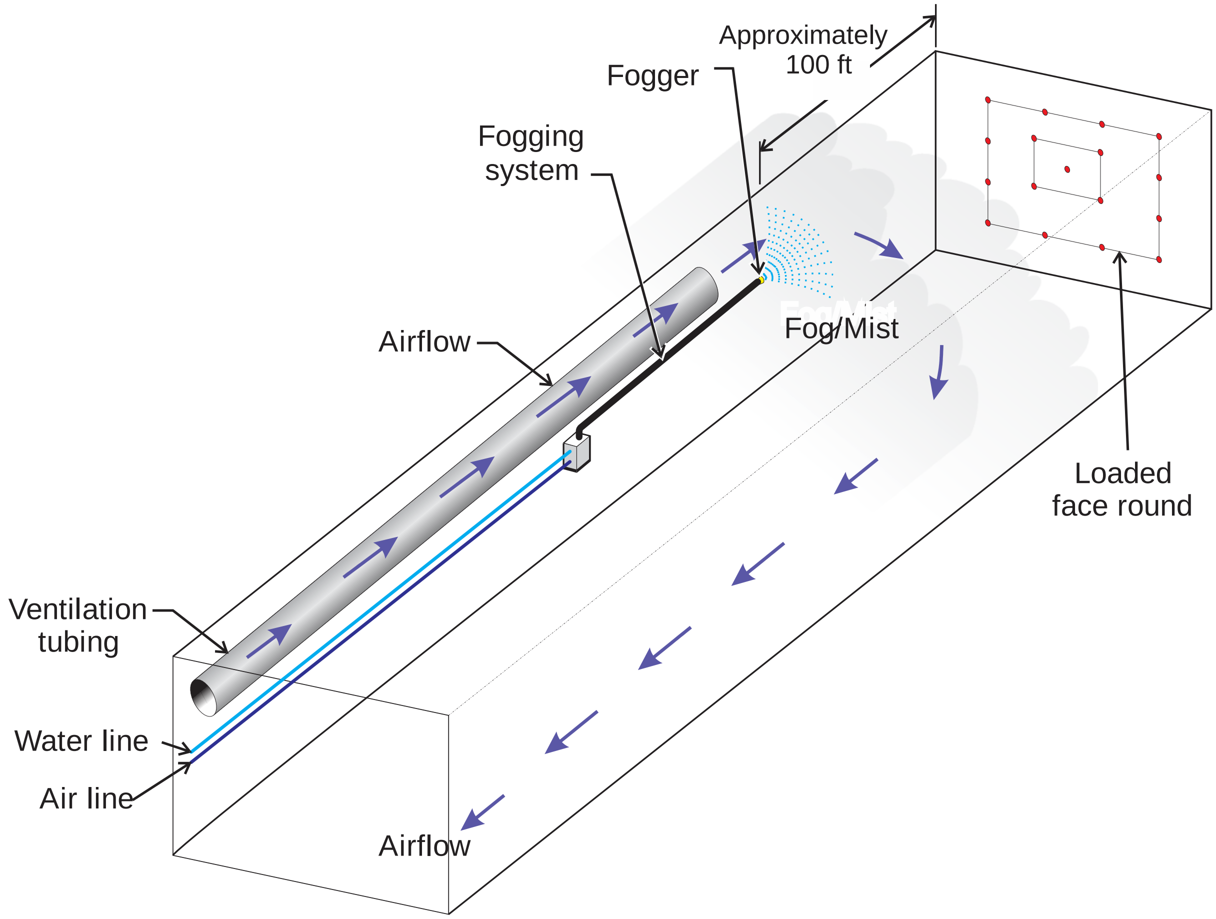

Figure 4.23. Illustration of a fogger spray used to create a mist for dust suppression in the heading where blasting will occur.

Air Filtration Systems

Another dust control method that has been used in underground mining operations in the past is to filter the return air of the ventilating air in the blasting area, as seen in Figure 4.24. One such filtration unit, used in South Africa, consists of a filter and a bed of vermiculite treated with sodium carbonate and potassium permanganate—a process that removes the dust and nitrous fumes from blasting [Cummins and Given 1973]. Figure 4.25 shows another method, which is to place filters inside the exhausting ventilation duct with water sprays, which spray on the filters and are oriented in the same direction as the airflow. The filters are only used during blasting, and the duct containing the filters is approximately twice the diameter of the ventilation tubing [ILO 1965]. Also, dry filters have been used successfully in the past for the same purpose.

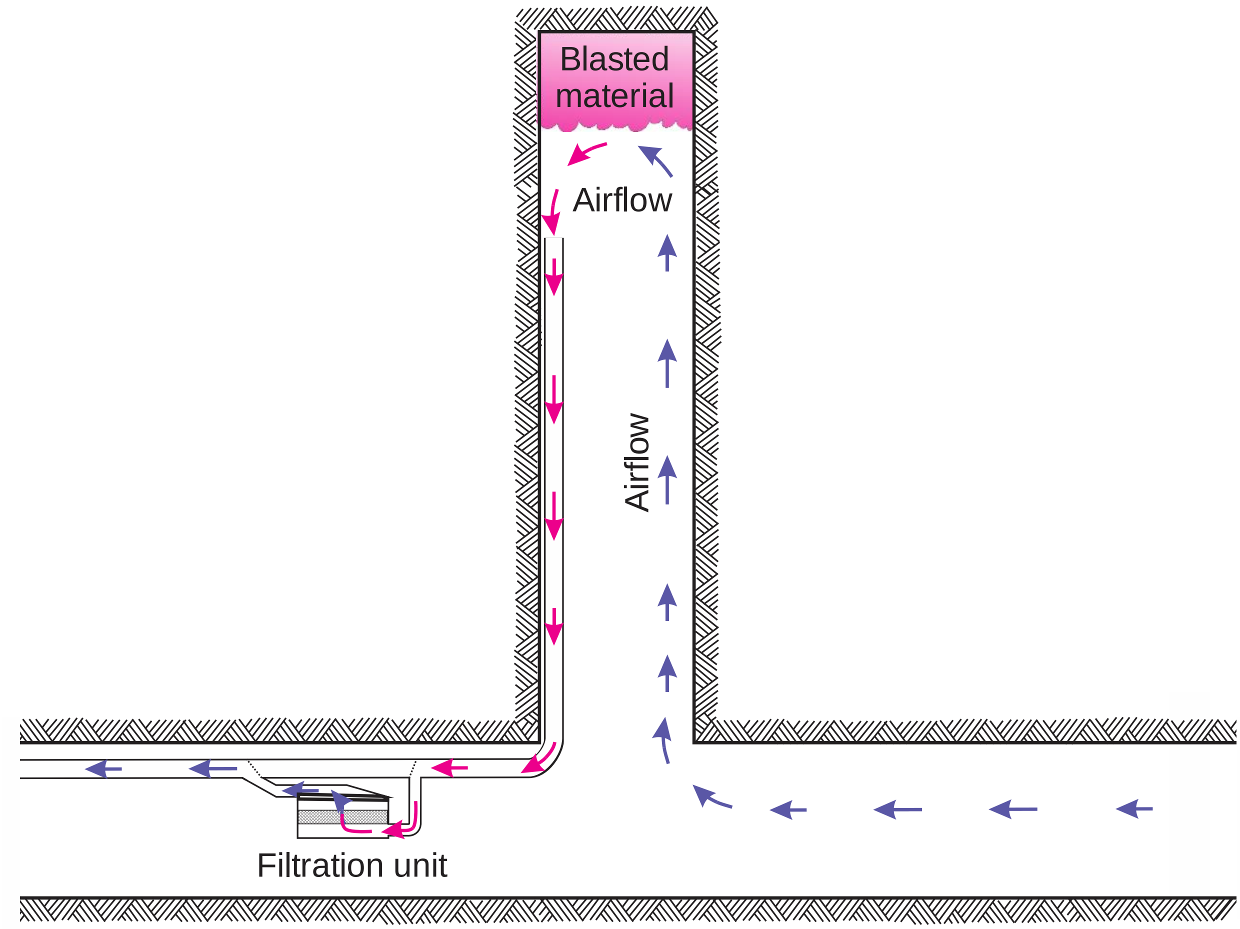

Figure 4.24. Illustration of a filtration unit, located adjacent to the blast heading, used for filtering contaminated ventilation air from the blast heading after blasting occurs.

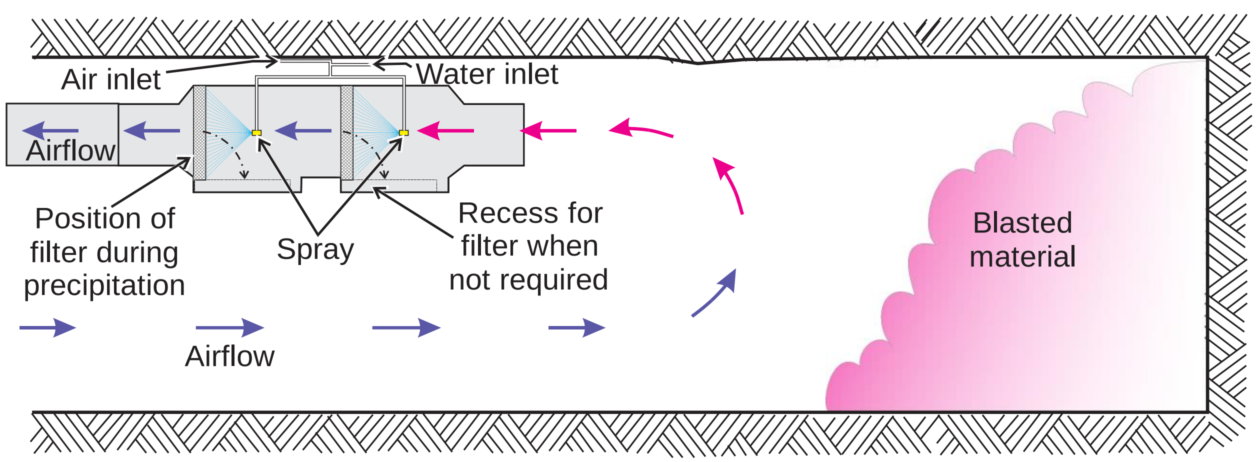

Figure 4.25. Illustration of a filtration unit, located in the blast heading, used for filtering contaminated ventilation air from the blast heading after blasting occurs.

Ventilation System Dispersal

The most common method of dust control is to allow the dust and gases from blasting to be dispersed and removed through the ventilation system, in the case of underground operations, or through atmospheric dispersion, in the case of surface operations. Underground operations generally schedule the blasting during off-shift times to allow sufficient time for the area to ventilate, for the dust and gases to disperse, and for removal of the dust and gases from the blasting [Cummins and Given 1973]. If off-shift blasting is not feasible, then areas affected by the blasting should be cleared and work should not commence until the dust and gases are removed.

The amount of time for dust and gas dispersal is mine-site specific, depending upon the efficiency of the mine's ventilation system. Therefore, it is important that the mine's ventilation system be maintained in good operating condition to optimize dust and gas removal and to minimize the time for the removal.

At surface operations, the area is cleared of personnel just prior to blasting. Scheduling the blast to take into consideration the meteorological conditions, i.e. low wind speed and low inversion potential, can minimize the impacts of dust generation from blasting. Generally, the dispersion of dust and gases occurs quickly after the blast, depending upon the wind speed and direction, and work is not allowed in the affected area until dispersion is completed. Additionally, it has been noted that the use of multi-delay detonators to initiate the individual explosive charges in millisecond time intervals may reduce dust generation from blasting, but this has not been verified [Miller et al. 1985].

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Chapter 5: Crushing, Milling, and Screening

CHAPTER 5: CRUSHING, MILLING, AND SCREENING

Mineral crushing, milling, and screening operations can be major sources of airborne dust due to the inherent nature of size-reduction and segregation processes. Control of dust generated by these operations can be achieved with proper analysis of the sources, identification of appropriate control technologies, and consistent application and maintenance of selected controls.

Worker exposure may be managed through engineering controls to coat, suppress, or enclose the dust sources, as described below, or by isolating the worker from the dust source, as discussed in Chapter 10— Filtration and Pressurization Systems for Environmental Enclosures. Administrative controls such as operating procedures, work practices, and worker training are also commonly applied to supplement engineering controls. Personal protective equipment (PPE) may also be necessary until feasible engineering and administrative controls are installed, or when they do not achieve the desired level of exposure reduction, in particular during maintenance, repair, and other unusual operating conditions.

As with any process component, installation of the selected dust controls, even if they are appropriate, will not guarantee continuing effective performance. The performance of installed dust control systems, which often represent large capital expenditures, should be periodically evaluated, maintained, and—when necessary—modified to maximize performance. For example, the effectiveness of dust control systems installed to protect worker health can be demonstrated by collecting personal and area air samples for comparison to the occupational exposure limit for the substances in question.

Different mineral processing equipment generates different amounts of dust emissions. Relative dust emission rate ratios (setting the primary crusher emission rate as the baseline) for common mineral processing equipment are presented in Table 5.1. This ranking is based on EPA-estimated particulate emissions for crushed stone operations, and is presented only to illustrate the relative magnitude of the various dust sources [EPA 2003]. It can be seen that emissions increase as the size of the material processed decreases, as one would expect.

Table 5.1. Relative emission rate ratios of crushing and screening equipment with the primary crusher (Row 1) as a baseline

Equipment	Relative Emission Rate Ratio
Primary crusher	1
Secondary crusher	(No data, tertiary crusher rate would be an upper limit)
Tertiary crusher (dry)	51
Tertiary crusher (wet)	2
Screen (dry)	214
Screen (wet)	12

PREVENTION AND SUPPRESSION APPLICATIONS

Wet Control Methods

Wet dust control systems can be very effective and are not usually costly to install and operate, but they may not be feasible due to characteristics of the mineral, subsequent processing steps, or customer specifications. Also, when operations are in cold climates, freeze protection is necessary, and ice buildup can create additional safety hazards for workers.

As discussed more fully in Chapter 3—Wet Spray Systems—the use of water to control dust may be classified into prevention applications and suppression applications. Prevention is the application of water to prevent dust from becoming airborne. Suppression is the use of water to wet dust particles that have already become airborne, increasing their mass and causing them to settle more rapidly.

In general, prevention is more effective than suppression [NIOSH 2003; USBM 1978]. However, when the wetted material is subject to further size reduction, as in crushing operations, effective prevention requires application of additional water to the dry—and larger—surface area of the material exposed by the size-reduction process. This may create a complication because additional application of water to improve prevention may cause the material to become too wet, interfering with efficient handling, subsequent processing operations, or product sizing specifications. As a result, some trade-off between wet dust control and process efficiency is often unavoidable. This trade-off can necessitate the use of other control approaches to achieve acceptable conditions.

Suppression of respirable airborne dust using water, usually through sprays directed into the dust cloud, is not always highly efficient. It is difficult with hydraulically atomizing spray nozzles to produce water droplets small enough to suppress respirable particles effectively. Appropriately sized water droplets can be produced with air atomizing nozzles, but this method requires a source of compressed air to atomize the water, and the very small nozzle orifices are subject to clogging, requiring increased maintenance attention. Additionally, air atomized spraying, due to the volume of the air/water mixture released, typically requires an enclosed area to avoid spreading dust into surrounding areas. These issues are more thoroughly discussed in Chapter 3—Wet Spray Systems.

Dry Control Methods

Control of dust generated by transport (see Chapter 6—Conveying and Transport) and processing of minerals can be achieved through containment, exhaust, and cleaning of dusty air. This approach, termed dry control, can be more costly to install and operate than wet control methods, but can be very effective. Additionally, dry dust control may be necessary when the product is adversely affected by the addition of water, such as trona or clayey materials.

Dry dust control must create conditions that will prevent the escape of dusty air from the controlled space to areas occupied by workers. This control is achieved by using exhaust ventilation to create a negative air pressure inside the controlled space relative to outside of the controlled space (see Chapter 2—Fundamentals of Dust Collection Systems). The amount of ventilation necessary to achieve control is affected by the following:

- the degree of enclosure of the controlled space, with required exhaust volume increasing as the area of unsealed openings into the enclosure increases;
- the airflow created by the movement and processing of the mineral, including air that is entrained within moving material, airflow induced by moving material and equipment, and air displaced by the material flowing into or out of an enclosure; and
- the effect of ambient wind speed and direction that can overcome the pressure differential between the interior and exterior of the controlled space.

CRUSHING

Size-reduction processes will always contain at least one crushing circuit and many times will have multiple crushers, often of different types. Selection of crushers is based primarily on material size-reduction and throughput requirements. Secondary selection considerations include the composition, hardness, and abrasiveness of the feed material or materials. The most common primary crusher type is the jaw crusher (Figure 5.1), which operates by compressing the feed material between a fixed and moving plate, or jaw. Cone (Figure 5.2, left) or gyratory (Figure 5.2, right) crushers may be used as primary or secondary crushers and also operate through compression.

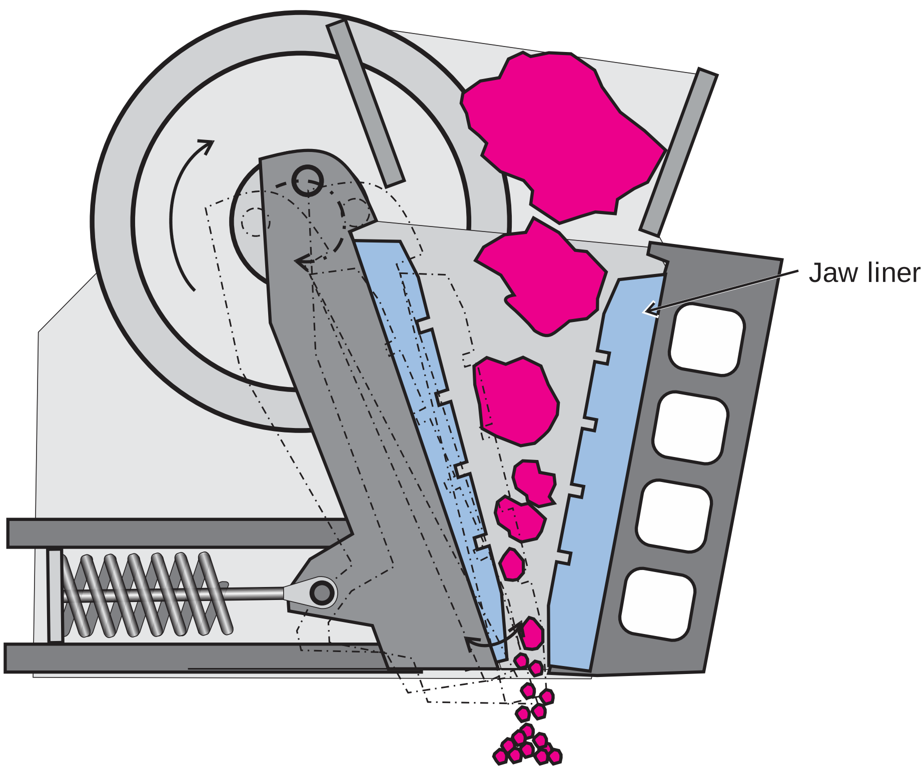

Figure 5.1. Illustration of a jaw crusher showing material being crushed between fixed and reciprocating jaws.

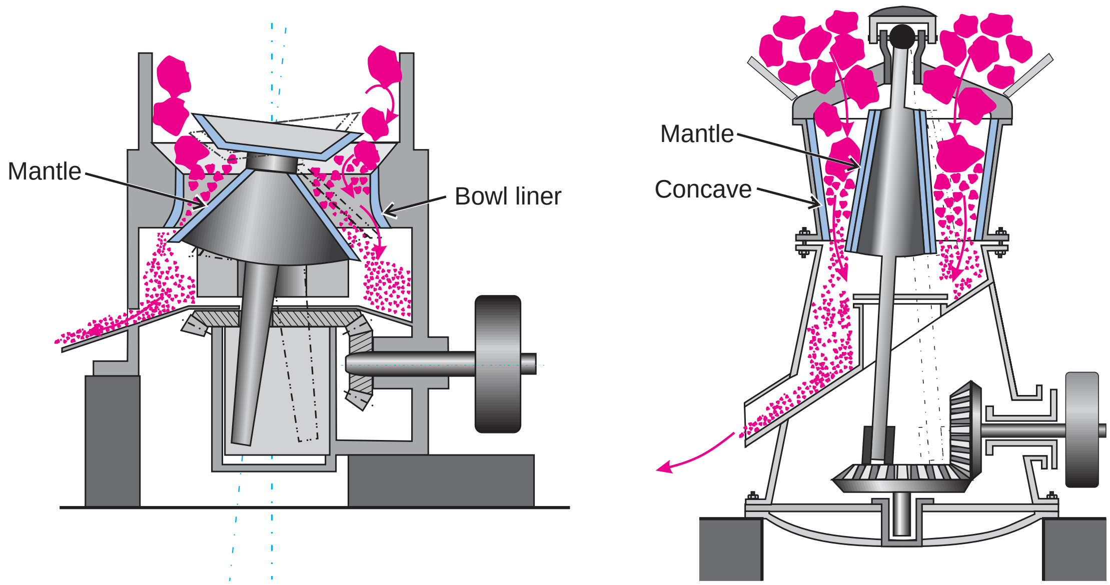

Figure 5.2. Illustrations of two examples of compressive crushers. The left illustration shows a cone crusher with material being crushed between the cone mantle and bowl liner. The right illustration shows a gyratory crusher with material being crushed between the gyratory head and the frame concave.

Hammermills (Figure 5.3, left), impact breakers (Figure 5.3, center), and roll crushers (Figure 5.3, right) operate primarily by impaction. The difference between compression and impaction is the speed at which the breaking force is transmitted from the crusher to the material. Compression involves a slower energy transfer than impaction, and compressive crushers produce somewhat less dust than impactive crushers.

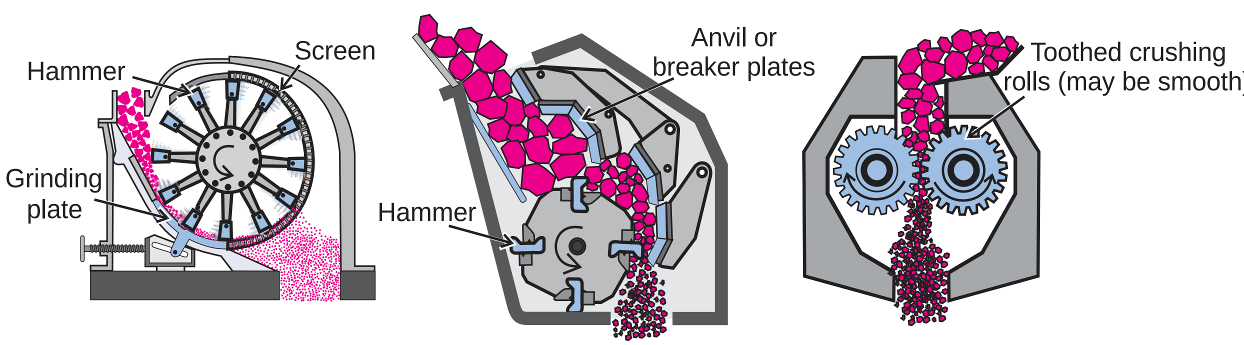

Figure 5.3. Illustrations of three examples of impactive crushers. The left illustration shows a hammermill crusher with material being crushed between the rotating hammers and a fixed grinding plate. The center illustration shows material being crushed between rotating hammers and fixed anvil plates in an impact breaker. The right illustration demonstrates the size-reduction action of a toothed roll crusher.

Dust control at crushers may be achieved through application of water, by enclosure of the dust source with or without exhaust ventilation, or a combination of wet and dry methods. Generally, the upper portion of the crusher (feed side) should be enclosed as completely as possible [USBM 1974]. Enclosures should be constructed of physically robust materials appropriate for the operating environment and climate conditions.

Figure 5.4 illustrates a wet dust control system at a crusher dump loading operation. The frontal open area of the enclosure may be reduced by installing hanging curtains and installing a high curb or berm at ground level. To conserve resources, operators should consider installing a photo eye sensing control with a timed duration to activate the wet spray system.

As described in Chapter 3—Wet Spray Systems—water sprays used for dust prevention typically use solid spray patterns or full cone spray patterns. Sprays used for dust suppression typically use hollow cone spray patterns. Sprays should overlap slightly to provide good coverage.

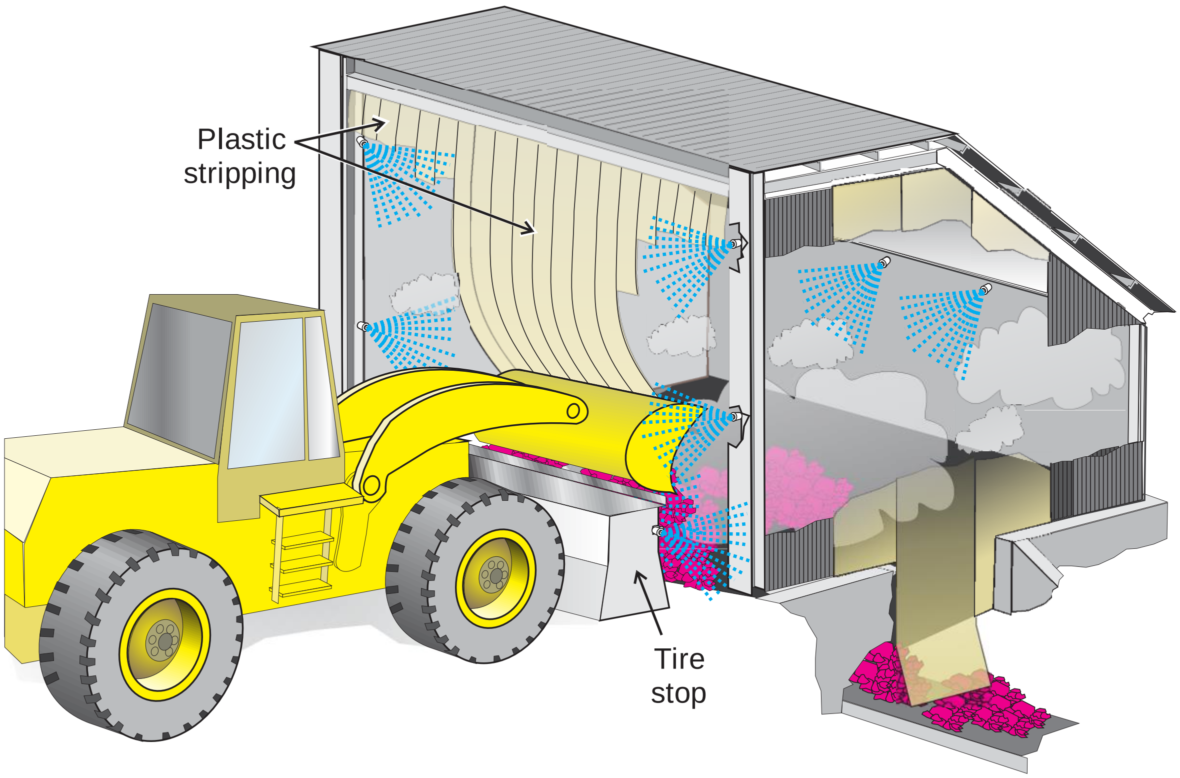

Figure 5.4. Illustration of a wet dust control approach with a partial enclosure at a crusher dump loading operation. Note the blue "fan patterns" signifying water sprays.

A local exhaust ventilation (LEV) dust control system at a crusher dump loading operation is illustrated in Figure 5.5.

Enclosure of the volume to be controlled should be maximized; in other words, the number and area of openings should be minimized as much as possible. Initial exhaust rates for the type of enclosure depicted in Figure 5.5 can be estimated by Equation 5.1, which accounts for air displaced by a dumping operation:

$$Q_E = 33.3 \times \left(\frac{600T}{G}\right) \tag{5.1}$$

where Q_E = exhaust air volume, cubic feet per minute;
T = weight of material dumped, tons per minute; and
G = bulk density of material, pounds per cubic foot.

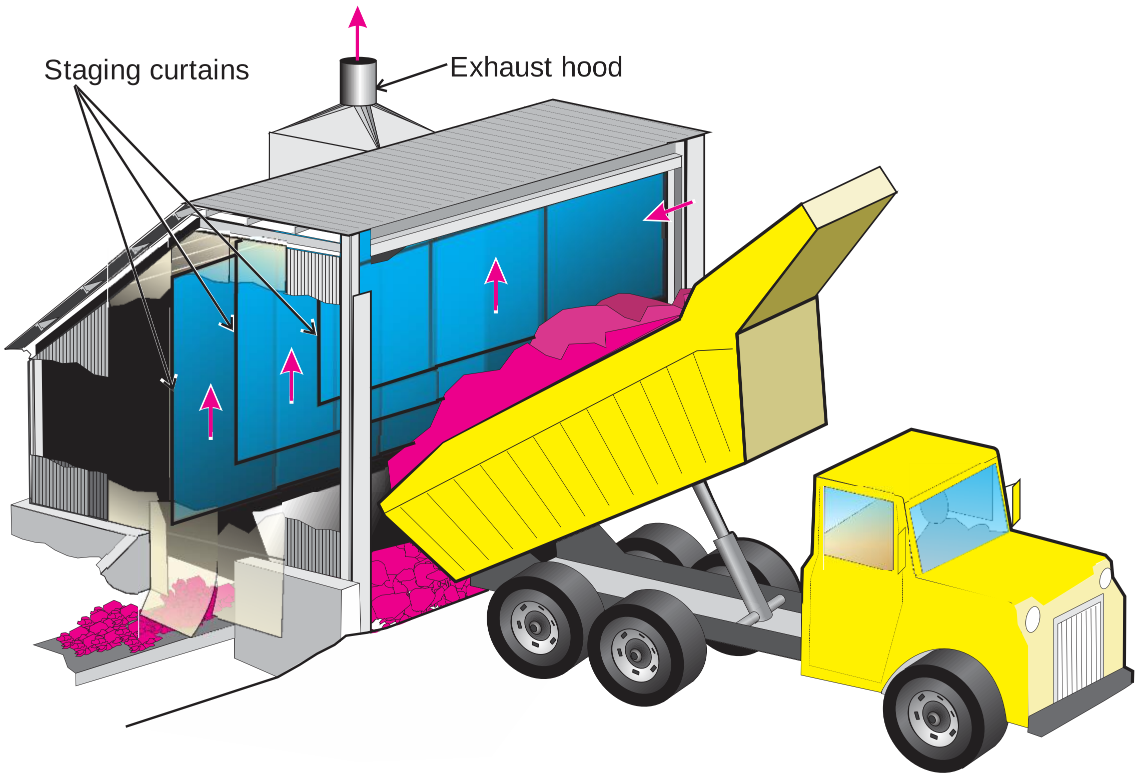

Figure 5.5. Illustration of a dry (exhaust) dust control system with a partial enclosure at a crusher dump loading operation.

If the dumping operation is not continuous, operators should consider utilizing a presence-sensing control with a timed duration to activate the exhaust system fan and water sprays as dumping occurs.

Whenever local exhaust ventilation is selected as a means of dust control, maintenance and clean-out openings should be designed into the enclosure and equipped with tight-fitting closures. Properly located and sized maintenance access openings will allow workers to perform their assigned tasks without having to modify the enclosure. This will reduce the potential for dust to escape through unintended openings.

It is recommended that a minimum air capture velocity of 200 feet per minute (fpm) be maintained at all openings into enclosures [USBM 1974]. Where feed or discharge belt openings penetrate dust control enclosures, it is recommended to add the belt speed in fpm to the 200 fpm design velocity to account for the process material volumetric flow and belt-induced air movement [Yourt 1969].

As an example, for an enclosure with an initial design capture velocity (V_{INIT}) of 200 fpm penetrated by a belt moving at 250 fpm (V_{BELT}), the recommended capture velocity (V_{CAP}) at openings into the enclosure becomes:

$$Capture\ velocity\ (V_{CAP}) = 200\ fpm\ (V_{INIT}) + 250\ fpm\ (V_{BELT})$$

$$Capture\ velocity\ (V_{CAP}) = 450\ fpm$$

Enclosure exhaust air volume (Q_E) in cubic feet per minute (cfm) can be estimated using the total area (in square feet) of all openings into the enclosure, with the capture velocity as:

$$Q_E\ (cfm) = V_{CAP}\ (fpm) \times open\ area\ (sq\ ft)$$

Again, these initial velocity and volume estimates should be verified as (1) providing acceptable dust control and (2) not excessively consuming energy. Exhaust ventilation concepts are discussed more fully in Chapter 2—Fundamentals of Dust Collection Systems.

When possible, dust control enclosures should be large in volume to allow settling of coarse dust. Removing large airborne dust particles by this method will reduce the load on subsequent air handling and cleaning systems.

Falling material at transfer points will generate airflow both by induction and displacement [Anderson 1964; Goldbeck and Marti 1996]. When materials have an average size greater than 1/8 inch (0.01 feet), this airflow can be estimated by Equation 5.2:

$$Q_E = 10 \times A_U \sqrt[3]{\frac{RS^2}{D}} \tag{5.2}$$

where Q_E = exhaust volume, cubic feet per minute;
A_U = enclosure upstream open area, square feet;
R = rate of material flow, tons per hour;
S = height of material fall, feet; and
D = average material size, feet.

Determining exhaust volume through the use of Equation 5.2 is illustrated in Figures 5.6 through 5.9. In each case, the height of material fall (variable S in Equation 5.2) is depicted. The value for the upstream open area variable—A_U—for a transfer point is the cross-sectional area of the chute transferring the material and any unsealed area between the chute and the enclosure structure. When chutes are not used, an estimate of the open area around penetrations (e.g., belt conveyor structure) into the enclosure is used for the A_U variable.

Figures 5.8 and 5.9 depict transfer from the discharge of a crusher to a conveyor. For jaw crushers, which have variable cross-sectional areas, the upstream open area value (A_U) is the area of the bottom of the jaw crusher opening into the enclosure structure (Figure 5.8). For crushers with constant cross sections, such as a cone crusher, the upstream open area is the crusher feed throat area (Figure 5.9).

More information on dust control at transfer points is found in Chapter 6—Conveying and Transport.

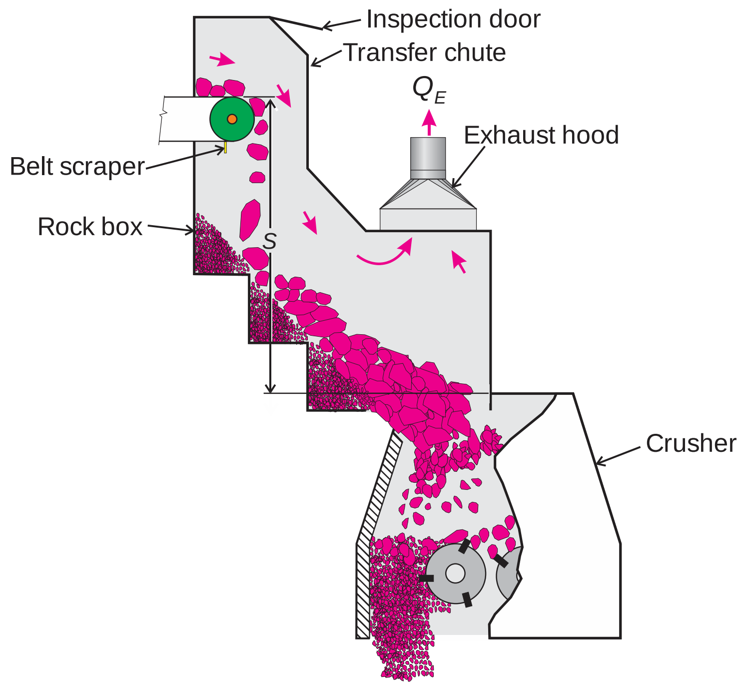

Figure 5.6. Illustration of a dry (exhaust) dust control system at the transfer point of a conveyor discharge to a crusher feed hopper.

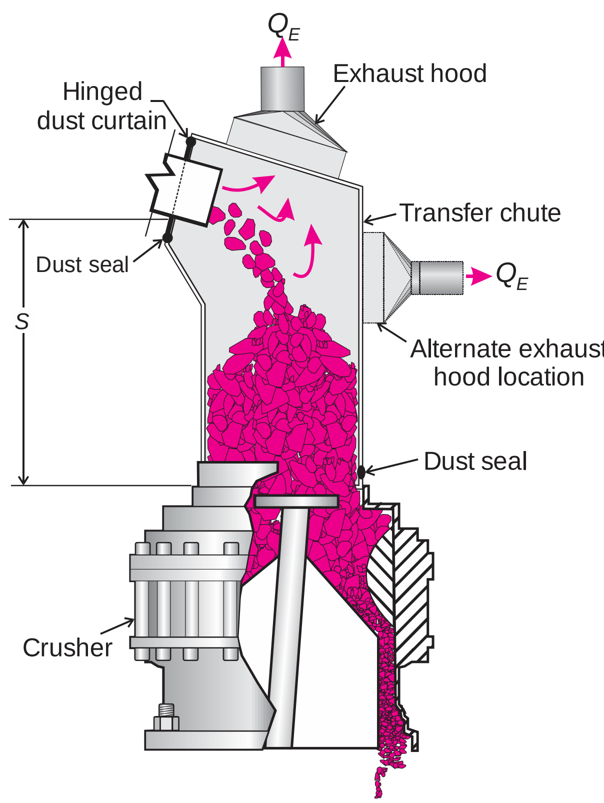

Figure 5.7. Illustration of a dry (exhaust) dust control system on a feed chute into a transfer chute feeding a crusher.

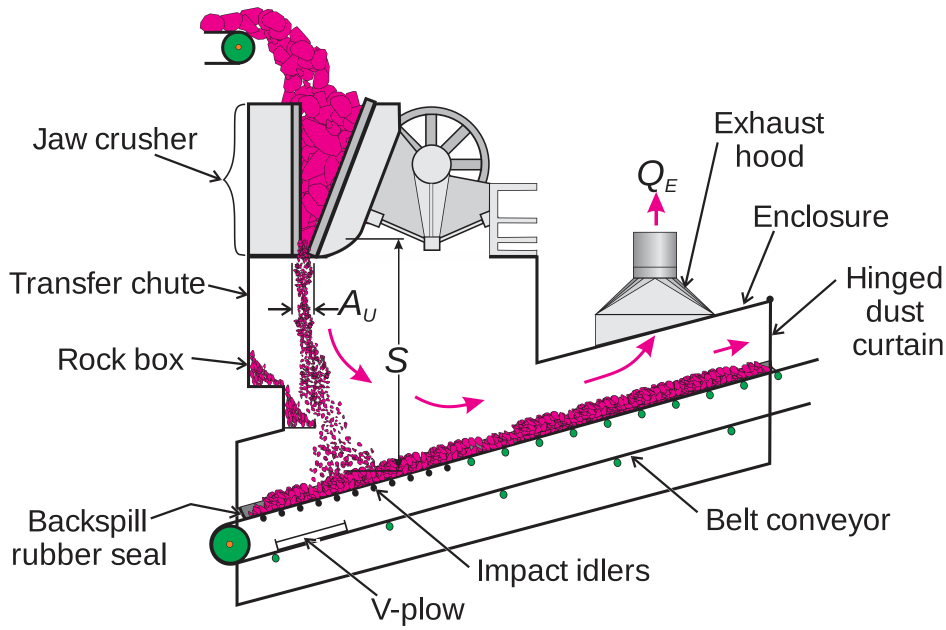

Figure 5.8. Illustration of a dry (exhaust) dust control system at the discharge of a jaw crusher onto a belt conveyor.

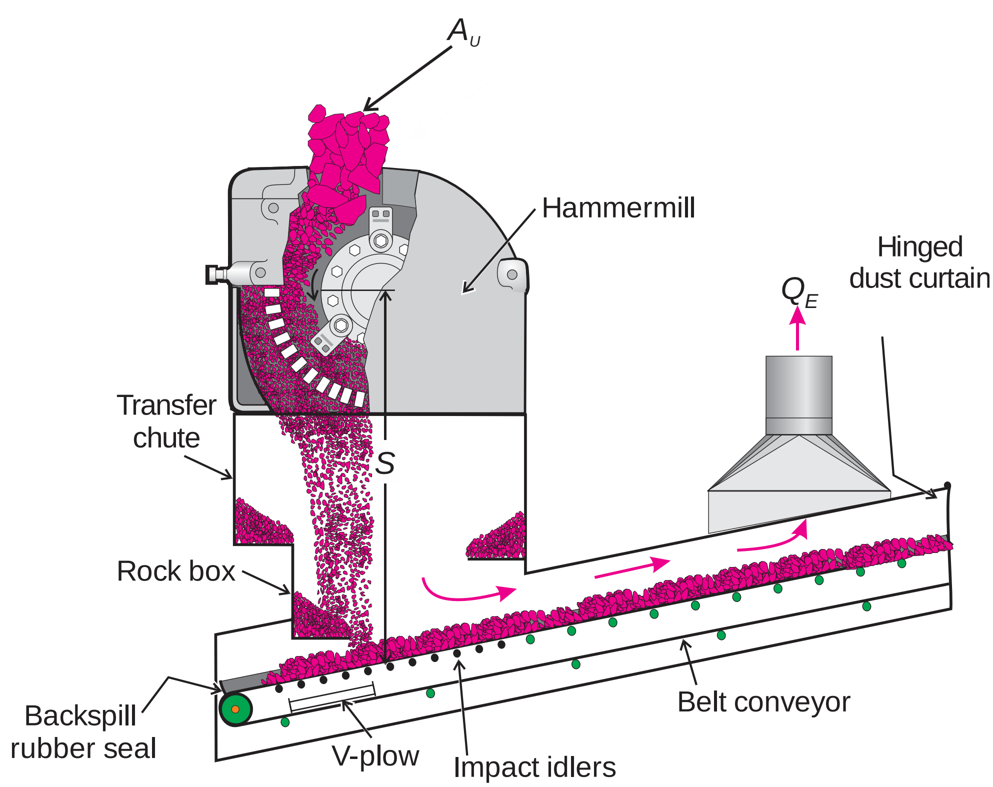

Figure 5.9. Illustration of a dry (exhaust) dust control system at the discharge of a hammermill crusher onto a belt conveyor.

Wet dust control methods for crushing operations, illustrated in Figures 5.10 and 5.11, involve wetting the process material before crushing, after crushing, or both. This is essentially treating the crushing operation as two transfer points, the feed side and discharge side. Crushing creates smaller-sized material with an attendant increase in surface area, which will be dry. Thus, material wetted prior to crushing for dust control will likely have to be wetted again to address the additional dry surface area.

Where dust control through water application is selected, recall that solid spray nozzles, or full cone spray nozzles, produce larger drop sizes than hollow cone nozzles. Hollow cone nozzles should be used when dust suppression (reduction of airborne dust) is desired, with spray patterns arranged to cover the entire area of the dust cloud. When prevention of airborne dust is desired in a static application such as a bin or hopper, then full cone nozzles should be used, with spray patterns overlapping the entire surface of the material to be wetted. In a moving application such as a conveyor, fan spray nozzles should be used, with spray patterns oriented perpendicular to conveyor travel and overlapping approximately 30 percent of the fan width. Further information on wet methods is found in Chapter 3—Wet Spray Systems.

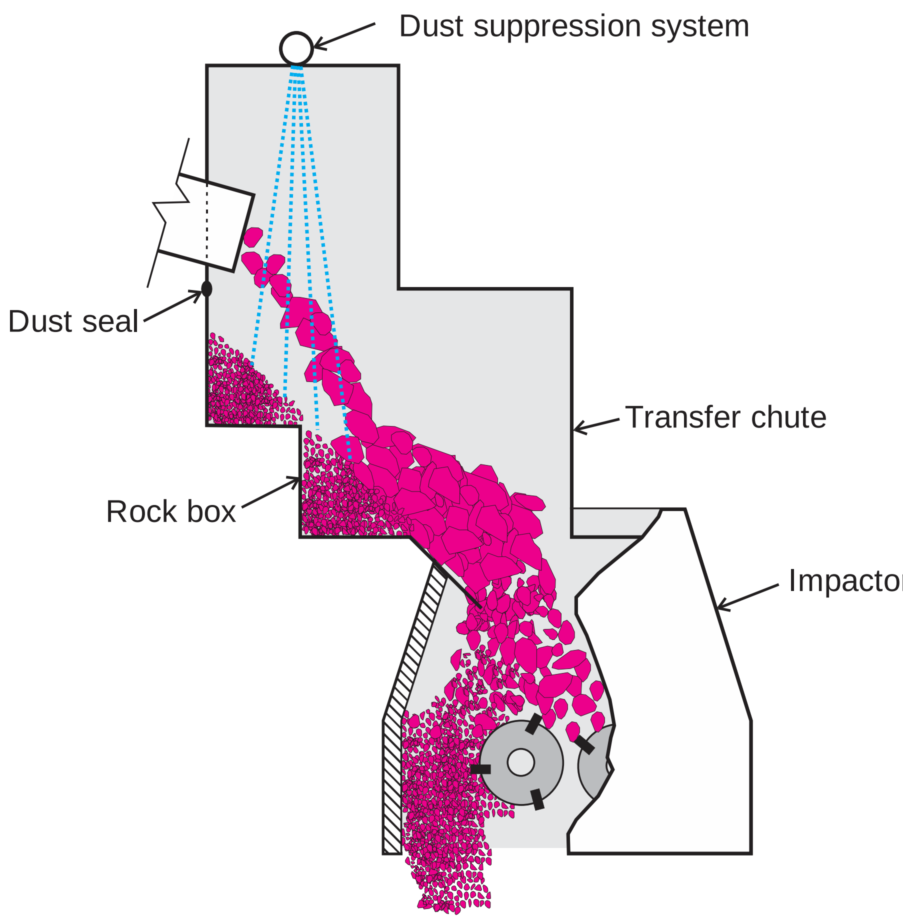

Figure 5.10. Illustration of a wet dust control approach with a transfer chute/rock box enclosure at a crusher loading operation.

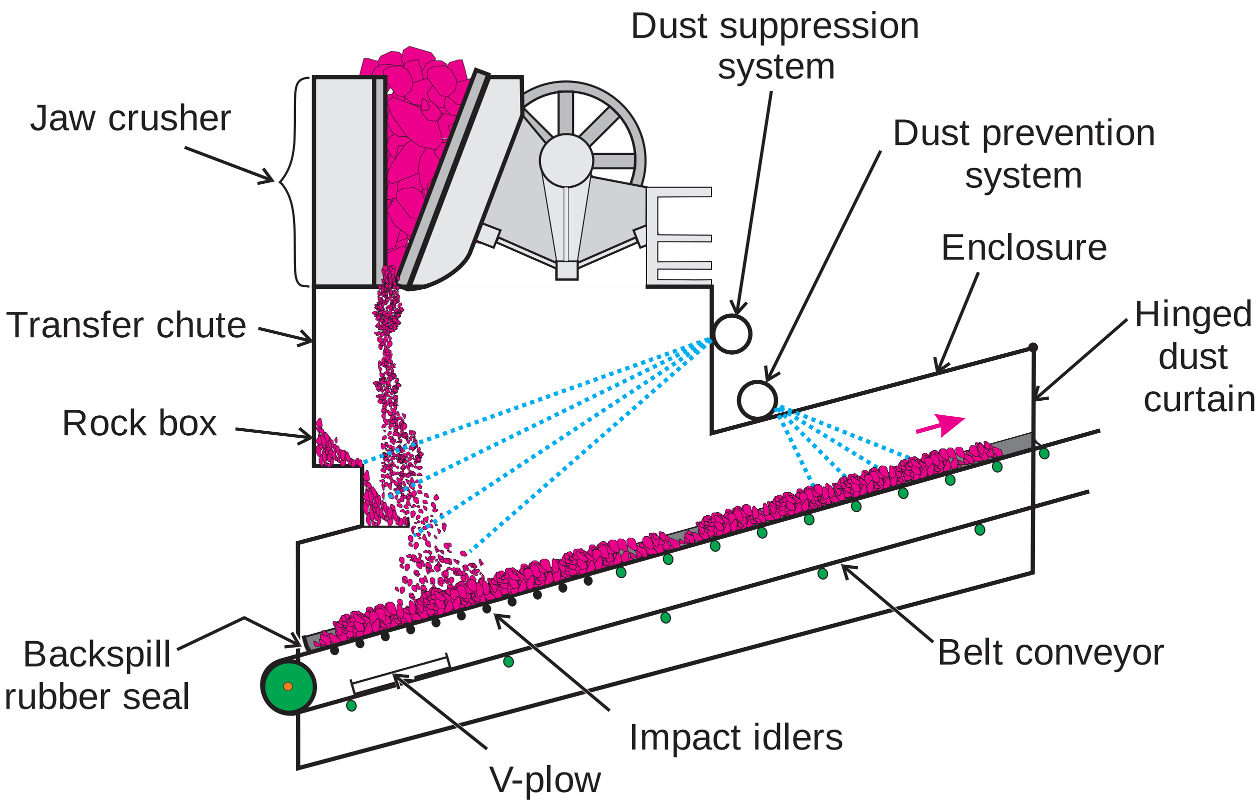

Figure 5.11. Illustration of a wet dust control approach on a crusher discharge/belt loading operation.

The mechanical action of crushers can generate air movement; i.e., jaw crushers can have a bellows-type effect, and cone or gyratory crushers can act as fans, although neither of these classes of crushers operate at high speeds. In contrast, hammermills operate with higher-speed components and can act as centrifugal fans. A method to estimate maximum generated airflow from this type of crusher has been described [Burton 1999]. The maximum volume (cubic feet) of air generated per shaft revolution (GEN REV) can be estimated by treating the hammer/shaft assembly as a fan using Equation 5.3:

$$A_{GEN\ REV} = \frac{\pi}{4D^2W} \tag{5.3}$$

where D = diameter of the hammer assembly from tip to tip, feet; and
W = the width of the hammers, feet.

The volume of air generated per minute (cfm) is then the product of $A_{GEN\ REV}$ and shaft RPM.

A more general method to evaluate this issue for any type of crusher is to measure inflow velocity at permanent openings into the dust control enclosure with the crusher on and then measure inflow velocity with the crusher off. If the inflow velocity is not satisfactory when the crusher is operating, it will be necessary to increase exhaust volume or install baffles inside the enclosure.

Work Practices to Minimize Dust Exposure from Crushers

The following practices can serve to reduce operator exposure to airborne dust at crusher operations.

- Maintain closure/locking devices such as clamps and other fasteners. Fasteners are only effective when used.
- Where compatible with the process, wash down areas on a periodic basis. Periodic washing prevents the accumulation of material, which can eventually become too large for wash down, necessitating a dry cleanup that will generate dust.
- Keep makeup air and recirculating air dust filtration systems on operator booths, front-end loaders, or other mobile equipment in place. Ensure that only correct filters are utilized, and maintain the systems to manufacturer specifications.
- Wear approved respiratory protection when working in dust collectors, mills, air classifiers, screens, and crushers. See Chapter 1—Overview of Dust Exposure Assessment and Control—for more information.
- Where feasible, automate the crushing process using sensing devices and/or video cameras. This removes the operator from the crusher area and reduces the potential for dust exposure.
- Where crusher operation must be supervised continuously, provide an enclosed booth with a positive-pressure filtered air supply for the operator. See Chapter 10—Filtration and Pressurization Systems for Environmental Enclosures—for more information.

MILLING

Milling, often called grinding, is a process by which granular minerals are reduced in size by compression, abrasion, and impaction. Mills may be classified into two broad types based on how they operate: *tumbling mills* (Figure 5.12) and *stirring mills* (Figure 5.13). Tumbling mills generally operate in a horizontal orientation, and the shell of the mill rotates to impart motion to the contents or charge. Stirring mills may be horizontal or vertical, and motion is imparted to the charge by an internal stirring element.

Tumbling mills employ some type of medium to perform the size reduction, often rods or balls, usually manufactured from iron or a steel alloy or from high-density ceramic material when metal contamination of the product is a concern. *Autogenous mills* use the feed stock (incoming ore) itself as the medium, and *semi-autogenous mills* use a combination of the feed stock and balls. Stirring mills reduce the size of the feed stock between fixed and rotating mill components. Materials discharged from mills can range in size from less than 40 to 300 micrometers (µm) for tumbling mills and from 40 to less than 15 µm for stirring mills [Wills 2008].

Although mineral processing milling is often done wet, the industrial minerals industry primarily utilizes dry milling. At some operations, the grinding mill is fed with coarse rejects or one of the products from their dry screening operation. These milling operations are fed dried granular minerals, usually less than 12 mesh (1.7 millimeters), and produce products in the 50-µm range, but some fine-grind products are less than 10 µm in size, which means that all of the fine-grind product is in the respirable-sized range.

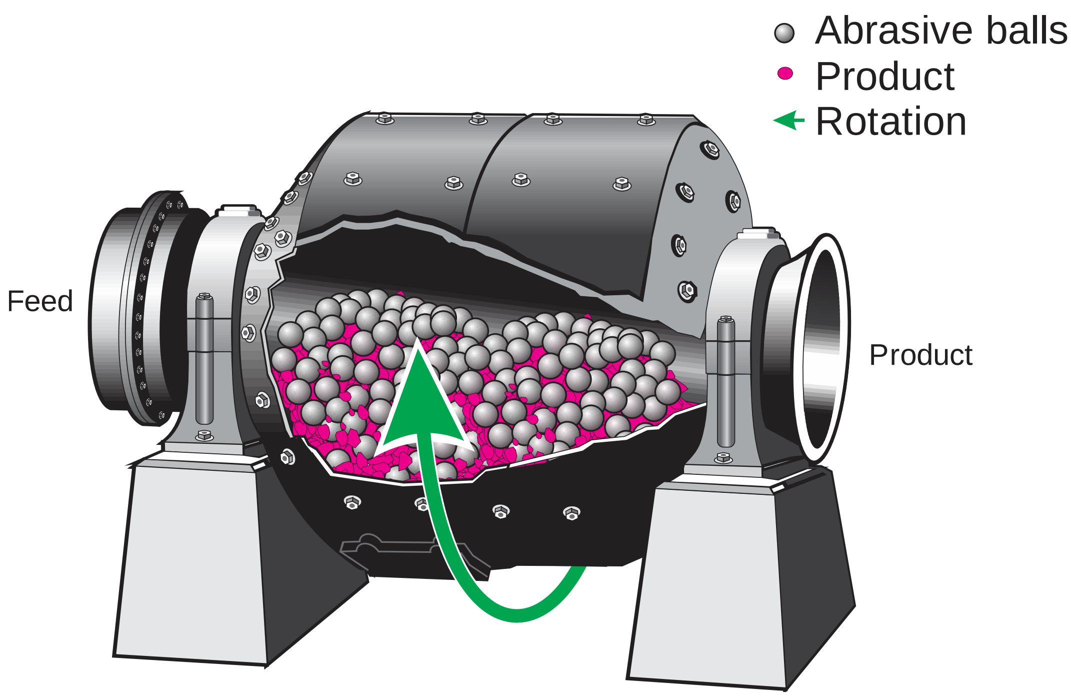

Figure 5.12. Cutaway illustration of a ball mill.

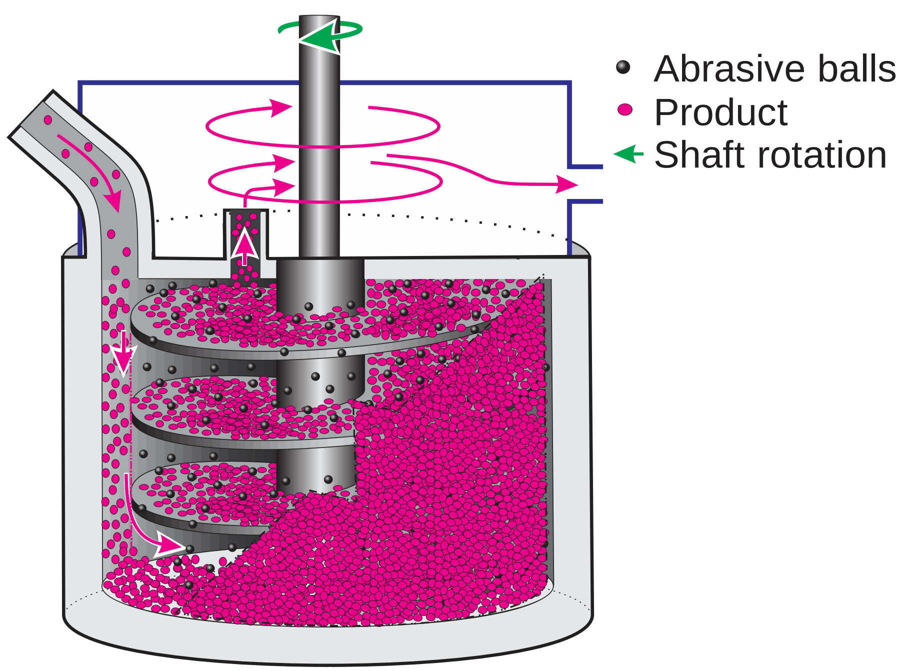

Figure 5.13. Cutaway illustration of a stirring mill.

Some specialty grinding operations purchase damp granular minerals and dry them before they are fed into the milling process. Regardless, all the processing equipment involved in preparing and feeding the grinding mill have their respective dust collection systems.

The most important consideration for dust control within a grinding/classification/product storage circuit is dust containment, and the second is dust collection. All of the material-conveying equipment related to a milling or grinding circuit must be enclosed. In addition, all transfer points must be fully enclosed.

Design and Work Practices to Minimize Dust Exposure from Milling

The following design and work practices can serve to reduce operator exposure to airborne dust around milling operations.

- During operation, grinding circuit equipment must be tightly closed and maintained under a slight negative pressure by a dust collection system. This means that any air leakage will flow into and not out from the equipment, keeping the dust contained.
- Sampling points must be designed so that when the access doors are opened, the milled material stays inside. All sample and inspection doors should be installed at least 45 degrees off the vertical or greater, with horizontal doors being preferable for easy access and lower risk of spillage (Figure 5.14).
- Grinding circuits and buildings should be designed so that they can be washed down for cleaning.
- A vacuum system should be installed and used for cleanup. Equipment should not be dry swept or brushed off because of the possibility of dust liberation. Never use compressed air to clean equipment or work areas.
- When processing equipment is located on upper levels, the upper levels should have solid floors. If a spill or leak were to occur over a solid floor, the material piles up instead of falling toward the next level where it will become airborne and contaminate the mill. This also aids in housekeeping and safety in that water does not fall to lower levels.
- Sections of the milling process should be isolated to improve containment efforts. Examples include uncovered storage, bagging areas, and bulk loadout areas.
- Above freezing conditions, floors should be kept wet so that any falling dust will immediately hydrate and be trapped.
- Whole structure ventilation with at least 10 air changes per hour (acph) is recommended.
- For classifier circuits, vendor guidelines should be followed for ducting and airflow to achieve optimum classification results. With other components of the grinding/loadout operation, the containment, pickup points, and ducting should be designed so that areas with high air movement do not occur at transfer points and other potential disturbance areas where the air stream will entrain product.
- When new or recently lined tumbling mills are started up for the first time, the air leaving the mill is fairly humid until the grinding action builds up enough heat to drive the moisture out of the curing grout. This can lead to a buildup of moist material in ducting and may cause blinded bags and cartridges in the dust collectors. These problems will typically be resolved once the mill reaches operating temperature and the grout has cured.

Photo by NIOSH

Figure 5.14. Sampling doors located on top of a collection/transfer point to prevent leakage.

SCREENING

Screening operations can produce high levels of dust because smaller-sized material is handled. Airborne dust is generated from the vibrating screen decks that accomplish the size separation. Additionally, material must fall some distance as part of the separation process, and some dust will be suspended by this process.

Dust control for screening systems is similar to that for crushers, although wet systems are generally not used due to blanking of the screen openings by the wet material. Also, screens are not normally subject to large surges of material flow as are crushers. This is due to the fact that screens operate most efficiently within a designed flow range. Overloading screens, whether through excessive feed rate or large surges of material, can cause accelerated wear of components, reducing the efficiency of the operation and potentially increasing dust emissions.

Screens should be totally enclosed, and water suppression systems (when compatible with the process) or dust collection and exhaust systems should be incorporated. Necessary openings in the screen enclosure must be minimized, and inspection and maintenance openings must be provided with tight-fitting closures.

Flexible materials (e.g., rubber or synthetic sheeting) must be used to seal openings between the moving screen components and stationary equipment and structures. Because the seal between moving and stationary components is under dynamic stresses whenever the screen is operating, it should be frequently inspected for signs of failure on a schedule that incorporates data from its operating history. Some screen original equipment manufacturers offer parts and materials, such as covers and flexible sealing components designed specifically to fit their equipment well, and thus enabling creation of an effective dust control enclosure. Equipment vendors should be consulted to explore available control options.

Initial design exhaust air volume may be estimated using the induced air method via Equation 5.2. Figures 5.15 and 5.16 illustrate exhaust ventilation dust control on screens. The dimension for material fall (Equation 5.2, variable S) is indicated in Figure 5.15. The upstream open area dimension (Equation 5.2, variable A_U) is the estimated area of the transfer chute plus any unsealed open area around the chute penetration into the dust control enclosure.

Alternatively, an exhaust volume of 50 cfm per square foot of screen area may be used as an initial value for flat deck screens [ACGIH 2010]. This value is not increased for multiple-level screens because the stacked construction of multiple-level screens presents no more "source area" than does a single screen. For cylindrical rotary screens, an exhaust volume of 100 cfm per square foot of screen cylindrical cross section with an in-draft velocity minimum of 400 fpm is recommended [ACGIH 2010].

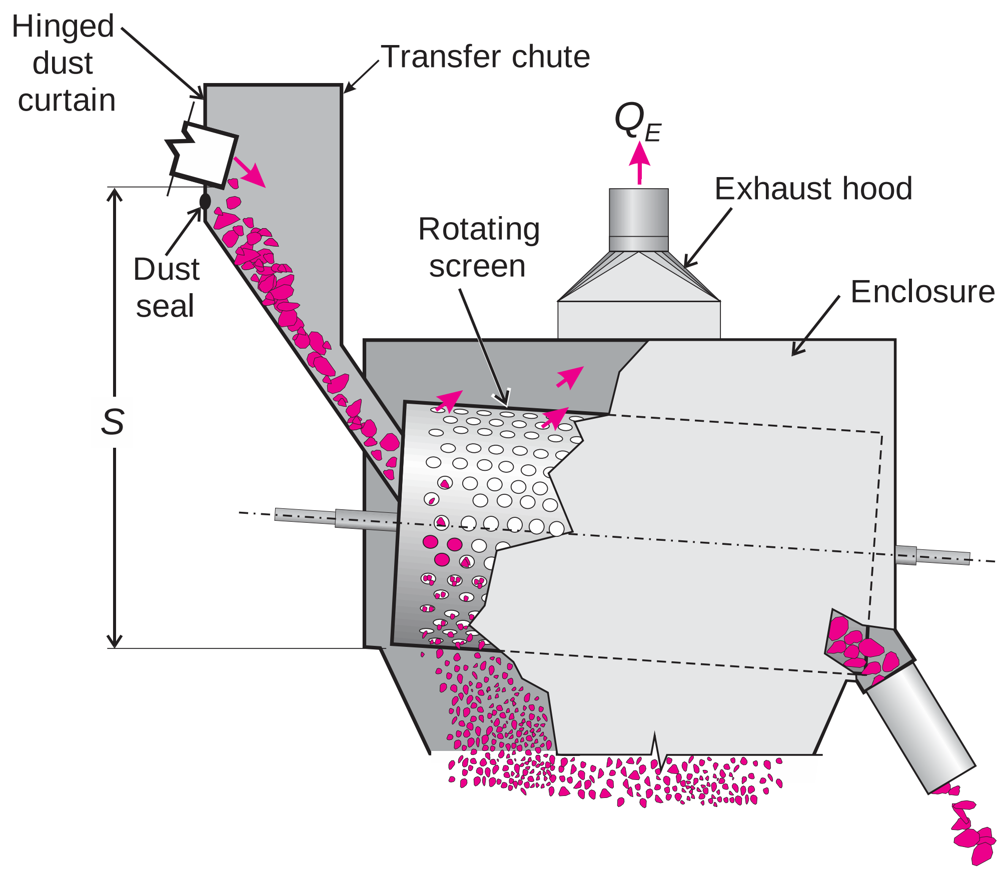

Figure 5.15. Illustration of a dry (exhaust) dust control system on the feed to a rotary screen with an enclosed transfer chute. See Equation 5.2 for a definition of variables.

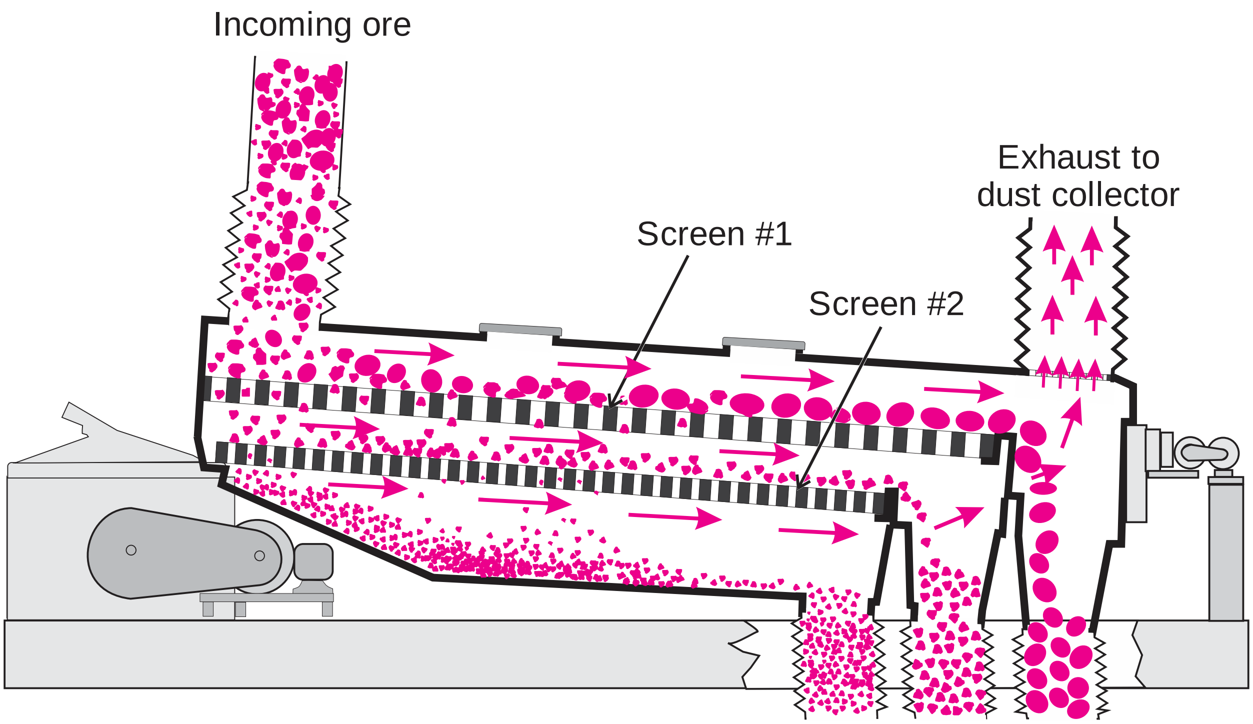

Figure 5.16. Illustration of a dry (exhaust) dust control system on a vibrating screen.

Exhaust air take-off location must be carefully considered so that desirable fines (product) are not collected. Locating the take-off closer to the discharge (away from the feed end) of the screen will help avoid the loss of desirable fines. Also, collection of undersized material can be reduced by using take-off openings large in area to reduce the air entry velocity.

Work Practices to Minimize Dust Exposure from Screens

The following practices should be observed where compatible with installed equipment and existing operating procedures.

- Clean equipment and area before and during work, when needed, preferably by washing or vacuuming.
- Stop material flow before cleaning screens if operationally feasible. The absence of flowing material minimizes the potential for dust emissions.
- When cleaning, only open the top or the bottom part of screen decks at a time. Do not open both at the same time. The larger the size of the opening, the less effective t*he ventilation system can be.
- Only open one screen at a time during cleaning. Do not open multiple screens simultaneously. Again, numerous openings decrease the capture effectiveness of a ventilation system.
- When cleaning screens, only use long-handled brushes that will provide more distance between the worker and the dust source.
- Consider variable-speed vibrators, which significantly reduce the frequency of manual cleaning of screens. The less time needed to clean screens, the less the potential for dust exposure.

- Open screen decks slowly to allow the internal exhaust system to function at the deck periphery. Opening decks rapidly can cause a swirling effect, with dust being released into the work area and potentially exposing personnel.
- Do not slam screen decks closed. Any material, no matter how slight, has the potential to become airborne due to the shock of deck closure.
- Decks must be kept clear of dust. A clean deck lessens the potential of dust emissions resulting from opening and closing decks, as well as from environmental factors such as wind.
- Maintain seals on screen decks where an airtight closure is desired. Decks that are properly sealed should remain sealed when all fasteners and sealing materials are in place.
- Closure and locking devices such as clamps and other fasteners must be well maintained. Fasteners are ineffective unless they are used as intended.
- Where compatible with the process, wash down areas around screens on a periodic basis. Periodic washing removes material before it accumulates to a degree where dry cleanup methods become necessary. Dry cleanup activities present a much higher potential for worker exposure.

MAINTENANCE

Maintenance of dust control systems is critical to ensure continuing worker protection [USBM 1974]. Crushers and screens are subject to constant vibration when in use, and this condition can cause accelerated wear on all components. Even small openings from worn seals, missing fasteners, and damaged flexible connectors can cause unwanted air infiltration, degrading capture velocity at necessary penetrations [Goldbeck and Marti 1996]. This could potentially result in worker overexposure, particularly when exposure limits are low.

Operators should document baseline parameters of an effectively functioning dust control system, including the following:

- inflow velocity at enclosure openings,
- static pressure in ducts,
- velocity pressure in ducts and at hood entry points, and
- water pressure and flow in wet systems.

The results of subsequent periodic checks should be compared to the baseline values. Significant deviations from the baseline values should be explored, and corrective action should be implemented when necessary.

A preventive maintenance schedule should be established based on manufacturer recommendations, observed component wear, system performance measures, and exposure sampling results.

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Chapter 6: Conveying and Transport

CHAPTER 6: CONVEYING AND TRANSPORT

There are numerous types of equipment used at mining and mineral processing operations to transfer material from one location to another. The material being transferred can range from raw unprocessed ore to fully processed finished product. Proper selection of the correct type of equipment is a function of the specific application, taking into account the material to be transferred, the transfer distance, and the nature of the transfer (i.e., horizontal, vertical, incline, or decline). This chapter will discuss some of the most commonly used transport systems and the methods available for controlling dust, carryback, and spillage.

BELT CONVEYORS

Belt conveyors are among the most commonly used pieces of equipment at mining and mineral processing operations. A conveyor and its associated transfer points are well known to generate significant quantities of respirable dust. Operations must control these emissions by containing, preventing, suppressing, or collecting dust—either before or after it becomes airborne—giving special attention to transfer points. A conveyor belt consists of many different parts, as seen in Figure 6.1. Terms from this figure will be used throughout this chapter.

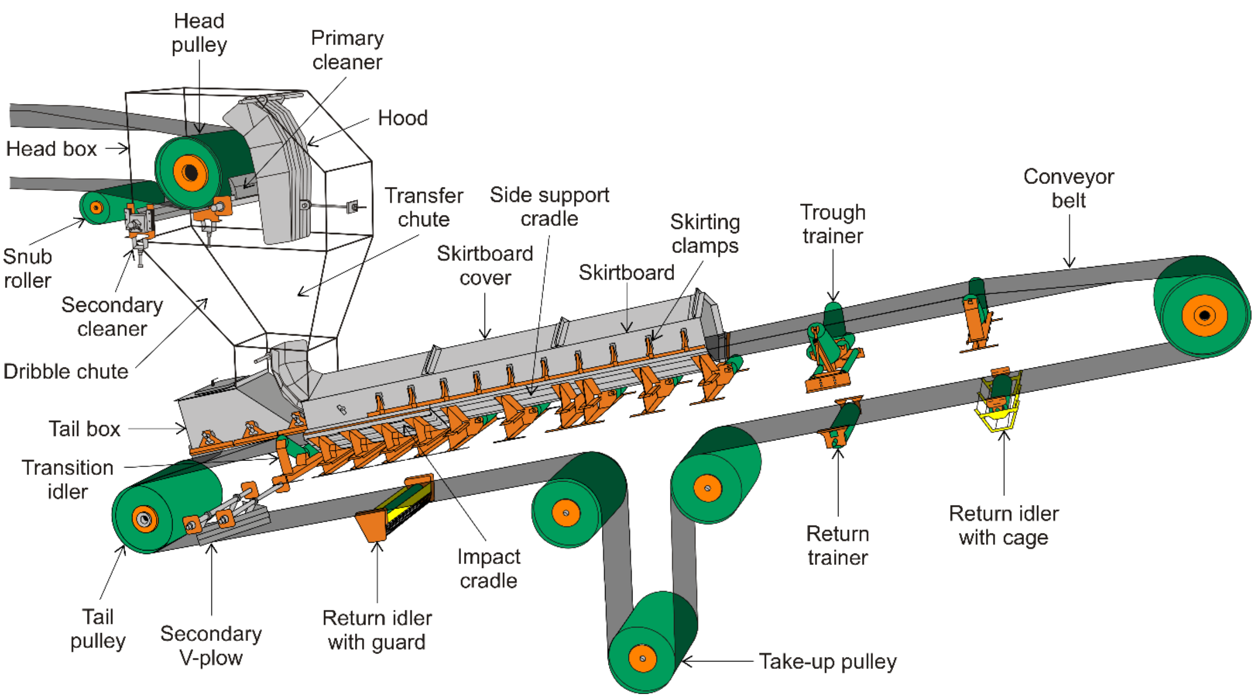


Illustration adapted from ASGCO

Figure 6.1. Illustration of the basic components of a conveyor belt.

The root causes for fugitive emissions associated with conveyor belts stem from issues with uncontained material from both carryback and spillage as well as from airborne dust (Figure 6.2). Spillage results from uncontained or improperly loaded material, and carryback comes from material failing to discharge from the belt as it is transferred or discharged from the conveyor belt. Spillage and carryback, besides being safety hazards, result in uncontained material that can become airborne dust. Airborne dust is created when small particles of insufficient weight are picked up by excessive airflow.

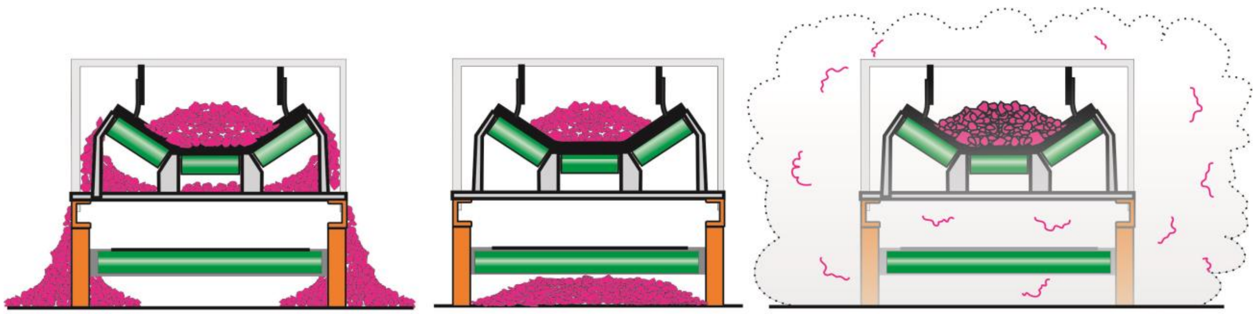


Figure 6.2. Illustration of types of fugitive emissions from conveyor belts.

Dust management efforts are generally based on one or more approaches, with many operations using a combination of methods to achieve maximum effectiveness, as follows.

- Containing the material as it is transferred from one vessel or conveyor belt to another vessel or conveyor belt.
- Implementing design and methodologies that prevent airflow from becoming excessive.
- Containing and slowing the velocity of any air that is developed in the material transfer process.
- Implementing measures to increase the weight of the particles to prevent them from becoming airborne.
- Removing dust particles that do become airborne by agglomerating them with moisture or by capturing them through a filter system.
- Cleaning the conveyor belt to ensure carryback material is returned to the material stream.

Each of these methods is discussed in detail in the subsections below.

Containing the Material

Material spillage from a conveyor belt is caused by a lack of material control, either at a transfer point or along the conveyor's route. Spillage along the route is generally associated with carryback. Carryback is normally located along the return run of the belt and is more prevalent below the belt idlers, as discussed later in this chapter.

The transfer of material normally happens from the head of the discharge conveyor onto the tail of the receiving conveyor. The most prevalent location for material spillage is at these transfer points, although overloaded or mistracking belts cause material spillage along with belt wear and damage to the overall belt structure (Figure 6.3).

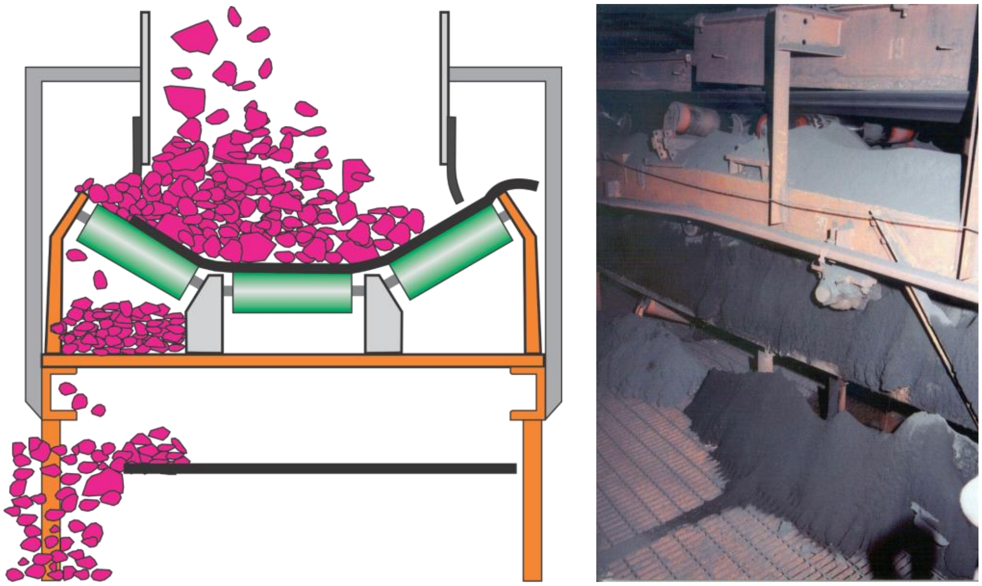


Photo by NIOSH

Figure 6.3. Example of material spillage from a conveyor belt, which is a safety hazard and a source of dust, and which causes premature equipment wear. The left illustration shows material spillage below the belt, causing equipment wear. The right photo shows major ore spillage from a belt, which will result in premature wear and more frequent repair. This spillage is also a constant source of respirable dust exposure to workers in the vicinity of the belt.

In order to effectively control material at transfer points, operators must ensure proper alignment, minimize vertical fall distance of the material, feed material to the center of the belt, and contain the transfer of material while minimizing transfer distance. Each of these controls is discussed in detail below.

Ensuring Proper Belt Alignment

Proper belt alignment must be ensured along the entire length of the conveyor, with special attention paid to the belt at the transfer point. The conveyor structure must be "true" (relative to the centerline) and "level" (side to side). All pulleys, snub rollers, and carrying and return idlers must be "square" with the frame (i.e., perpendicular to the belt centerline) and parallel to each other. Finally, the conveyor belt must be straight (less than 0.5 percent camber) and in good working condition (no cupping or damage), and the ends must be squared and properly spliced.

Good conveyor belt tracking requires cleanliness—therefore, no buildup of carryback on the idlers or pulleys can be allowed. The pulley lagging should not be worn nor irregular in shape. Belt tension should be adjusted to meet the manufacturer's recommendations. The tension must be high enough to prevent slippage between the drive pulley and the belt while also causing the belt to conform to the pulley crowns. Slippage will cause excessive wear to both the drive pulley lagging and the bottom side of the belt.

If possible, operators should observe the belt being loaded and while it is operating, checking to ensure the belt is properly loading in the center and, if not, making any adjustments possible to correct this condition. For safety, operators must ensure that the belt is stopped—following all lockout/tagout procedures—when making adjustments, remembering that making several small adjustments is preferable to making one or two large adjustments that may result in overcompensation.

Importantly, tracking adjustments to the conveyor belt should never be done by adjusting pulleys. This can cause uneven conveyor belt stretch and/or pulley and shafting problems. The following process is recommended.

- Spread tracking adjustments over some length of the conveyor preceding the problem area.
- Begin by tracking and adjusting idlers on the return run, working toward the tail pulley
- Adjust the idlers on the top run in the direction of belt travel. Start with the belt empty, and then begin loading the belt gradually while observing the operation of the belt up to full load condition.

If the belt runs to one side at a particular point or points along the conveyor structure, the cause will probably be due to the alignment or leveling of the structure, the idlers and pulleys immediately preceding that particular area, or a combination of these factors. In such a circumstance, the belt will move toward the edge of the roll (idler) where it first comes in contact. In extreme cases, belt alignment devices may be required to overcome short-term tracking problems.

Finally, material spillage leads to fugitive material being piled around operating conveyors. This material poses a safety hazard and lends itself to being picked up by the wind and blown around and off the property, creating environmental issues and affecting nearby businesses or residences.

Minimizing Vertical Fall Distance of Material

Minimizing the vertical fall distance of the material being transferred in turn minimizes the impact of the material on the belt and reduces air entrainment into the material (as a demonstration of air entrainment, see Figure 2.6 in Chapter 2). Many of the methods for minimizing drop height are also effective for controlling air. To ensure both material containment and dust control, operators should design transfer systems that minimize drop heights, absorb rebound from the material dropping onto the receiving belt, contain the material on the belt, and contain and slow the air entering and leaving the containment. Higher vertical drops and heavier lump sizes also create more impact on the receiving belt. This impact causes belt damage and increases the material rebound and likelihood of material spillage.

An impact cradle system (impact bed) installed under the receiving belt will absorb material impact, softening the rebound, and provide protection to the receiving belt (Figure 6.4, left). These impact systems consist of an impact-absorbing material covered by a friction-reducing top cover and serve to flatten the belt's surface at the edge. This flattened surface provides a location where system sealing is performed in order to keep the material on the belt. In areas of low impact or no impact, light-duty, side support cradles (slider beds) can be used (Figure 6.4, right).

Photos by Martin Engineering

Figure 6.4. Impact cradle and side support cradle. The impact cradle (left) reduces material rebound and spillage, while the side support cradle (right) is specified in "no impact" zones or for lighter-duty ore transfer applications. These cradles are often combined in systems to provide the foundation necessary for properly sealing the belt.

For effective design of impact cradles, refer to Conveyor Equipment Manufacturers Association (CEMA) Standard 575–2013 [CEMA Standard 575–2013]. CEMA is a trade association composed of leading manufacturers of conveyors and conveying systems that design, produce, and install all types of conveying machinery. Impact energy should be calculated from formulas in Figure 6.5, determining both impact energies and selecting the larger of the two values. Impact energies are determined using the following procedure:

- Find the weight of the largest lump carried (W) and multiply it by the vertical fall distance (h) to calculate impact energy (IE).
- Compute the equivalent weight (W_e) by dividing the square of the bulk material flow rate (Q^2) by the spring rate of the equipment considered (k).
- Multiply W_e by h to determine the alternate impact energy.
- Apply the larger of the two values to Table 6.1 to determine the duty rating required for the impact cradle.

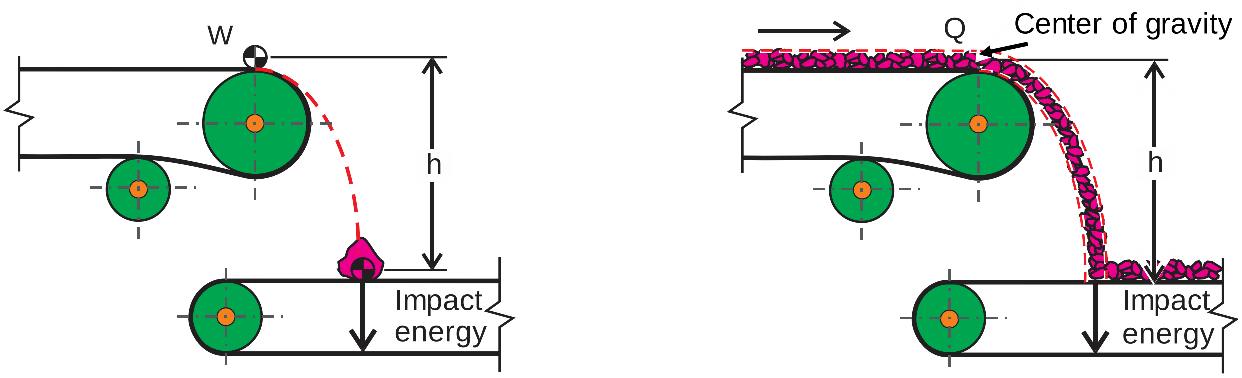


Figure 6.5. Calculations for determining material impact loading at a conveyor transfer point [adapted CEMA Standard 575–2013], with illustrations depicting the impact from a single lump (left) and a homogenous stream (right).

W: Mass of single lump in pounds.
h: Vertical fall distance of a lump from the center of gravity of the homogeneous load or lump to the belt in feet.
Q: Flow rate of the bulk solid in short tons per hour.
k: The spring constant for the impact cradle including the sliding surface and support structure in pounds per inch.

Table 6.1. Impact cradle ratings to be used based on impact loading [adapted from CEMA Standard 575–2013]

Duty Rating	Description	Impact Energy, lbf-ft
L	Light duty	< 200
M	Medium duty	201 to 1,000
H	Heavy duty	1,001 to 2,000*

* Consult a CEMA member for impact energies > 2000 lbf-ft

Rock boxes and other loading devices are utilized to soften the load and reduce impact cradle code requirements. Rock boxes allow ore to fall onto ore rather than directly onto the belt. This approach shortens the drop and alters the speed and the direction of the material being transferred in order to minimize wear on the conveyor belt and the inner surfaces of the chute (Figure 6.6).

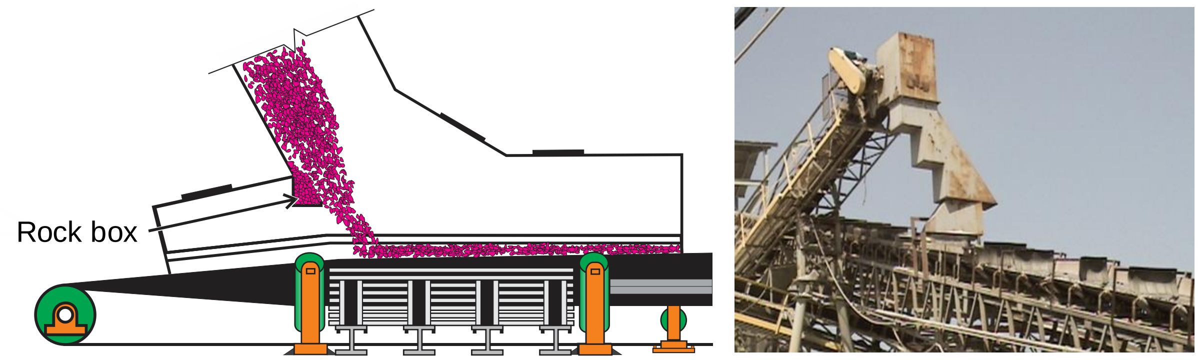


Photo by Martin Engineering

Figure 6.6. Rock boxes used to minimize impact of falling material. The left illustration shows a rock box softening the load by reducing the drop height, with ore used as the deflection mechanism in order to reduce wear on metal parts. The right photo shows a series of rock boxes redirecting the material from one belt onto the next belt.

Feeding Material to the Center of the Belt

Feeding material to the center of the conveyor belt protects the belt's integrity and controls material spillage at transfer points. Material fed more to one side of a belt than the other (Figure 6.7) causes the belt to shift sideways and run off-center. A belt that runs off-center can damage the belt and its supporting structure while spilling material over the edge of the belt outside of the transfer point.

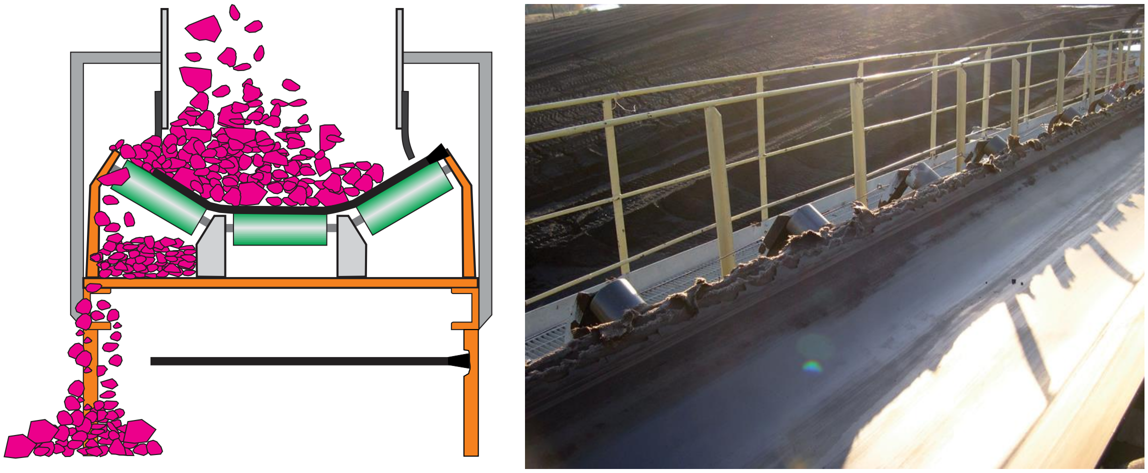


Photo by Martin Engineering

Figure 6.7. Material being improperly fed onto a conveyor belt. The left illustration shows how improper loading can move the belt into the structure with the consequence of damage to the belt and support structure. The right photo shows the resulting belt damage that can occur from long-term belt structure contact.

In addition to feeding material onto the center of the conveyor, it must also be fed in the direction of belt travel and at the same speed as the receiving conveyor. This reduces damage, avoids material being thrown from the belt as it settles, and increases its speed to that of the belt.

Figure 6.8 depicts the simplest of transfer points, where the feeding and receiving conveyors are in line with each other. The material is being fed from the top conveyor onto the bottom conveyor. The bottom conveyor's width and trough—and therefore its carrying capacity and speed—should match that of the top conveyor. If the fall distance is minimized as described above, then the material will not have the opportunity to spread and should land in the center of the belt. When necessary, alternative methods for centering the load can also be applied in this situation as long as they follow this principle of feeding material to the center of the conveyor.

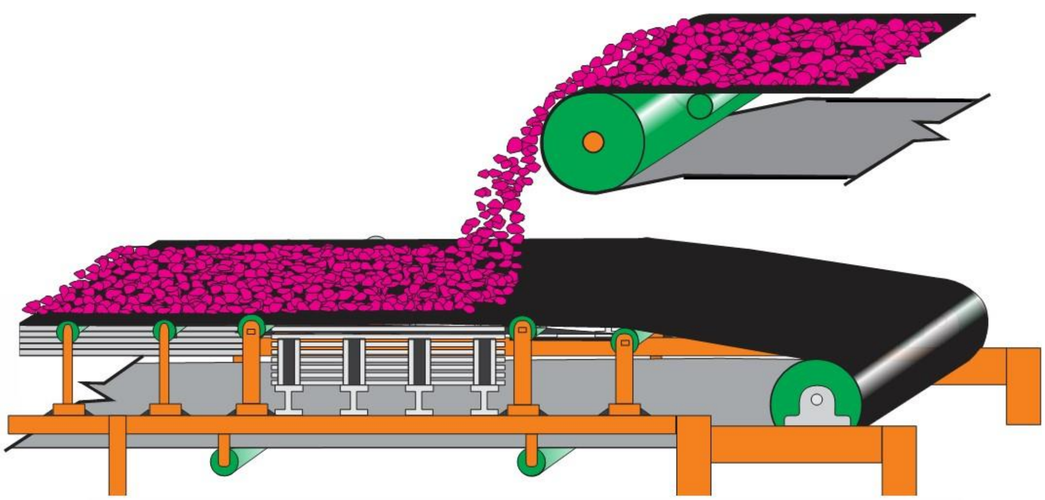


Figure 6.8. Basic illustration of material transfer from a top conveyor to a bottom conveyor.

Achieving effective transfer of material in the same direction and at the same speed when conveyors are, for example, perpendicular to one another, is more challenging. In such cases, loading devices are used to soften and steer the load. A rock box can assist in centering the load and slowing the speed of drop (Figure 6.9).

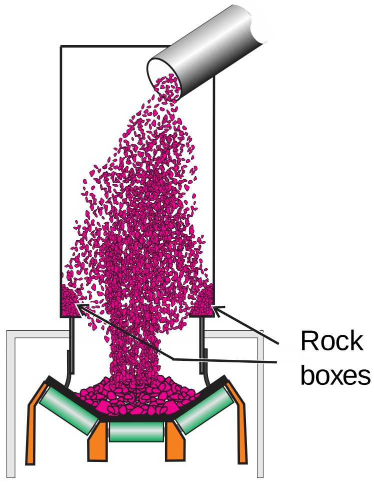


Photo by Martin Engineering

Figure 6.9. Rock boxes used to soften the drop of and redirect the flow of falling material. The left illustration depicts two rock boxes creating a location for ore to accumulate, and the piled ore redirects flow to the center of the belt below. The right photo is an overhead view looking down into the chute, with rock boxes encircling the chute to redirect the ore onto the center of the belt below.

To help control placement of the material, deflector plates can be installed to redirect the load. Engineered curved plates placed near the surface of the receiving belt redirect the material being fed in order to control its placement in the belt center, in the direction of belt travel, and at the same speed as the receiving belt (Figure 6.10). Care must be taken in applying any load-altering devices to ensure sufficient space is created to allow any belt splices to pass.

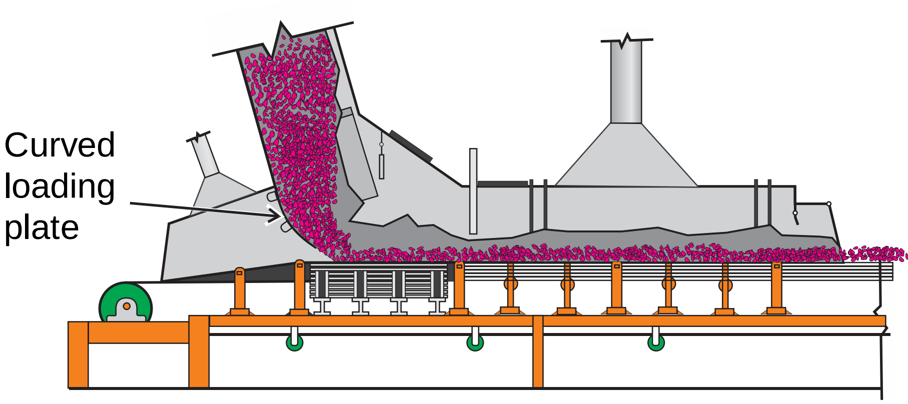


Photo by Martin Engineering

Figure 6.10. A curved loading plate (spoon) to help steer loaded material in a particular direction. The left illustration shows the curved loading plate within a chute. The right photo shows an end view of a curved chute.

Containing the Transfer of Material and Minimizing Transfer Distance

Containing the material as it travels through the transfer point and for a distance on the receiving belt maintains it on the belt and provides time to allow it to settle.

Belt sag is a cause of material spillage. Idlers spaced too far apart in the load zone allows material to release along the belt in the areas between the idlers. This results in material spillage along the conveyor and entrapped fugitive material that grinds away at the conveyor belt and its components, creating more dust and premature equipment damage (Figure 6.11).

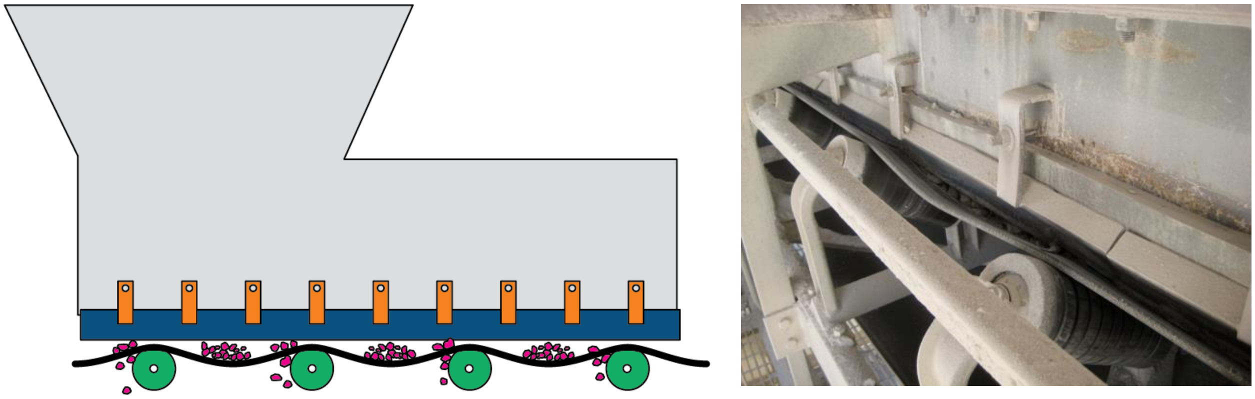
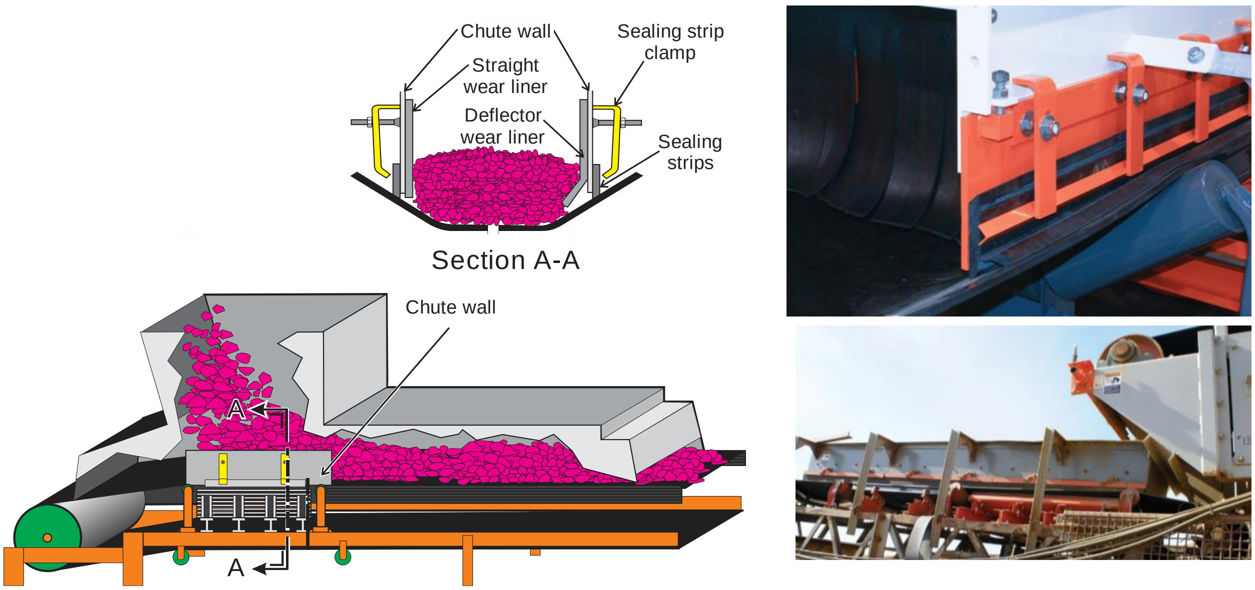


Illustration and photo by Martin Engineering

Figure 6.11. Material spillage and entrapped fugitive material resulting from belt sag. Both the left illustration and the right photo show belt sagging between idlers.

By removing idlers, installing impact cradles in the load zone, and using side support cradles (slider beds) with intermediate idlers through the remainder of the transfer zone, the outside edge of the belt can be somewhat flattened out, enabling material and air sealing. Applying a wear liner close to the belt will serve as a material barrier.

A wear liner is a hardened or otherwise extended-life sacrificial material used to contain the material load in the transfer zone. It provides time and space for the particles to settle. The wear liner should be extended far enough along the skirtboard to a length sufficient to allow the material to gravitate to the center of the belt. Ideally, the wear liner is placed close to the belt to ensure that it keeps material on the belt (Figure 6.12). It provides clearance for any splices and is relieved toward the exit of the transfer zone to avoid material entrapment under its edge. The existing chute wall provides the support structure for the wear liner and should be at the same level or higher to avoid material entrapment.



Photos by Martin Engineering

Figure 6.12. Wear liner and chute wall installed near the belt and within a transfer zone to maintain the loaded ore on the belt. The left illustration shows a transfer zone of a belt with a cutaway (Section A-A) view of the chute wall, the wear liner, the sealing system, and the belt. The top right photo shows an actual application of the chute wall, wear liner and sealing system, which includes a sealing strip and clamp system. The bottom right photo shows a transfer zone application in the field.

PREVENTING THE CREATION OF EXCESS AIR VELOCITY

When material is discharged from a head pulley and travels through the air, it tends to open up and spread out. The amount of spread the material achieves depends on a combination of the amount of vertical drop, the discharging belt’s speed, the angle of the discharging belt, and whether there is anything in place to limit the spread of the material—such as a chute wall, deflector plate, or wear plate. As the material spreads it gathers air (venturi effect) within the material load, and when the material with its encapsulated air drops onto the receiving belt, the material collapses back onto itself, pushing the air out and increasing the quantity and velocity of air in the transfer. The resulting air with its greater velocity picks up light particles, thus creating and liberating airborne dust. By implementing measures to avoid this material spread by shortening the drop or controlling the material flow, much of this added velocity can be avoided, reducing the ability of the air to pick up dust.

Engineered flow chutes are designed to control the material in a tight stream and place it on the receiving belt with a minimum creation of air velocity. The hood maintains the material in a tight stream and glides it down to the spoon. The spoon continues the process of maintaining the tight stream and guiding the material onto the belt with a minimal drop while matching the speed and direction of the material.

As an example, Figure 6.13 shows an engineered flow chute depicted by way of a coupled computational fluid dynamics (CFD) and discrete element method (DEM) simulation [Goniva et al. 2012]. The top illustration shows the original design of a bulk material (lead and zinc concentrate) transfer process, and the bottom illustration shows a modified design that directs the material through a diverter and onto one of two receiving conveyors. Dust was escaping from the hood in the original design, which used a flat deflector plate to direct material toward the receiving conveyor, and was building up on the ground below. Areas of airflow greater than 200 feet per minute (fpm) were highlighted as potential concerns, as dust could remain entrained in the moving air and be carried out of the enclosed transfer into the surrounding environment [Swinderman et al. 2009]. To address this issue, the modified design (bottom) uses a “hood and spoon” transfer with an enlarged settling zone—an enclosure with a series of staggered rubber curtains that slow down the air flow exiting the lower portion of the chute. This design minimizes material and air turbulence inside the chute, keeps the entrained air flowing along with the bulk material, and allows dust to settle back on the main material flow before it exits the transfer chute.

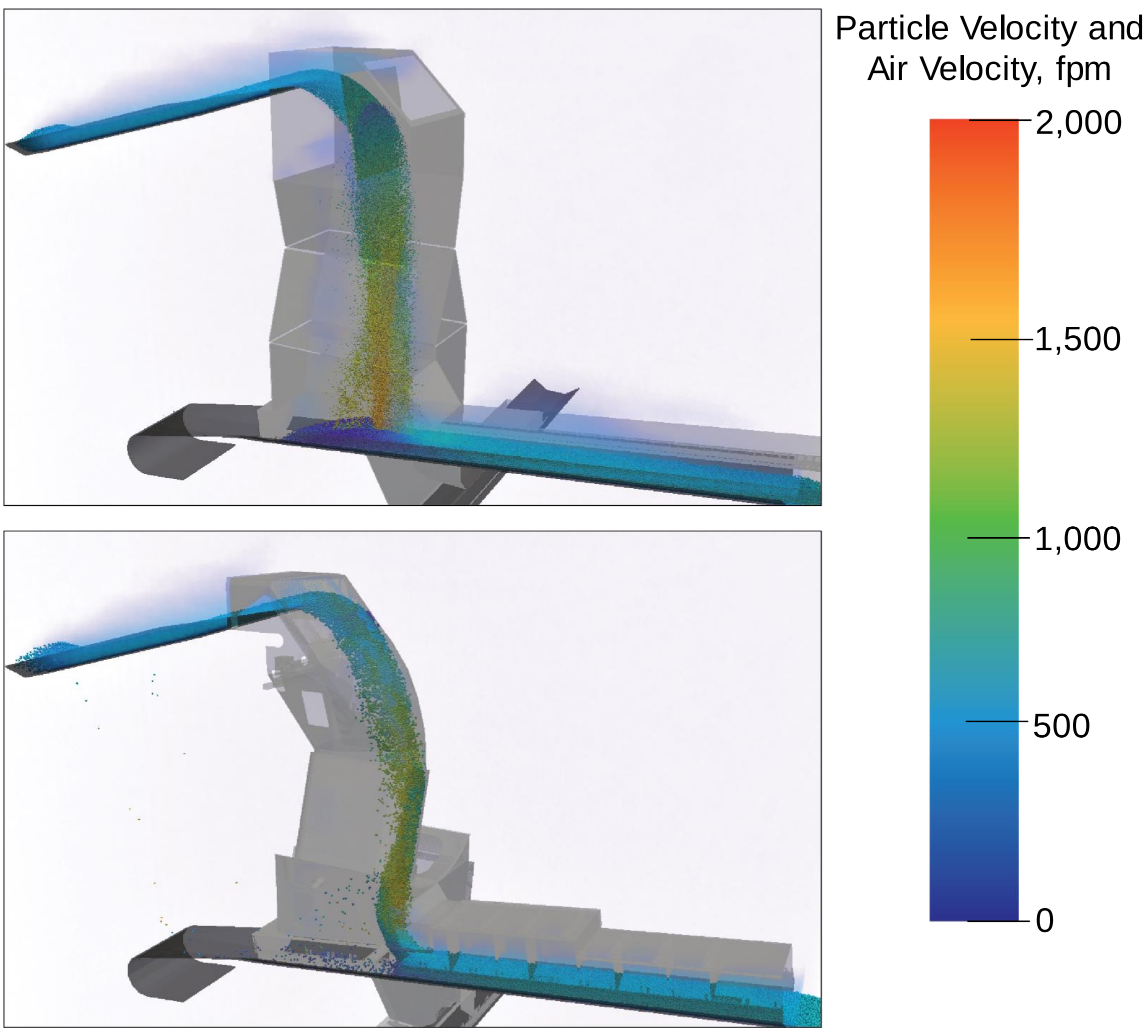


Illustration by CWA Engineers

Figure 6.13. Simulation of engineered flow chute, with particle velocity and air velocity represented. The top image shows the original design in which the material was escaping from the hood. The bottom image shows the modified design resulting in improved flow of air and material.

Importantly, engineered chutes require accurate field measurements and extensive engineering calculations, increasing overall system costs. These systems also require a larger footprint than some of the alternative methods discussed earlier, such as rock boxes and deflector plates. As changes occur to the ore conditions or to the quantity or speed of the ore being conveyed, recalculations and adjustments to flow chutes may be necessary to avoid excessive chute wear or the plugging of material, which further increases costs.

Another measure that can be implemented to avoid entraining air into the process is to seal the entry to the unloading zone—i.e., the area around the head of the discharge conveyor. A head box to enclose the head of the discharging conveyor with seals to limit the air intake reduces the amount of air that is induced into the transfer zone (Figure 6.14).

Photo by Martin Engineering

Figure 6.14. Demonstration of material being transported into a sealed head chute.

CONTAINING AND SLOWING THE AIR

After limiting air velocity creation, steps should be taken to create a "stilling zone." A stilling zone is an enlarged area beyond the transfer zone of a belt conveyor designed to slow the airflow and allow airborne dust to return to the ore. This enclosure is implemented to seal up the load zone, enlarge the air space, and allow for the implementation of measures to lengthen the amount of time provided for the material to settle out of the air.

The foundation for the stilling zone should be created by flattening the outside edge of the belt using impact and side support cradles. Wear liners should be installed close to the belt in order to contain the material. The gap that remains between the wear liner and the belt is in turn sealed by a flexible elastomer sealing strip (skirt rubber, with both a primary and secondary seal) normally attached by a clamp system to the outside wall of the skirtboards (Figure 6.15). These seals are designed to capture small fines that escape past the wear liner. Primary and/or secondary seals are employed in a variety of ways to block any fines and dust from escaping to the atmosphere.

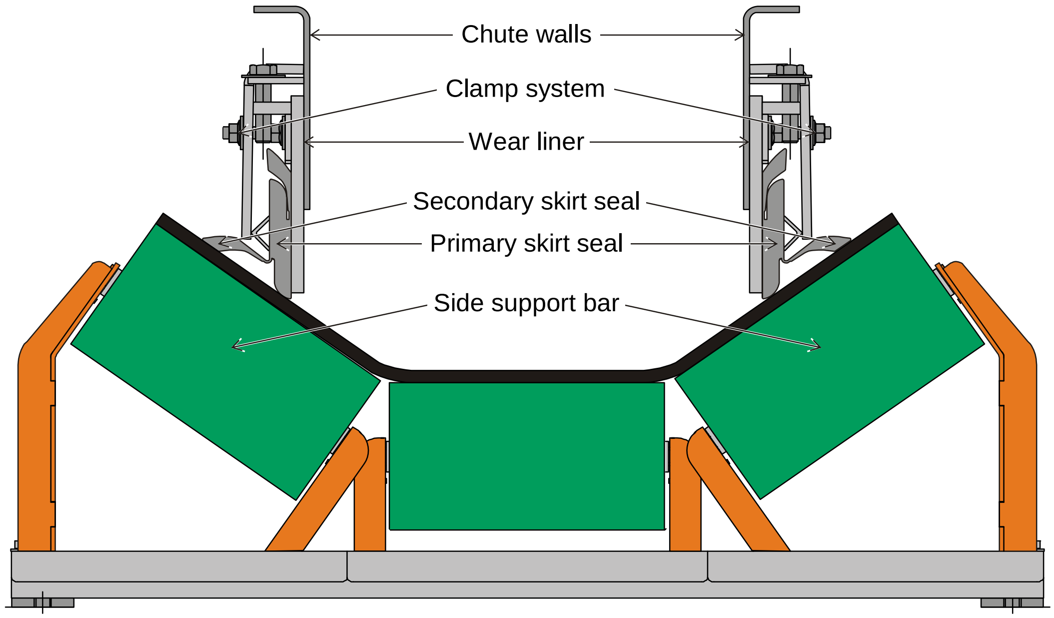


Illustration by Martin Engineering

Figure 6.15. Illustration showing how the foundation for a stilling zone is built.

Enclosures at the head end of the feeding conveyor and at the tail of the receiving conveyor are a common practice in that they are effective at controlling dust and eliminating sources of air entrainment at these locations. While the total elimination of dust generation at conveyor transfer points is probably not feasible, effective dust control is achievable. Designing the proper size enclosure with easily accessible covers is a critical factor because as ore is dumped onto the conveyor, it entrains a measurable amount of air (venturi effect) and thus can pressurize the enclosure. Enclosures for both conveyor and transfer points can be either full or partial, depending on the various components of the system.

Assessing the correct amount of the required air volume is essential to effective dust control when sizing chutes and for effective implementation of air cleaning or dust collection. Total airflow at a given transfer point can be calculated by Equation 6.1 [Goldbeck and Marti 1996]:

$$Q_{tot} = Q_{dis} + Q_{ind} + Q_{gen} \tag{6.1}$$

where Q_{tot} = total air movement, cubic feet per minute;
Q_{dis} = calculated displaced air, cubic feet per minute;
Q_{ind} = calculated induced air, cubic feet per minute; and
Q_{gen} = determined generated air, cubic feet per minute.

The amount of displaced air increases as the volume of moving material increases. The amount of displaced air can be calculated by Equation 6.2 [Goldbeck and Marti 1996]:

$$Q_{dis} = \frac{conveyed\ product\ (lb/min)}{bulk\ density\ (lb/ft^3)} \tag{6.2}$$

$$conveyed\ product\ (lb/min) = \frac{{}^{t}/_{hr} \times 2000}{60}$$

Material conveyed along the belt will have a small amount of air entrapped in the product bed. As the product leaves the head pulley in the normal trajectory, it increases in volume as each particle of material collects an amount of air. Once the product lands, this induced air is released, causing substantial positive pressure flowing away from the center of the load zone. The movement of this induced air can be calculated as follows using Equation 6.3 [Goldbeck and Marti 1996]:

$$Q_{ind} = 10 \times A_U \sqrt[3]{\frac{RS^2}{D}} \tag{6.3}$$

where Q_{ind} = induced air, cubic feet per minute;
A_U = enclosure upstream open area, square feet (where air is induced into the system by the action of falling material);
R = rate of material flow, tons per hour;
S = height of material free fall, feet; and
D = average material diameter, feet.

Other sources of moving air (Q_{gen}) may be devices feeding the load zone, such as crushers, and these devices can create a fan-like effect. Equipment manufacturers can provide operators with additional information to help quantify the amount of air generated by these mechanical devices.

Air calculations will assist in assessing how much to increase the volume of space for the stilling zone (enclosure) by extending the height of the skirtboard. This vertical extension provides more space for the air to expand and slow down. Extending the length of the chute work provides more time for the dust to settle.

Skirtboard length should, in theory, extend in the belt's direction beyond the point where the material has settled into the profile it will maintain for the remainder of its journey to the head pulley. CEMA notes that the length of skirtboarding is "a function of the difference between the velocity of the material at the moment it reaches the belt and the belt speed" [CEMA Standard 575–2013].

In essence, CEMA recommends two feet of skirtboard for every 100 fpm of belt speed, with a minimum length of not less than three feet (Table 6.2). While this rule of thumb is generally sufficient for easily conveyed materials, it has proven to be insufficient for ultrafine materials that typically require dust collection or larger materials that roll on the conveyor, making their management more complex. When belts have a greater calculated air movement, transfer point length should approach three feet per 100 fpm of belt speed [Goldbeck and Marti 1996]. Operational conditions must be evaluated with the behavior of the material under conditions of conveyance as a primary consideration and further adjustments may also need to be considered.

Table 6.2. Skirting length recommendations

CEMA	**Heavy Dusting Materials**	
2 ft of skirting for every 100 fpm of belt speed	cfm < 1,000 cfm > 1,000	2 ft per 100 fpm 3 ft per 100 fpm

Dust curtains are an effective and inexpensive containment device that should be installed at the entrance and exit and within the chute enclosure. The head chute should be sealed by installing entry curtains at the feeding conveyor discharge as discussed above. It is also important to add curtains at the exit of the stilling zone. At the exit, dual rubber curtains should be hung roughly 18 inches apart from each other to form a "dead" area where dust can settle and should extend to approximately one inch below the top of the product pile [Goldbeck and Marti 1996] (Figure 6.16). The last exit curtain should be placed approximately one foot back into the enclosure in order to prevent dislodging of material from the top of the ore. Also, implementing intermediate curtains in the stilling zone will lengthen the path the air must travel and will allow additional particles to settle from the air.

Photos by Martin Engineering

Figure 6.16. Exit curtain and intermediate curtain. The left photo shows an exit curtain designed to keep the dust and air inside the chute. The right photo shows intermediate curtains, which lengthen the route the air must travel and slow its velocity, allowing the dust to settle on the ore before being conveyed. In the right photo, the last section of the chute containing exit curtains has been removed for demonstration purposes.

INCREASING PARTICLE WEIGHT WITH MOISTURE

For belt discharge to the open air or where processes allow light material particles to accept some moisture, wet spray systems can be utilized to assist in controlling dust. Wet spray systems involve the application of water to control dust and may be classified into prevention applications and suppression applications. Prevention involves implementing measures to increase the cohesiveness of dust particles in order to increase the weight of the particles and prevent them from becoming airborne. Prevention is normally completed by using sprays that apply water or water combined with surfactants and/or binders that serve to reduce the volume of water required and to increase effectiveness throughout the process. Applications involving the addition of surfactants and/or binders can be applied through a water spray or with the addition of air applied as a foam.

Suppression involves removing the dust particles from the air, usually by incorporating a fine mist of water and/or air and returning the now heavier particles to the material flow. Suppression applications typically require containment to be effective and usually require reapplication at each dust source as the material is transported.

These technologies are discussed in greater detail in Chapter 3—Wet Spray Systems. When properly designed and installed, water spray combinations are a cost-effective method for controlling dust from conveyors. Best practices for the application of water sprays include the following.

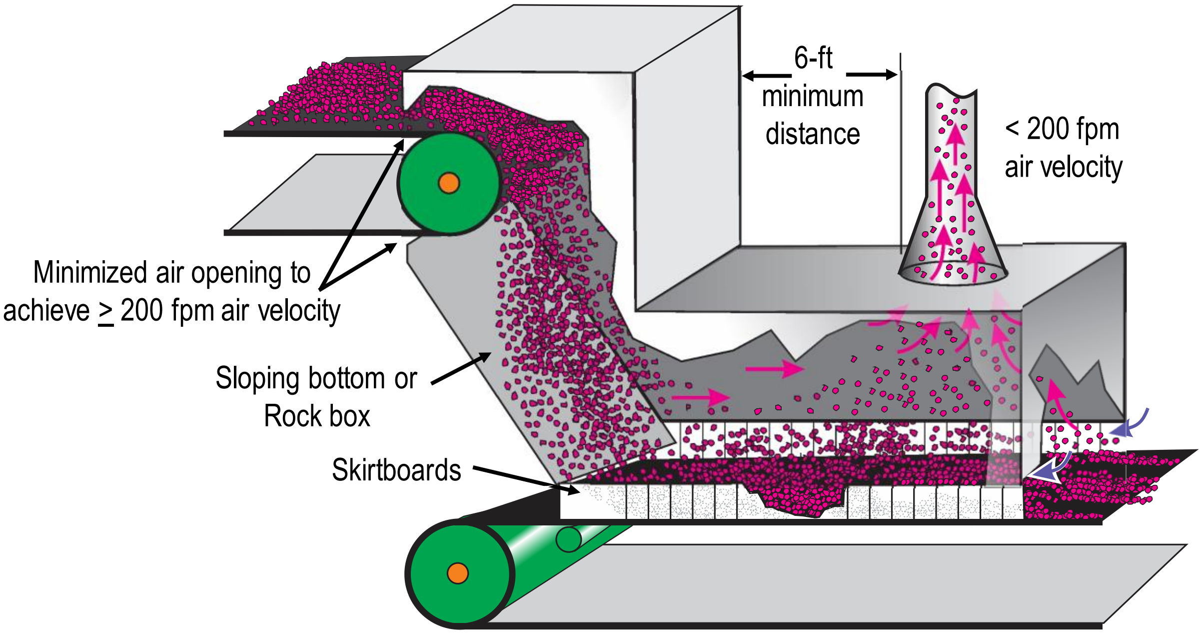
- The use of high-volume, high-pressure sprays should be avoided. The energy of the spray transfers to the material particles, resulting in more dust production [Goldbeck and Marti 1996].
- The amount of moisture applied should be varied and tested at each operation to determine the optimum quantity. Best Practices for Dust Control in Metal/Nonmetal Mining [NIOSH 2010] recommends starting at 0.5 percent moisture to product ratio. Excess moisture promotes belt slippage, increases carryback, causes chute plugging issues, and adversely affects conveyor belt performance in cold weather conditions.
- Studies indicate that wetting the return side of the conveyor belt also helps to minimize dust liberation. This practice reduces dust generation from the idlers as well as at the belt drives and pulleys [NIOSH 2010].
- Fan spray nozzles are most commonly used because they tend to minimize the volume of water added for the amount of coverage. It is more advantageous to locate the water and/or water with surfactant and/or binder sprays at the beginning of the process (i.e., at the dump or transfer location), which allows the moisture addition to be effective throughout the transportation process. When the ore is crushed, additional surfaces are exposed and additional small particles are created, requiring reapplication of moisture.
- Using more spray nozzles at lower flow rates and positioning them at locations closer to the ore is more advantageous than using fewer sprays at higher flow rates [NIOSH 2003].

REMOVING AIR AND CAPTURING DUST PARTICLES AT TRANSFER POINTS

In lieu of adding moisture to increase the weight of dust particles, air removal devices can be implemented in order to reduce the velocity of the air below 200 cubic feet per minute (cfm) at the conveyor exit and scrub or filter the dust from the air. Dust bags, air cleaners, and/or dust collectors should be implemented when necessary to remove excess air from the conveyor system while capturing the dust particles. These technologies are discussed in detail in Chapter 2—Fundamentals of Dust Collection Systems.

Significant dust generation and liberation can result from transfer points if they are not properly designed and installed. The following are some important design considerations for an effective transfer point or chute design, along with considerations for the inclusion of an exhaust ventilation system (Figure 6.17).

- It has been shown that the exit of the transfer point enclosure should be a least six feet from the dump point to minimize the entrainment and pickup of oversized particles [MAC 1980]. The air velocity at the base of the exhaust chute should also be kept below 500 fpm to avoid the pickup of larger particles [Yourt 1990].
- Transfer point enclosures should be designed to have a 200-fpm intake velocity at any unavoidable opening to eliminate dust leakage from the openings [USBM 1974]. The Mining Association of Canada (MAC) recommends adding 25 percent to the 200-fpm guideline [MAC 1980].
- It is also important to minimize openings and thus preserve intake velocity by using plastic stripping and other types of sealing systems. It is recommended that the transfer point enclosure (stilling zone) be made large enough so that the air velocity within the enclosure is below 200 fpm [Goldbeck and Marti 1996]. The larger enclosure can serve as a plenum where air velocity can dissipate. If an enclosure is undersized, air will be forced from the interior high pressure of the enclosure to the lower-pressure area outside, carrying dust particles outside the system.
- Transfer chutes should be sized to allow ore to flow without clogging or jamming. A general rule of thumb is that the chute width should be at least three times the maximum lump size to avoid clogging [USBM 1987].
- The skirtboard (chute wall) for the transfer point should be high and long enough to serve as a plenum so that the dust has a chance to settle. On belts with minor air movement, a good rule of thumb is two feet per 100 fpm of belt speed [Goldbeck and Marti 1996]. When belts have a greater calculated air movement, the transfer point should approach three feet per 100 fpm of belt speed [Goldbeck and Marti 1996].
- The fall height of ore should be minimized whenever possible. Some methods to accomplish this are through the use of rock ladders, telescopic chutes, spiral chutes, and bin-lowering chutes.
- Any abrupt changes in product direction or flow should be avoided.



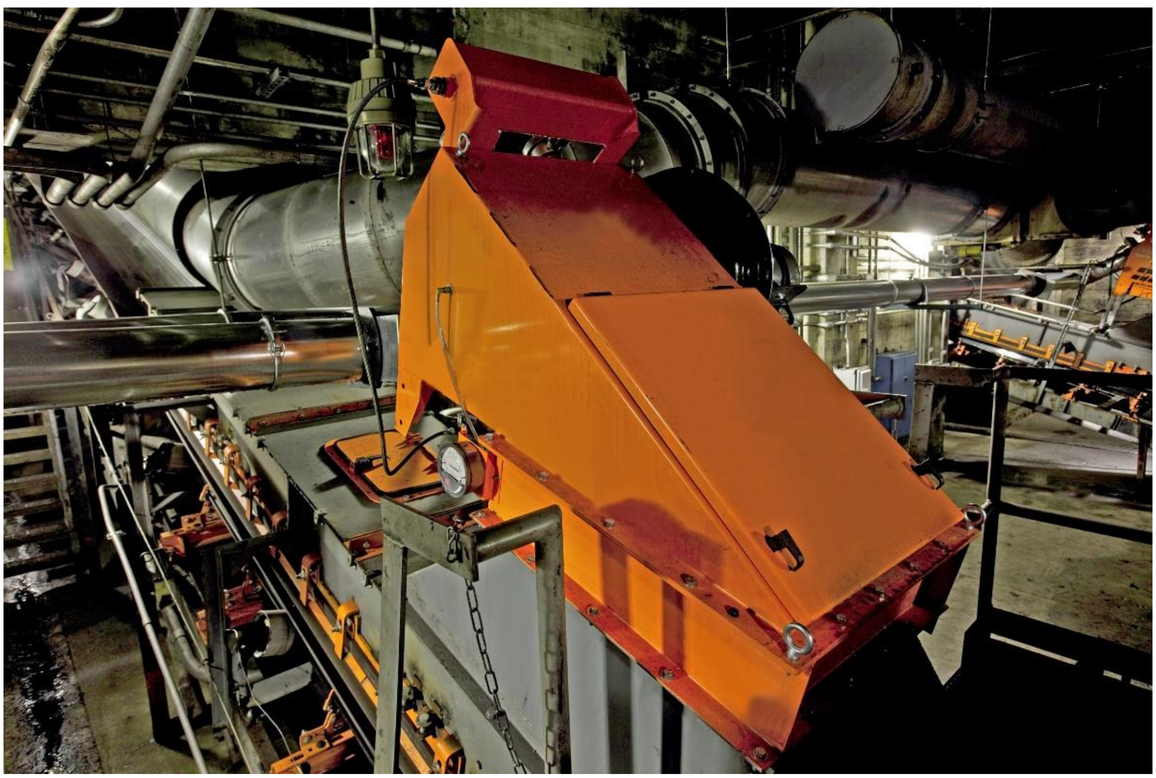


Photo by Martin Engineering

Figure 6.17. A conveyor transfer point enclosure used with an exhaust ventilation system. The top illustration shows some of the key design considerations. The bottom photo shows an exhaust ventilation system (air cleaner) mounted on top of a transfer system.

BELT CLEANLINESS

Material that sticks or clings to a conveyor belt after passing over the head pulley is called carryback. Carryback tends to fall from the belt as it passes over return idlers. This creates piles of material that increase worker dust exposure, are safety hazards, require cleanup, and can shorten belt and component life. Carryback should be addressed at the head pulley. This allows the carryback to remain in the flow of material instead of becoming a source for dust emissions.

The primary means of controlling carryback is to clean the belt as it passes over or past the head pulley (i.e. shortly after material is discharged from the belt). The most common way to clean a conveyor belt of carryback is to mechanically "scrape" the belt via cleaners or brushes or to wash the belt.

Belt Scraping

There are a myriad of different types and configurations of belt cleaners, and addressing them all is beyond the scope of this handbook. Instead, the basic principles and types of cleaners will be addressed. Although belt cleaner systems come in many different styles, types, and trade names sold by numerous commercial manufacturers, their function remains the same: to reduce the amount of carryback on the belt once the ore is discharged. Material can be either peeled or scraped from a belt. When fines are peeled from the belt, the cleaner is sharply angled toward the belt. This is normally done at the primary cleaner position, but is also applied with some cleaners at the secondary position. When fines are scraped from a belt, the cleaner is angled with the direction of belt travel, as shown by the secondary cleaner in the illustration in Figure 6.18 (left).

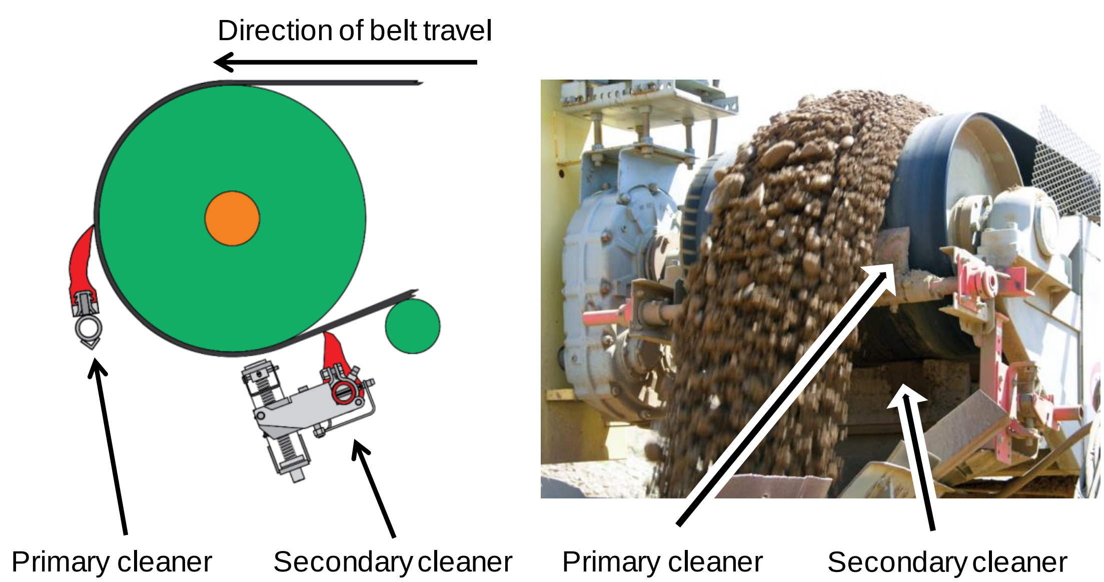


Illustration and photo by Martin Engineering

Figure 6.18. Primary and secondary cleaners used to scrape material from a belt. The left illustration shows the location of the primary and secondary cleaners in relation to the head pulley and belt. The right photo shows ore being discharged from the belt with the primary and secondary cleaners in action.

Multiple belt cleaner systems provide a way to address carryback, with the use of a primary cleaner on the face of the head pulley to remove most of the material followed by secondary cleaners to perform final cleaning. The secondary cleaners can be installed either where the belt leaves the head pulley or further along the conveyor return. To be effective as well as to reduce belt wear, multiple cleaners should be incorporated with low blade-to-belt pressure [Goldbeck and Marti 1996]. When dust levels are high, it is not uncommon to use two or three belt cleaners at different locations in an effort to further reduce the amount of carryback material on the belt [Roberts et al. 1987].

It is most desirable to return the scrapings to the primary material flow through chutes. Chutes should therefore be designed large enough to capture the scrapings and their walls should be steep enough to prevent scrapings from building and stacking up within the chute. In cases where the chute is not large enough to allow the material from the secondary cleaner to enter, a dribble chute or extension of the original chute is needed (Figure 6.19).

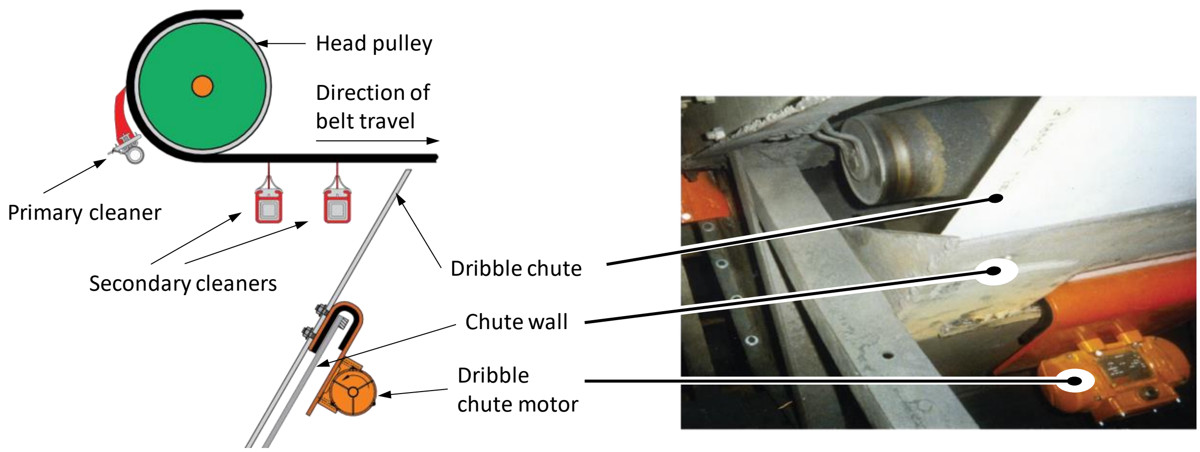


Illustration and photo by Martin Engineering

Figure 6.19. Illustration of a dribble chute applied to return material to belt flow.

Belt Washing

When an application requires minimal carryback, washing the belt is an alternative when belt cleaning does not remove particles adhering to the belt. A belt wash system (wash box) sprays the conveyor belt with water while simultaneously scraping it to remove the product (Figure 6.20). A wash box system has a series of spray bars and secondary cleaners to ensure the belt is clean and all ore is contained in the system. The nozzles apply a spray of water that softens the ore carryback and lubricates the belt to maintain effective cleaning pressure. The number of sprays and secondary cleaners are determined by the required cleanliness and the type of ore being conveyed.

Photo by Martin Engineering Photo by ASCGO

Figure 6.20. A wash box installed and being used to clean a conveyor belt. The left photo shows a wash box (in orange) installed. The right photo shows spray bars and cleaners inside a wash box being used to clean a conveyor belt.

CONVEYOR OPERATION AND MAINTENANCE

Maintaining a clean, safe mineral processing plant is a challenge due to the number of conveyors involved and the total distance material travels through a mineral processing plant. Some belts are located outside where dust liberation may not be as critical as when the belts are located within a building where workers are present.

Conveyor belts can generate or liberate dust whether they are loaded heavily with ore or running empty. Therefore, the practice of operating conveyor belts without load should be minimized.

Controlling dust from conveyors requires constant daily vigilance by the maintenance staff to repair and replace worn and broken parts, including conveyor belting. Belt examinations are required every working shift to ensure all parts of the system are performing to their capacity. Material can escape through chutes worn from rust or abrasion, and even small holes created by missing bolts or larger holes created from open access doors can be a pathway for fugitive dust. In some cases, it may become necessary to replace an entire loading chute to ensure proper containment.

Belt Splices

All conveyor belts require at least one splice to connect the ends together and thus close the loop. Due to belt failures, conveyors can often have more than one splice. Mechanical and vulcanized splices (Figure 6.21) are commonly used in the mining industry.

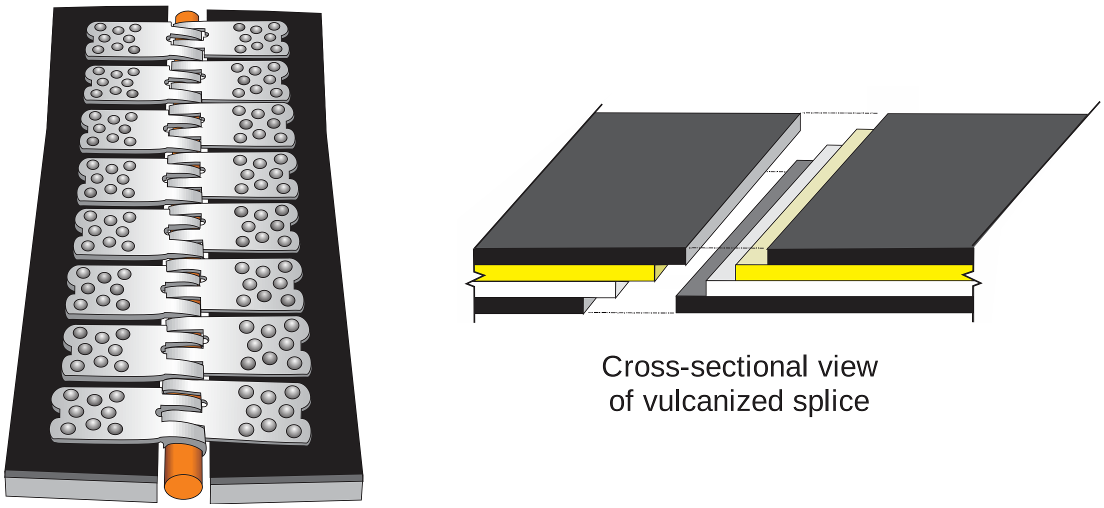


Figure 6.21. Illustration of a mechanical belt splice (left) and a vulcanized belt splice (right).

Mechanical belt splices can often be a source of spillage, with product and dust falling through small openings in the splice. Mechanical belt splices should be properly installed, incorporating belt skiving to enable the splice to impart as little an effect to the operation as possible.

Vulcanized belt splices can also be used to eliminate this source of spillage. Vulcanized splices provide a method of joining the ends of conveyor belts without interrupting the continuity of the belts and usually without altering the geometry or dimensions of the belt. It is recommended that vulcanized belt splices be used, where feasible, to reduce dust and spillage.

SCREW CONVEYORS

Screw conveyors are one of the oldest and simplest methods for moving bulk materials (Figure 6.22). Screw conveyors consist of a conveyor screw rotating in a stationary trough. Material placed in the trough is moved along its length by rotation of the screw. Screw conveyors can be mounted horizontally, vertically, and in inclined configurations.

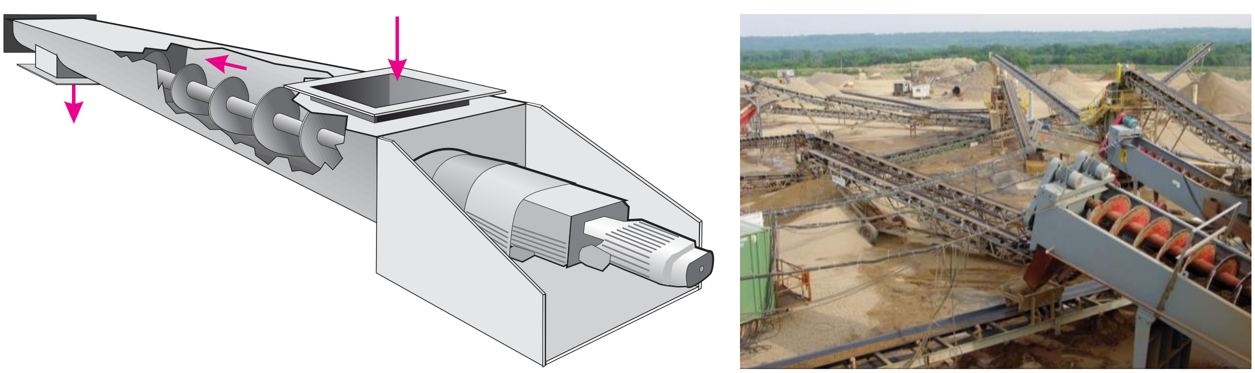


Photo by Martin Engineering

Figure 6.22. Screw conveyors designed to move material through a stationary trough. The left illustration shows a typical screw conveyor, with arrows representing the direction of material flow. The right photo depicts two screw conveyors installed at a mining operation.

Normally, screw conveyors are totally enclosed except at the ends, where dust emissions can be controlled by proper transfer chute design. The screw conveyor cover is usually fastened by nuts and bolts. However, to maintain a proper dust seal, a self-adhesive neoprene rubber gasket should be installed. Screw conveyors are essentially dust- and spillage-free as long as the casings, packing glands, and transfer chutes are properly designed and maintained. The only location where spillage typically may occur is where the screw shaft exits the screw conveyor housing.

BUCKET ELEVATORS

A typical bucket elevator consists of a series of buckets mounted on a chain or belt that operates with head and boot pulleys (Figure 6.23). The buckets are loaded by scooping up material from the boot (bottom) or by feeding material into the buckets. Material is discharged as the bucket passes over the head pulley. Bucket elevators are efficient in hauling materials to height at steep to vertical angles while utilizing a small footprint.

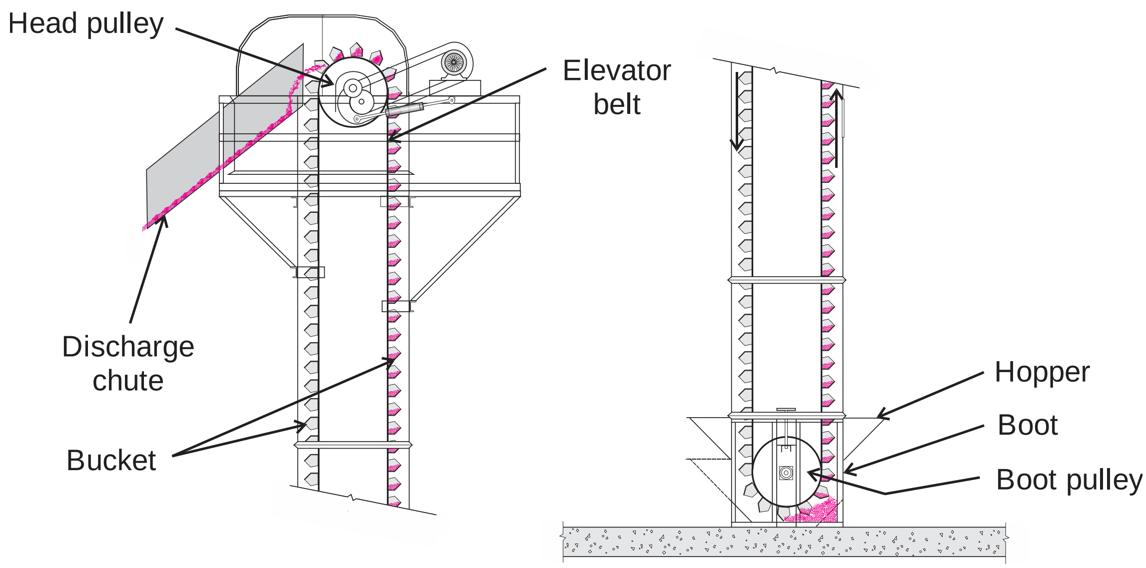


Figure 6.23. Illustration of a bucket elevator.

A steel casing usually encloses the entire assembly and effectively contains dust. Casings should be kept closed and should be monitored for the development of holes. Dust emissions typically occur at the boot of the elevator where material is being fed into the elevator or at the head of the elevator where material is being discharged.

Emissions at the boot of the elevator can be controlled by proper design of a transfer chute (similar to belt conveyors) between the feeding equipment and the elevator. Dust can be reduced significantly by keeping the height of material fall to a minimum and by gently loading material into the boot of the elevator.

Controlling dust emission at the discharge end of the bucket elevator can be accomplished by proper venting to an air cleaning or dust collection device (see Chapter 2—Fundamentals of Dust Collection Systems), as well as through the use of proper enclosures and chutes between the elevator discharge and the receiving equipment. It is recommended that at least 100 cfm of dust collection air be provided for every square foot of casing cross-sectional area [ACGIH 2010] Dust collection pickup should be provided from the top of the casing just above the head pulley (Figure 6.24). Additional ventilation may be needed for belts traveling over 200 fpm. If the elevator is over 30 feet tall, a second pickup should be installed on the side of the casing just above the tail pulley. Dust collection ventilation should also be provided where the material is being discharged into the elevator.

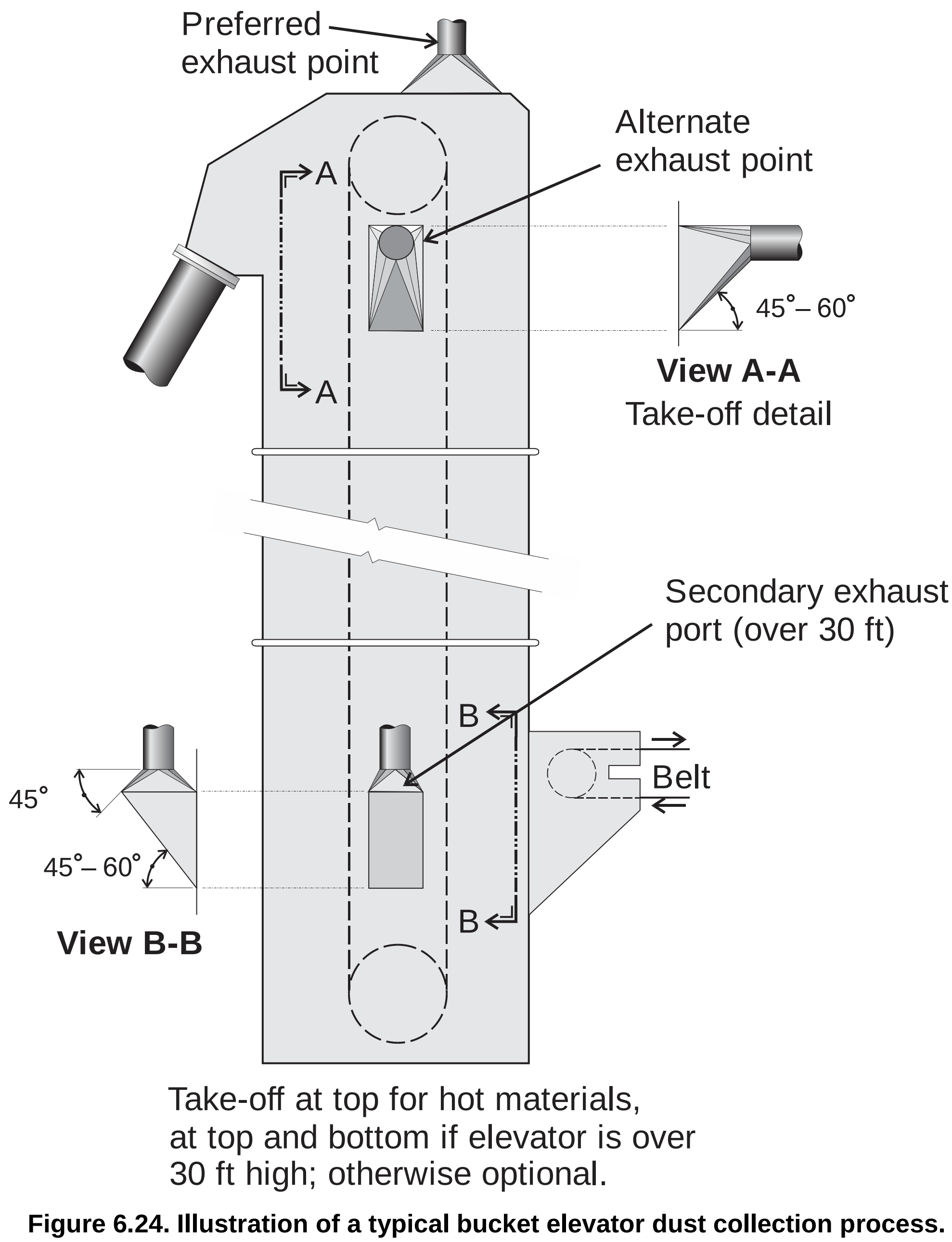


Figure 6.24. Illustration of a typical bucket elevator dust collection process.

PNEUMATIC CONVEYANCE

Pneumatic conveyors are tubes or ducts through which material is moved by pressure or vacuum (suction) systems. Positive pressure systems can be either *dilute phase* or *dense phase*. Dilute phase uses a low (dilute) product to air ratio for transport, while dense phase uses a high (dense) product to air ratio. Dilute phase flow is when the air velocity in the conveyor line is high enough to keep the product being conveyed airborne. Dense phase does not require the product to be airborne. Material being conveyed lies for periods of time in the bottom of a horizontal line and sometimes flows through the line in slugs. Dilute phase systems typically operate at pressures obtainable from a fan, and dense phase systems use a high-pressure compressed air source.

When material is fed into a pressure system, the material is conveyed to a storage bin where a dust removal device (dust collector, cyclone, or filter-type collector) is installed. The conveying air escapes through the cyclone vent or a filter while the conveyed product drops into the hopper (Figure 6.25).

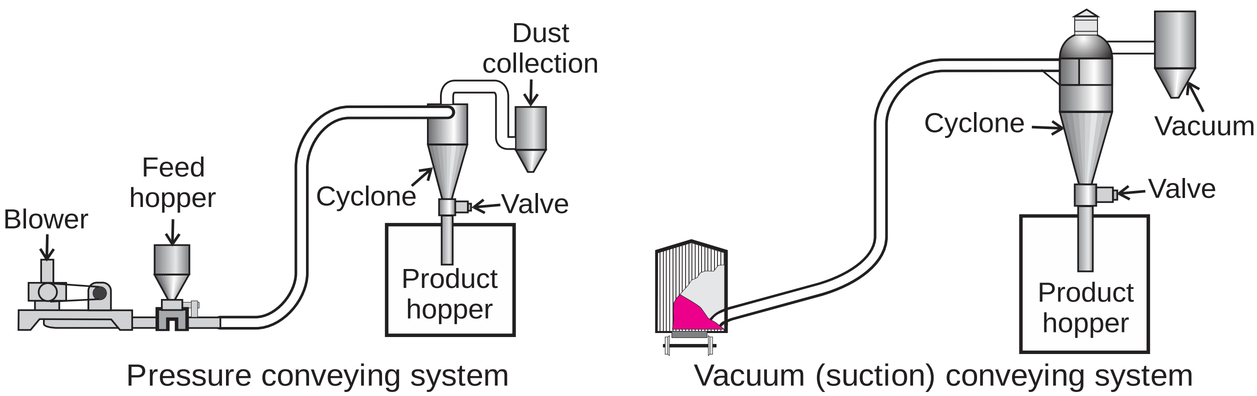


Figure 6.25. Illustration of two types of pneumatic conveying systems.

Positive pressure pneumatic systems are totally enclosed and by nature should be low dust emitters. However, these systems must be monitored for wear areas where dust emissions are likely to occur. Maximum wear in the conveying ductwork occurs at elbows; therefore, long-radius elbows made of heavy-gauge material should be incorporated. Numerous styles of wear-resistant elbows are available, some of which use the rock box principle—i.e., the force of the material striking captured material instead of striking the elbow wall (Figure 6.26). The elbows can also be lined with refractory or ceramic material to further reduce wear and abrasion. In low-pressure pneumatic systems, dust may also leak through joints. Therefore, self-adhesive neoprene gaskets should be used at all joints to provide a dust-tight seal.

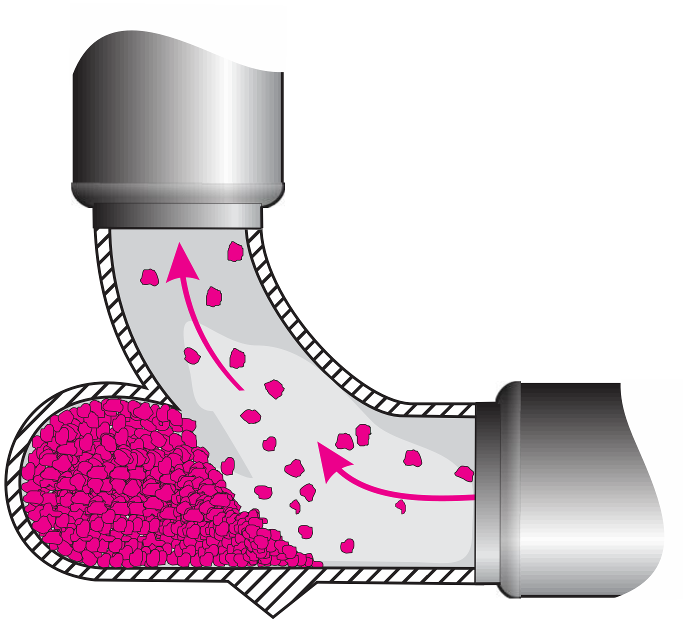


Figure 6.26. Illustration of a wear-resistant elbow installed in conveying ductwork.

Dilute phase pneumatic conveying systems operate under pressure and require some mechanical means, such as a rotary valve or double dump valve, to provide an airlock and prevent transport air from short-circuiting into the feed material storage bin (Figure 6.27). These types of devices employ moving parts and seals that are often subject to high wear and significant maintenance. The dismantling of these airlock devices can also be a significant source of dust for mechanics and requires downtime for processing equipment.

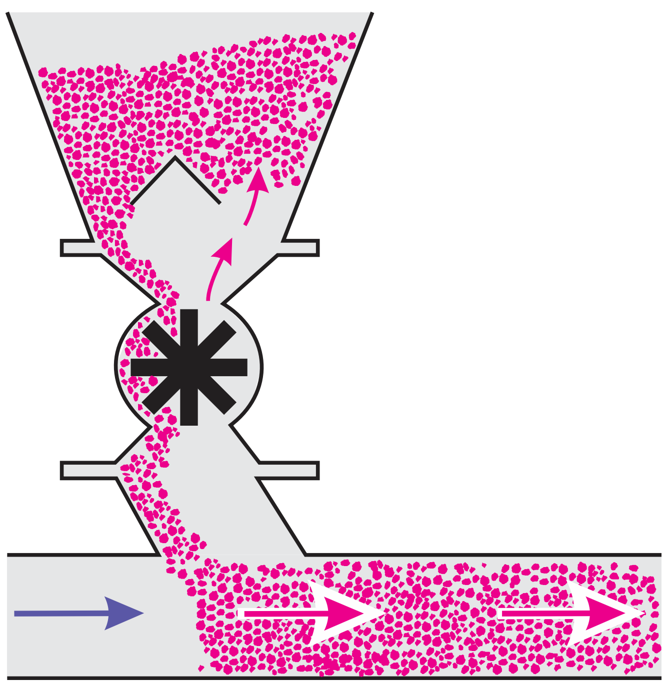


Figure 6.27. Illustration of a rotary airlock feeding a pneumatic conveying line.

Venturi eductors are often a good alternative to the mechanical airlock devices. Eductors convert the blower output into a suction that is then used to draw the feed material into the conveying line (Figures 6.28 and 6.29).

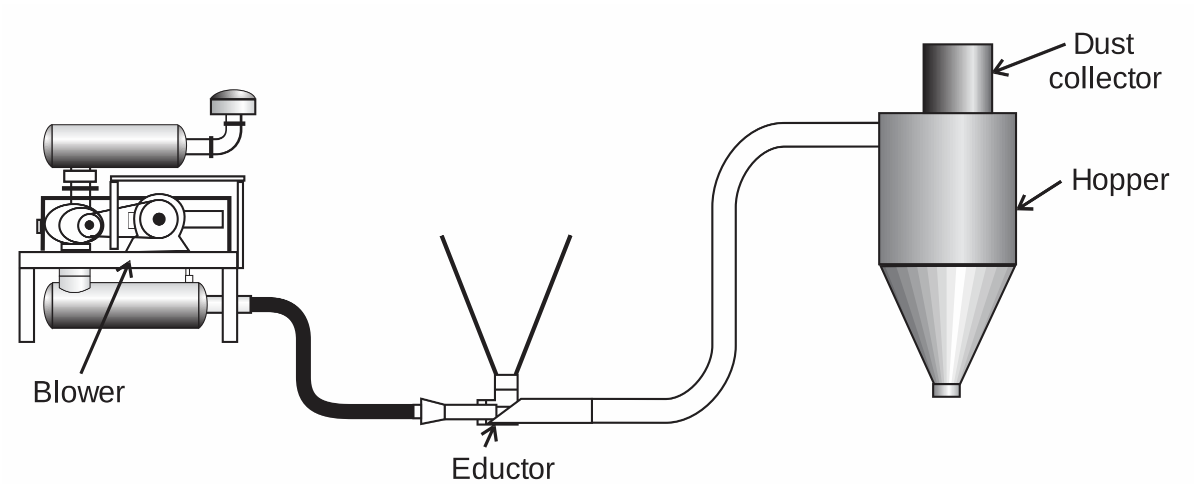


Figure 6.28. Illustration of a conveyance system utilizing a venturi eductor device.

These devices have no moving parts and typically require minimal repair and downtime for maintenance activities. The venturi eductor can be used on dust collectors, grinders/mills, belt and vibratory feeders, etc. Systems utilizing this type of device are generally designed by the manufacturer due to variables associated with the process.

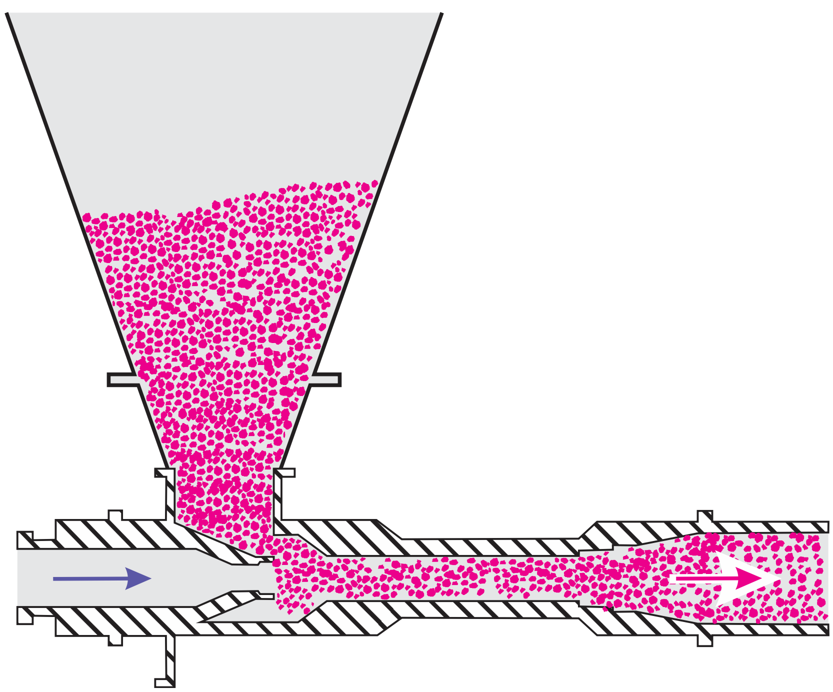


Figure 6.29. Illustration of a venturi eductor utilizing suction to draw the feed material into the conveying line.

Vacuum systems offer clean, efficient pickup of material from railcars, trucks, bins, and hoppers for unloading into other types of equipment. Since the systems are under a negative pressure, dust leakage is not normally a problem. Cyclone receivers or filters are used at the end of such systems to separate the material. The level of separation desired determines the type of separation equipment required.

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Chapter 7: Bagging

CHAPTER 7: BAGGING

This chapter discusses techniques used by mineral producers for controlling worker dust exposures while bagging and stacking product in various types of bags for shipment to customers. The loading of product into some type of container is normally called “bagging.” The stacking of these bags of product onto pallets for shipment to customers is typically called “palletizing.” There is a wide spectrum of different types of bags that are used to ship product to customers, ranging from 50-pound to over one-ton bulk bags. Only the smaller bags (100 pounds or less) are typically palletized because the larger bulk bags are, in most cases, individually shipped. Both the bagging and palletizing process can be performed manually or through some type of semi-automated or totally automated process. Dust generated by the manual bagging and palletizing of 50- to 100-pound bags directly affects a number of workers’ dust exposures.

Workers performing bagging and stacking tasks, or working in and around these areas, typically have some of the highest dust exposures of all workers at mining and mineral processing operations. Some of the difficulties with controlling dust in work processes associated with bagging and palletizing are the wide range of different equipment being used and the variety of bag types. The bagging process can range from single-station manual bagging units to fully automated multi-station machines.

In addition to the potential for high respirable dust exposures from the bagging and palletizing process, there is also a significant risk for musculoskeletal disorder (MSD) from all the repetitive motion and the significant weight lifted by workers while performing tasks associated with these processes. These dust exposure and MSD concerns have motivated many operations to pursue the implementation of equipment that either semi-automates or totally automates these work tasks.

BAGS AS DUST SOURCES

To address problems associated with the bagging process, a number of different dust sources need to be addressed and controlled, specifically product blowback, product “rooster tail,” and contaminated bags. When manually bagging and stacking 50- to 100-pound bags, these dust sources directly affect the worker’s exposure. Two different types of bags that are used to transport product within this weight range are open-top bags and valve bags (closed bags with an internal valve).

Open-top bags are slid up over the loading chute and filled with product in a mass loading technique. Open-top bags are typically used for larger particle sizes called whole grain, which are normally greater than 120 mesh (0.125 mm) in size. The dust sources when loading open-top bags are leakage from the loading chute once the bag is removed and liberation from the open bag before it is sealed. Sometimes these open-top bags are moved into a cage device to properly position the bag before sealing; this task of moving the bag into the cage can also be a dust source. Since these bags are typically used with large particle sizes, dust generated or liberated is not normally as significant as with the valve bags.

For valve-type bags, three major dust sources need to be addressed for effective dust control. The first dust source is from product blowback, which occurs during bag filling and results from product spewing out of the bag valve. Product blowback occurs as excess pressure builds inside the bag during bag filling and is then relieved by air and product flowing out of the bag valve around the fill nozzle.

The second major dust source is product spewing from the fill nozzle and bag valve as the bag is ejected from the filling machine. This is typically called a “rooster tail” because of the spray pattern of the escaping product.

Both product blowback and product “rooster tail” occur because of the air pressure injected into the bag with product during filling. Both release dust into the air and contaminate the outside surface of the bag. The contaminated bags then become the third significant source of dust exposure for the bag stackers, or for any other individuals handling the bags, including the end user of the product.

Figure 7.1 shows product blowback during bag filling, product “rooster tail” as the bag is ejected from the fill nozzle, and dust contamination on the outside of the bag after loading is completed. If bags are undersized, they create a greater amount of product blowback and “rooster tail” during the bagging process, and this needs to be considered when evaluating these dust sources.

Photos by NIOSH

Figure 7.1. Dust sources during bagging. The left photo shows product “rooster tail.” The top right photo shows product blowback. The bottom right photo shows dust-soiled bag.

With 50- to 100-pound bags, another area that impacts the amount of dust generated is the bag valve. The valve is an internal sleeve in the bag through which the fill nozzle is inserted prior to the bag being filled with product (Figure 7.2). The type of bag valve used impacts the amount of product blowback and product “rooster tail.” Once the bag falls from the fill station, the weight and volume of the product inside the bag is supposed to force the valve closed, sealing the area and keeping product from leaking from it during the conveying, stacking, and transportation process. However, many times the bag valve is lined with product and does not seal properly, causing product and dust to leak from the valve during movement/transportation. This sealing ability also varies for different types of bag valves.

One last dust source at bagging operations is from broken, torn, or ruptured bags. When a bag breaks, a significant amount of product and dust is released into the plant atmosphere. Defects caused during manufacturing, including improper gluing and improper storage of empty bags, are just a few of the factors that can cause bag breakage. The location of the break has a significant impact on the amount of dust liberated. Bags that break during filling tend to be more violently affected than those that break during ejection or conveying. In all cases, bag breakage liberates a substantial amount of dust and significantly impacts workers in these areas.

Photo by NIOSH

Figure 7.2. Fill nozzle and bag valve. The left illustration shows a typical bag valve. The right photo shows an interior view of a bag valve. The fill nozzle enters through the bag valve and delivers product into the bag.

BAG CONSIDERATIONS

A number of different factors ultimately impact the amount of dust generated or liberated from bags of product material: bag construction, bag perforations, bag fill type, and the effects from bag failures.

Bag Construction

The multi-wall pasted valve bag is by far the most common bag used for the packaging of mineral products and is the only style discussed below. Many of the considerations discussed for pasted valve bags are also applicable to open-top bags.

A very important element in controlling the amount of dust liberated during the bagging process is the design and construction of the paper bag itself. The composition of the paper, its porosity, the number of plies/layers used, the “basis weight/thickness” of the paper sheets (to provide strength), the type of pasted valve, and the use of bag perforations are all factors that affect and can minimize the amount of dust generated or liberated from the bag.

One area of significant advances by bag manufacturers over the years has been the improvements in “paper” technology [Kearns 2004]. Currently, conventional natural kraft (NK) paper, also known as flat kraft (FK) paper, is the industry standard. Normal constructions for 50- to 100-pound bags are to use either three or four plies of NK paper. Due to the low porosity of NK paper—meaning that air does not flow through the paper material—bag perforations are normally required for most industrial mineral processing applications to keep the bag from rupturing/exploding.

Another development in paper technology is the use of extensible kraft (EK) paper, sometimes referred to as “high-performance paper.” The strength of this EK paper has been increased to such an extent that the number of plies can be reduced by approximately 30 percent in multi-layer bags when compared to conventional kraft papers. A savings in paper can be achieved in one of two ways. The first, and the most common approach, is to reduce the number of plies/layers in the bag. For instance, rather than using NK or FK paper, which would normally require three or four plies/layers to obtain the needed strength, EK paper can typically be used to reduce the number of plies/layers to just two. For every ply/layer that is reduced, there is a benefit from an increase in the bag’s porosity, thus allowing the bag to breathe better. Despite its popularity, extensible kraft paper does not allow for the proper ventilation required for many packaging applications; therefore, bag perforations are still required to provide the necessary air escape during bagging to avoid ruptures. The second way to reduce paper is by reducing the weight/thickness of each ply/layer of paper.

Airflow extensible kraft (AEK) paper was developed in the 1990s and offers the same cross-directional and machine-directional strength as EK paper, but with an air-permeable (breathable) characteristic. A great benefit from this air-permeability characteristic is that it eliminates the requirement for void spaces in the bag construction, allowing for a smaller bag size. The porous paper is superior to perforated paper as far as strength and air evacuation (ability to relieve air pressure). No bag perforations are required when using this AEK paper type, and by eliminating perforations, bag strength can be increased by as much as 20 percent. The faster the air is evacuated from bags, the faster they can be filled and palletized, thus increasing production and profitability.

The AEK paper also allows the flow of air to depressurize the bag at a rate three to four times faster than standard kraft (NK or FK) paper and at the same time retains bag strength. The paper acts as a filter during the bag filling process which allows the product to flow freely into the bag while containing dust that could be liberated into the work environment and expose workers. Because of this, the outer surface of the bag stays cleaner. When considering the various options available for bag construction, the use of AEK paper appears to be the best choice to minimize the amount of dust generated and liberated from the bag during the filling process.

Bag Perforations

As product enters the paper bag during the filling process, fluidizing air entrapped in the product must be evacuated in order to fill the bag with product. In order to remove the air as the product is introduced into the bag, perforations are integrated in the paper used in the bag to serve as vent holes. For this purpose, manufacturers use multi-wall bag perforations, which are small vent holes punched through the walls of the paper bag to allow air to escape rapidly during the filling process.

There are two common types of perforations used in bags: overall perforations and undervalve perforations. Both types of perforations reduce the strength of a paper bag by as much as 20 percent.

Overall Perforations

The use of overall perforations is a critical factor to consider when evaluating the effectiveness of bag performance. Each ply of paper is individually perforated during the manufacturing process, creating staggered perforations throughout the bag. The perforations (pinholes) do not go directly through all layers (two, three, or four plies/layers) and are not aligned with each other. The goal is to allow the fluidizing air to work its way out of the bag while still containing the product/material. Perforations allow the bag to depressurize, minimizing the possibility of it rupturing during bag filling (Figure 7.3). Since the perforations are staggered for each of the different plies/layers, it is uncommon for the product being bagged to escape through the perforations; however, this can sometimes occur for very fine product sizes—i.e., 325 mesh (0.045 mm) and finer. As previously mentioned, the bag strength can be lessened by up to 20 percent when using perforations. Standard perforation sizes are 1/8, 3/32, and 1/16 inches, and patterns range from 3/4- x 3/4-inch centers up to 2- x 3-inch centers.

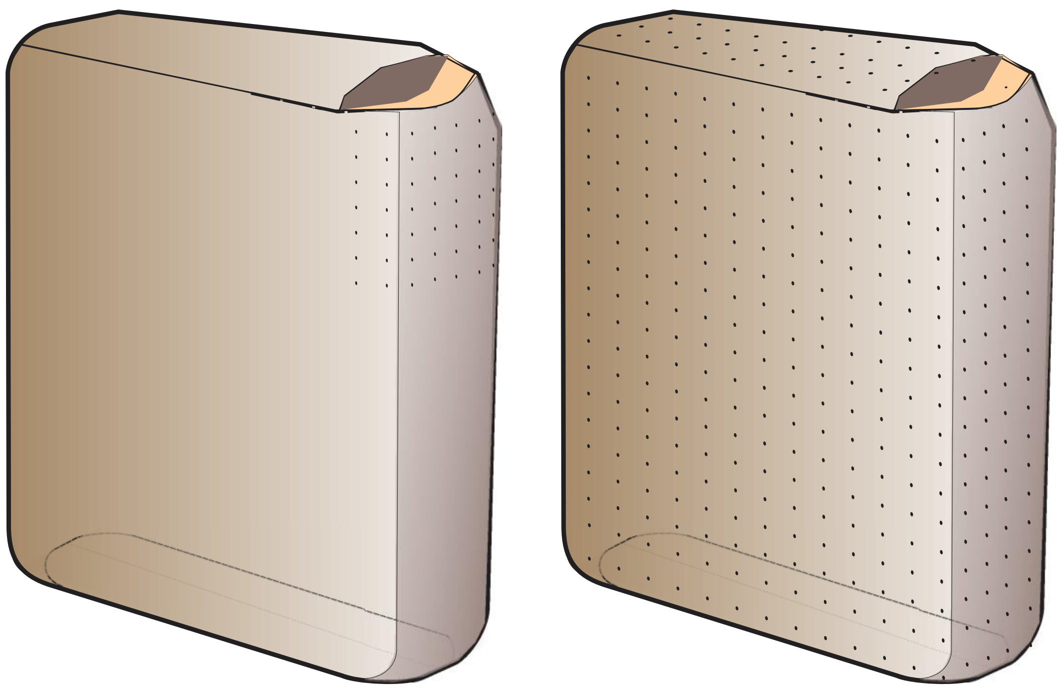


Figure 7.3. Two types of bag perforations. The left illustration shows undervalve perforations. The right illustration shows overall perforations.

Undervalve Perforations

Unlike overall perforations, undervalve perforations are created after all plies are positioned into the finished bag stage. They are punched through all two, three, or four plies/layers at the same time and are aligned. Since the fluidizing air is most likely to escape out of the bag valve around the fill nozzle (product blowback), having perforations as close as possible to the valve area is the most effective design to depressurize the bag and keep it from rupturing or exploding during bag filling (Figure 7.4). In addition, this location minimizes the amount of bag contamination as the excess air and product escape. The perforation pattern can range from1/4- x 1/4-inch centers up to 1- x 1-inch centers. Perforation sizes are the same as for the overall perforations: 1/8, 3/32, or 1/16 inches. Using an exhaust hood with a local exhaust ventilation (LEV) system is most beneficial in this application because of the likelihood of product escaping from the bag during the filling process.

Photo by NIOSH

Figure 7.4. Photo showing how undervalve perforations relieve excess pressure from a bag during the filling process to minimize the possibility of bag failure. Product and dust are seen escaping along with excess air.

Because of the product and dust emitted from the perforations during bag filling, most filling operations require some type of ventilation system to capture this dust. Two common techniques to achieve this dust capture are to place exhaust hoods around the bag loading nozzles and/or to use an exhaust hopper located below the bag loading station with an LEV system incorporated. These techniques can be used individually or together, depending on the level of dust control needed. Both of these techniques are discussed in greater detail later in this chapter.

Bag Fill Type

Two types of bags will be discussed in this section: open-top and valve bags. Figure 7.5 shows a typical open-top bag loading process. The bag operator slides an open-top bag up over a loading spout and then activates a start button to begin the loading process. The bag is then filled relatively quickly in a bulk loading fashion. During filling, the top of the bag is well sealed and typically tied into an LEV system to exhaust any dust generated during the loading process. When filling is completed, the bag automatically releases from the loading spout and drops a short distance down onto a conveyor. The top of the bag is then sealed using either heat sealing/gluing or is sewn (stitched) by a machine with nylon thread. Both of these sealing techniques are effective and create minimal amounts of dust.

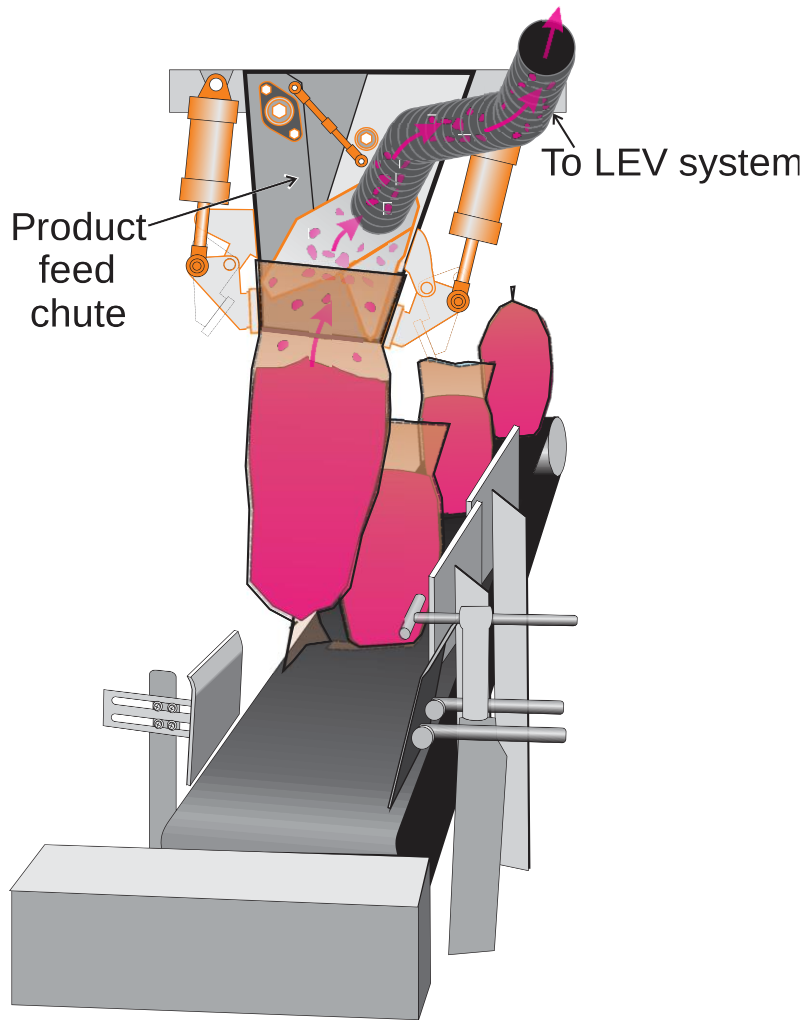


Figure 7.5. Illustration showing an open-top bag being loaded with product. The product is normally whole grain material, which is less dusty.

The second and most common bag type used in mining and mineral processing operations is the pasted valve bag. The choice of valve type from among different commercially available bag valves can be a significant factor in the ability to effectively seal 50- to 100-pound bags of product and to minimize the amount of dust liberated during the bag filling, conveying, and stacking process. In a study performed a number of years ago, five different valves were tested to compare their effectiveness at sealing the bag and minimizing dust liberation: standard paper, polyethylene, extended polyethylene, double trap, and foam [USBM 1986a; Cecala and Muldoon 1986]. By far, the most effective valve was the extended polyethylene (Figure 7.6). This is simply a plastic valve approximately two inches longer than the standard paper or polyethylene valve.

In the study, two factors determined the effectiveness of the bag valve: valve length and valve material. The longer valves were more effective in reducing the amount of product blowback and bag-generated dust. However, it is speculated that when the valve length became too much longer than the fill nozzle, it began to negatively impact the bag filling performance.

For the second factor, which is valve material, foam was the most effective material tested. The foam valve was the shortest valve tested for the evaluation at four inches in length, while the extended polyethylene valve was six inches long. The rankings of valve types from the most to least effective were as follows: extended polyethylene, foam, standard paper, polyethylene, and double trap. Figure 7.7 shows a comparison of the extended polyethylene and foam valves to the standard paper valve. Respirable dust levels ranged from approximately 45 to 65 percent lower with the extended polyethylene valve as compared to the standard paper valve [USBM 1986a; Cecala and Muldoon 1986].

Photo by NIOSH

Figure 7.6. Photo of an extended polyethylene bag valve, interior view.

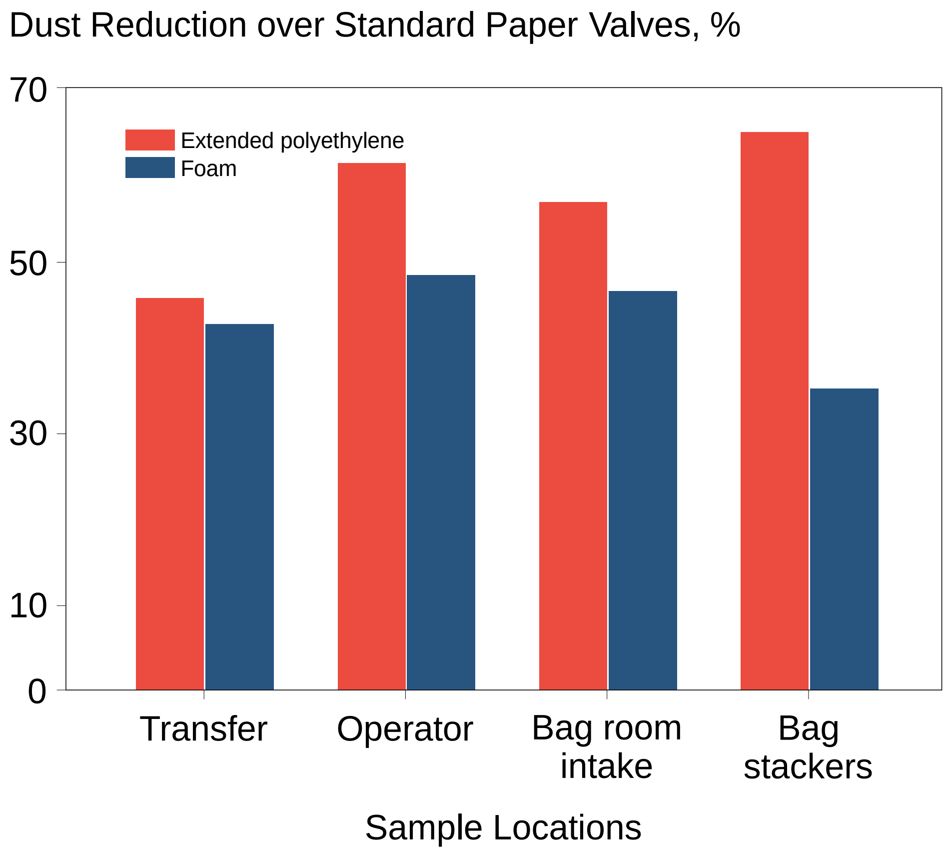


Figure 7.7. Bar chart showing dust reductions with extended polyethylene and foam valves as compared with the use of the standard paper valve.

Bagging operators should be aware that changes in product leakage and dust liberation are directly based on the type and effectiveness of the bag valve used in their bags. The extended polyethylene valve was the most effective valve, with only a minor cost increase over the standard paper valve.

A recent review of bag valves by the handbook authors revealed that the standard paper, polyethylene, and extended polyethylene valve types are still the main valves being used by industry. Based upon these choices, operators should definitely consider using the extended polyethylene valve type to minimize the amount of dust liberated during bag loading, conveying, and bag stacking processes.

Another commercially available bag valve type is the sonic energy sealed bag valve, in which the valve is glued after filling. This valve construction has adhesive on the inner surface of the valve, activated by sonic energy applied either at the packer fill nozzle or from ancillary equipment downstream. Theoretically, heating/melting of the adhesive should provide improved sealing of the inner surface of the valve and thus minimize leakage.

A problem that sometimes occurs with this valve type is that the glue does not properly seal because of product in the valve area, which then leads to product spillage. Another drawback with this valve type is that the cost to perform this sonic energy sealing is typically much higher than for the other types of valves.

Effects of Bag Failures

In addition to the considerations mentioned above, bag failure from broken, torn, or ruptured bags can occur during the bag filling, transportation, or handling process and can have catastrophic effects on the amount of dust generated or liberated into the work environment. When a bag breaks during bag filling, it can be a violent occurrence that quickly releases a significant amount of dust and product into the plant atmosphere.

Another concern from this type of bag failure is that most dust control equipment is not normally sized adequately to handle the large volume of dust released when this occurs. Gluing defects during manufacturing and the improper storage of empty bags (storing for long periods of time in high humidity and/or high temperatures, or damages to bags during storage) are just some of the circumstances that can cause bag failure problems during filling.

In addition to bags rupturing during loading, another problem can be bag failures during the conveying or pallet loading process, which can also cause a significant amount of dust to be liberated into the work environment. Bag failures most often occur from rips and tears from sharp edges during conveying, or damage from mishandling during pallet loading.

Every operation needs to address how it will deal with bag failures because of the significant impact that they can have on overall plant respirable dust concentrations and ultimately to workers in the plant. Some operations use a bag scale (weighing) system during conveying, which identifies underweight (broken) bags and diverts them onto another conveyor line. This secondary conveyor then takes the bags and discards them into a disposal device, normally a dumpster unit, so the bags do not need to be rehandled. It is recommended that this dumpster unit be located outside the plant to minimize the possibility that the dust liberated as the bags are discarded contaminates the plant air. Once the dumpster is full, it is taken away, and the bags are disposed of in a safe manner. A new dumpster is then positioned at the dump point and the cycle is repeated.

CONTROL TECHNOLOGIES FOR FILLING 50- TO 100-POUND BAGS

The bag filling process can range from a single-station manual bagging unit to a fully automated multi-station machine. This section addresses various control techniques to reduce respirable dust during bag filling of 50- to 100-pound bags.

Exhaust Hood Placed around Bag Loading Nozzles

One of the earliest techniques developed to capture dust generated from bag filling machines was a simple exhaust hood, which surrounds the bag to capture the dust generated and liberated during the bag filling process [USBM 1983]. If the machine is a multiple bag filling unit, an individual exhaust hood is placed around each fill nozzle. The exhaust hood is normally shop-fabricated from sheet metal and can be adapted to fit most valve-type bag fill machines (Figure 7.8).

To minimize installation and maintenance time, the hood is normally constructed in quarter-piece sections to allow it to be more easily installed and bolted together. The bottom of the hood should be sloped to allow product to slide from the hood and fall down into a hopper, normally located below the bag filling station. The exhaust hood also needs to be designed to allow the bag clamp, fill nozzle, or pinch tube to enter through the back of the hood.

To accommodate the installation of an exhaust hood on retrofit systems, one item that sometimes needs to be relocated is the start/stop button, which can easily be moved to a location outside the hood. The intent is for the hood to capture the respirable dust generated during the bag filling process (blowback and "rooster tail") while allowing the oversized and heavier product to fall into the hopper and be recycled/reused.

Each exhaust hood should be connected to an LEV system to capture the dust generated and liberated during bag filling and bag ejection. The hood's exhaust volume requirement is a function of the open hood area, with tests showing that air velocities of 200 feet per minute (fpm) into the hood are adequate for dust capture/containment. A typical hood size is in the range of 4 ft^2 of open face area, which requires an exhaust volume of 800 cubic feet per minute (cfm). Exhaust ventilation hoods have been shown to be from 90 to 100 percent effective at reducing dust leakage into the plant [USBM 1981]. For information on tying these hoods into LEV systems, refer to Chapter 2—Fundamentals of Dust Collection Systems.

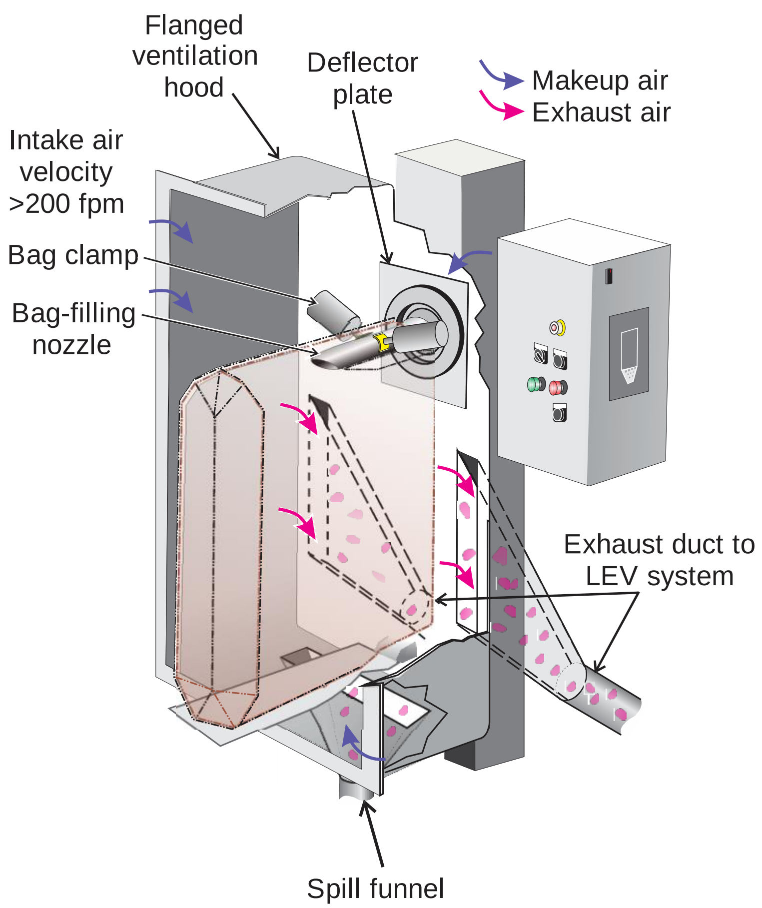


Figure 7.8. Illustration of exhaust shrouding to capture and exhaust respirable dust away from each fill nozzle.

Exhaust Hoppers (Below Entire Fill Station)

Similar to the above technique, which places an exhaust hood around each individual bag loading unit, a hopper can also be placed below the entire fill station to capture and recycle all the dust and product lost from the entire bag loading area or station. This is especially beneficial with three- and four-fill-nozzle bag loading systems. In these cases, incorporating the LEV into a single-hopper design is easier and more financially advantageous than trying to connect ductwork to individual hoods around each fill nozzle.

Figure 7.9 shows a typical design for a single-hopper LEV system. One critical design component is to locate the exhaust system takeoff points high in the hopper unit and in close proximity to the actual bag loading area. The heavier dust and product that is not captured by the exhaust system simply falls into the base of the hopper and is recycled back into the product line using a screw conveyor.

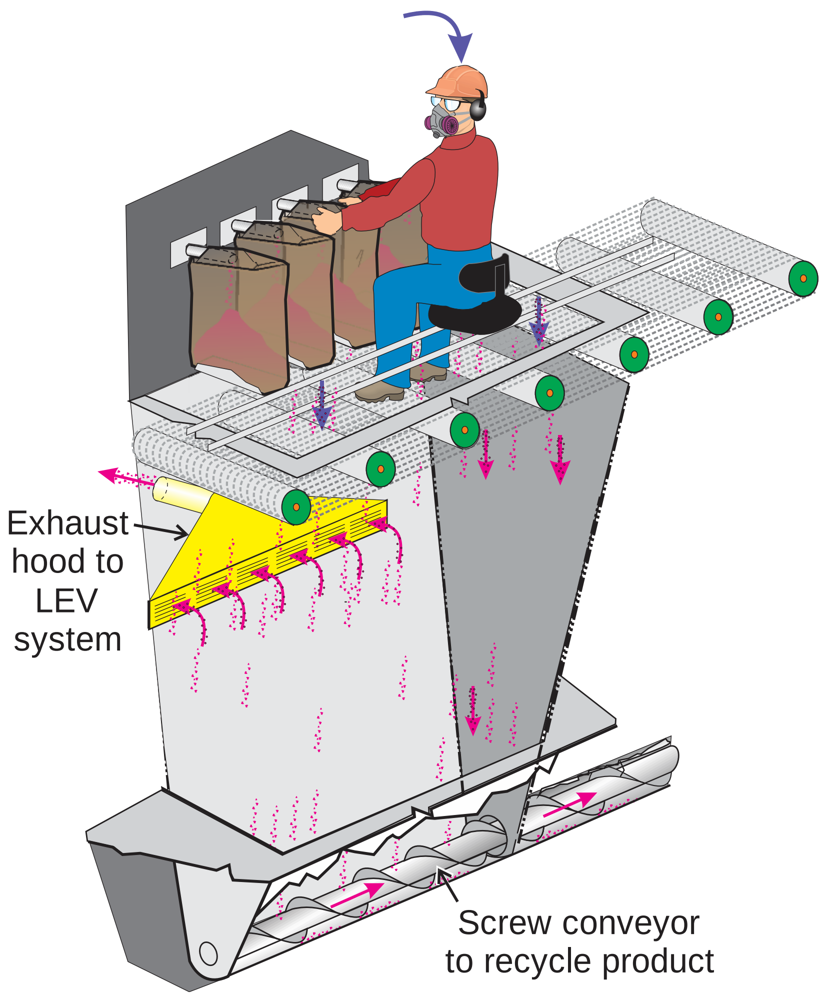


Figure 7.9. Illustration of an exhaust hopper below a bag loading station with an integrated LEV system to capture dust generated during the bag loading process.

One critical component for both the exhaust hood being around each bag loading nozzle and the exhaust hopper being below the entire fill station is to provide clean (dust-free) makeup air to the bag filling area. Any time an LEV system is used to capture dust generated at a bagging station, air will be drawn from the surrounding area as makeup air. Since this makeup air flows over the bag operator before being captured by the LEV system, it is important that it be dust-free so as to not increase the exposure of the bag operator [USBM 1986b; Constance 2004]. Outside air can be used as makeup air when there are no outside dust sources near the intake location and when outside air temperatures are acceptable.

Dual-nozzle Bagging System

The primary dust sources for manual bagging have been identified as product blowback, product “rooster tail,” and contaminated bags. The dual-nozzle bagging system is designed to reduce these major dust sources and lower the exposure of the bag operator. Figure 7.10 depicts the major components of the dual-nozzle bagging system. This system uses a two-nozzle arrangement with an improved bag clamp to reduce the amount of product blowback and product “rooster tail.”

In the original design, a single nozzle is used to fill the bag with product. With the two-nozzle arrangement, the inner nozzle is used to fill the bag and the outer nozzle relieves excess pressure from the bag after it has been filled. Once filling is completed, depressurization of the bag is accomplished with the aid of an eductor, which uses the venturi principle (compressed air entraining additional exhaust air) to exhaust excess air from the bag at approximately 50 cfm. This exhaust is controlled by a pinch valve, which is opened when the exhaust is on. The bag is slightly overfilled and held in place by the bag clamps. The pinch valve is then opened and the exhaust is initiated to depressurize the bag. After a few seconds, the bag clamp opens and the bag falls from the fill station. The exhaust system also continues to operate as the bag falls away, cleaning the bag valve area. The exhausted material can then be recycled back into the system.

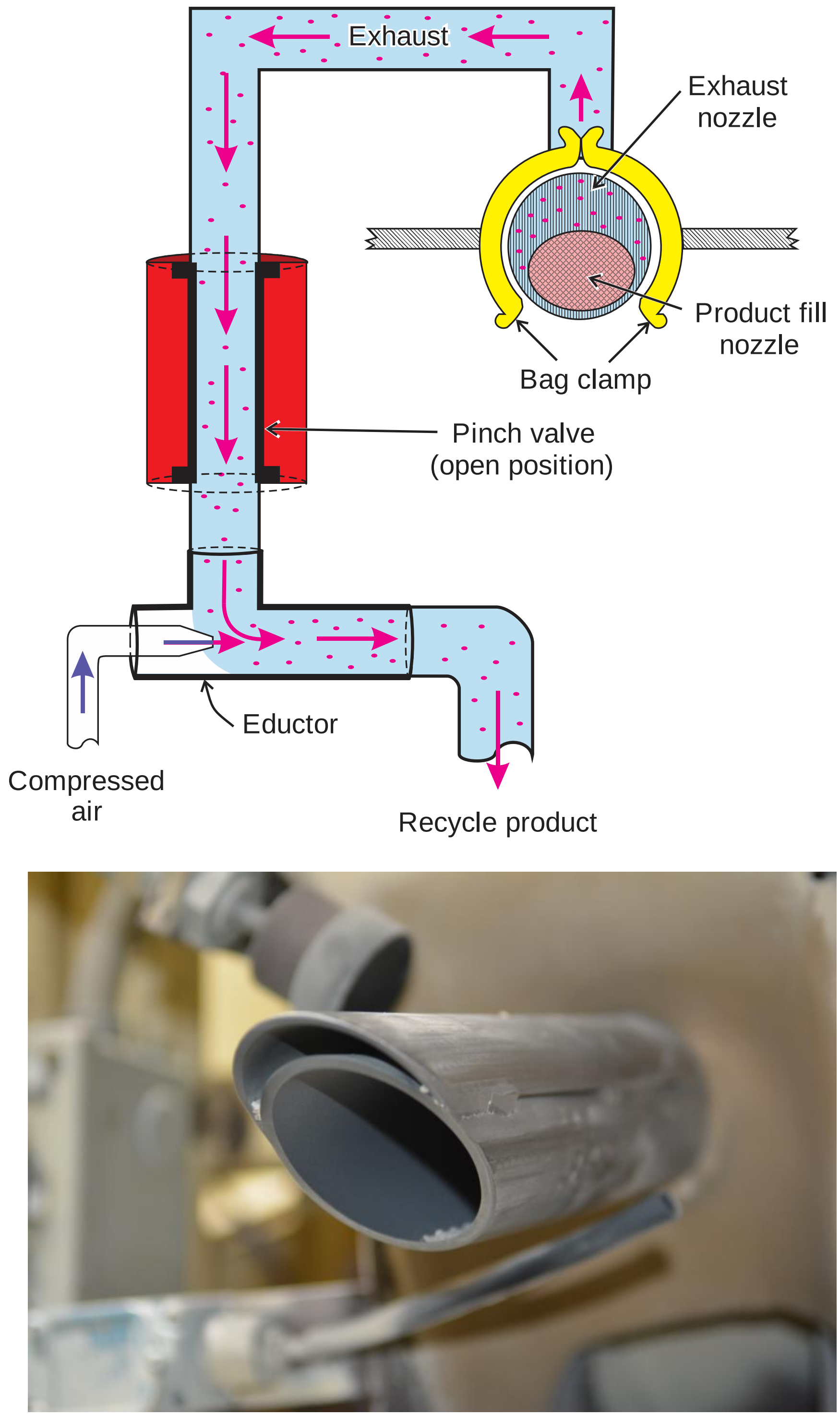


Photo by NIOSH

Figure 7.10. Major components of a dual-nozzle bagging system. The top illustration shows an overall design diagram. The bottom photo shows a close-up of a dual-nozzle device.

Another key component of this dual-nozzle bagging system is an improved bag clamp. With the original bag clamp, there were only two small points of contact with the fill nozzle. The improved bag clamp makes direct contact with approximately 60 percent of the nozzle (concentrated at the top and sides), thus reducing the amount of product blowback during bag filling. A controlled amount of blowback is necessary so the bag does not rupture during filling, but this should occur at the bottom of the nozzle to minimize the amount of dust contamination to the outside of the bag.

The dual-nozzle bagging system can be very effective at lowering respirable dust levels to workers performing the bagging and palletizing tasks [USBM 1984a,b]. Figure 7.11 indicates an 83 percent reduction in the bag operator's respirable dust exposure before and after the installation of a dual-nozzle bagging system at one plant. For a 325 mesh product, a 90 percent reduction was also measured in the hopper below the fill station. This represents a substantial reduction in product blowback and product "rooster tail" during the bagging process. The dual-nozzle bagging system also resulted in less product and dust on the outside of the bags and accounted for a 90 percent reduction in the bag stacker's dust exposure while bags were being loaded into an enclosed vehicle.

The dual-nozzle bagging system is mainly recommended for operations with three- and four-fill-nozzle bag machines because there is a slight decrease in production due to the time needed to depressurize the bags after filling is completed. The system can be used on one- and two-nozzle filling machines, but the decrease in the production rate is even more significant because the bag operator must wait for each individual bag to be depressurized, rather than waiting on a cycle of bags. Other similar systems that depressurize the bag after filling is completed have also been designed and sold [Case History 2006a].

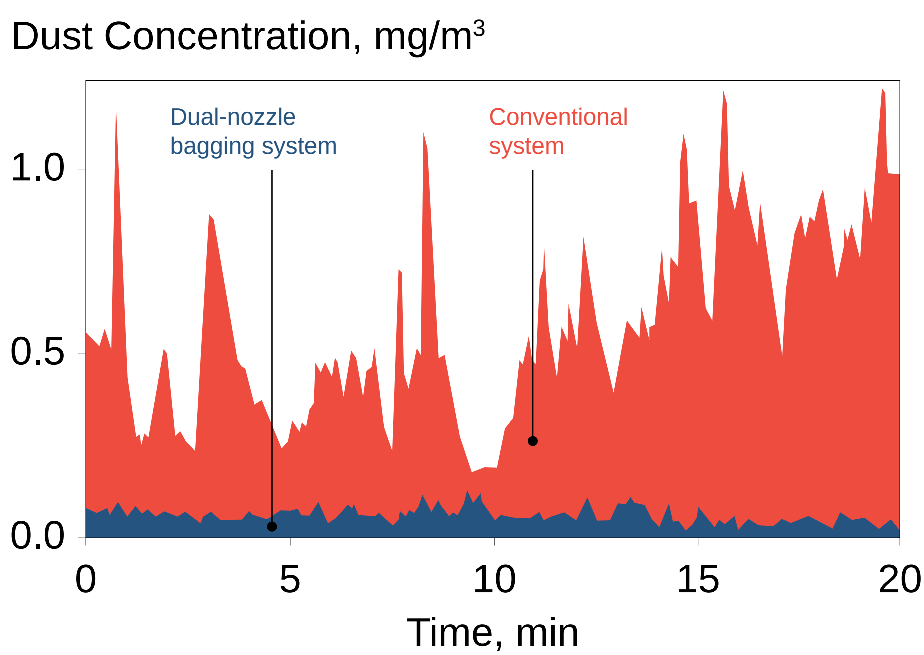


Figure 7.11. Graph showing a bag operator's dust exposure with a conventional (single-nozzle) and dual-nozzle bagging system for a 325 mesh product.

Overhead Air Supply Island System

The Overhead Air Supply Island System (OASIS) can be used to provide an envelope of clean, filtered air to a worker at a stationary bagging or palletizing unit. One of the main advantages of the OASIS is that it is suspended over a worker and operates independently of any processing equipment. Figure 7.12 shows an OASIS located over a bag operator.

The OASIS is a relatively simple design and system. Plant air is drawn into the unit and passes through a primary filtering chamber, normally using high-efficiency particulate air (HEPA) filters. After the air exits the primary chamber, it passes through an optional heating or cooling area, which can be incorporated into the unit if temperature control is desired. The air then flows through a distribution manifold filter when exiting the unit. This provides an even distribution of clean filtered airflow down over the worker while providing backup filtering in case there is a problem with the primary filtering chamber. If the bagging or palletizing process generates a significant amount of dust, it will contaminate the envelope of clean air from the OASIS after it flows down over the worker. In these cases, it is normally advisable to then capture this dust-laden air with an LEV system.

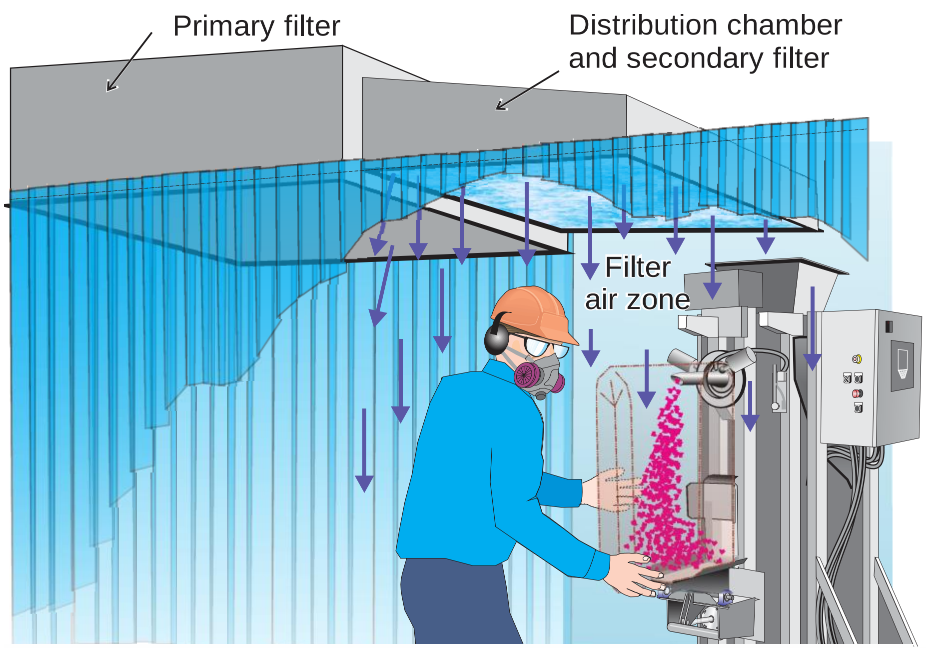


Figure 7.12. Illustration of an Overhead Air Supply Island System (OASIS) positioned over a bag operator to deliver clean filtered air down over the work area.

With the OASIS, the target is to have an average velocity of roughly 375 fpm flowing down over the worker, which normally keeps any dust-laden plant air from entering the clean air core [Volkwein et al. 1986]. One important feature with an OASIS is to incorporate a self-cleaning primary filter design. There are a number of different self-cleaning techniques used to remove the dust cake from the filters. For example, the reverse air jet pulse collector is a very common and effective method to perform this task (refer to Chapter 2—Fundamentals of Dust Collection Systems).

The OASIS is very effective at lowering workers' respirable dust exposures. A bag operator's respirable dust exposure was reduced by 82 and 98 percent at two different operations using the OASIS as compared to when the unit was not being operated [Robertson 1986]. At both of these operations, the dust concentration within the clean filtered air of the OASIS remained under 0.04 mg/m^3.

When the OASIS is used with standing workers, it can be advantageous to place clear plastic stripping down the sides of the device. This allows the workers to recognize the boundary of the clean air zone and the inability to be protected once exiting the physical barrier of the plastic stripping.

An additional benefit provided by the OASIS is a general improvement to the overall plant air quality. This occurs because the OASIS is drawing air from the plant environment, filtering it, and then blowing this clean air down over a worker. After flowing over the worker, it then becomes part of the general plant air again. At one site using the OASIS, there was a 12 percent reduction in respirable dust levels throughout the entire building [Volkwein et al. 1986]. The volume of clean air delivered by the OASIS is variable based upon the size of the unit, but it is normally in the range of 6,000 to 10,000 cfm. Other studies have also shown the benefit of recirculating air back into a plant after it has been cleaned [Godbey 2005]. The OASIS is generic in design and can be fabricated and installed in-house or through any local engineering company that handles ventilation and dust control systems.

Automated Bag Placer and Filling Systems

Many manufacturers provide automated bagging systems that eliminate the operator from performing the bagging task manually. These systems normally include both a mechanical bag placer and a product filling system. For most automated systems, a worker is only required to place empty 50- to 100-pound bags on a storage rack. From this point forward, the system becomes automated. Normally some type of robotic arm using suction cups takes the unfilled bags from a storage rack and places them on the individual fill nozzles of the bag filling unit. When the bag is in place, the filling process starts and continues until a sensor indicates that the bag has reached the correct weight. The bag saddle then actuates to eject the loaded bag from the fill nozzle/fill station. Figure 7.13 shows an example of a bag storage area and an automated device to place the bag on the fill nozzles.

For open-top bags, typically a semi-automated bagging system places, fills, and weighs the bags of product, and then a worker manually feeds the bags through a closer device. For fully automated systems, all tasks are performed automatically and the operator/worker only needs to monitor the system's performance.

There are many different factors to evaluate when an operation is considering some level of automation (semi-automatic to fully automatic) [White 2006]. For facilities only bagging one shift per day, semi-automated systems are more commonly used. When operations bag many different product types, the cleanout or changeover between batches is also easier with semi-automatic systems. Automated bagging systems require more care and maintenance than nonautomated systems. It is also important to stock some spare parts for these systems, especially if the vendor is not located nearby. There are fewer parts necessary for semi-automated systems; thus, a smaller inventory of these critical parts is necessary.

Photos by NIOSH

Figure 7.13. Example of a bag storage area and an automated device to place the bag on the fill nozzles. The left photo shows bag storage shelves and the right photo shows a robotic arm with suction cups to place empty bags on the fill nozzle.

With a totally automated system, greater production can be achieved. In addition, savings can be achieved with automated systems because they eliminate the worker at the bagging process. Eliminating the need to have workers performing tasks manually reduces their respirable dust exposure, MSD, and lost-time injuries.

One aspect that does not change from manual to automated bagging systems is to have an LEV system incorporated into the bagging station to capture and remove the dust liberated from product blowback and product “rooster tail.” Although workers are not located directly within the bag filling area, if the dust is not captured during bag loading and ejection from the fill station, it will flow out into the work environment and contaminate workers in and around the automated bag filling system. One very effective technique often used is to enclose the bag filling area with clear plastic stripping. This provides a physical barrier that indicates the potential dust-laden air zone to workers and aids the LEV system in containing and capturing the dust liberated from bagging.

The initial costs of automated systems are much greater than for manual systems. If a cost analysis is performed, costs must be evaluated on a long-term basis, considering the respirable dust exposure and MSD exposure to workers performing the tasks manually.

FORM-FILL-SEAL (FFS) SYSTEMS

Bagging machinery exists in a range from semi-automatic to fully automatic. Traditional systems are made up of a filling hopper, screw conveyors, and manually actuated filling nozzles activated by a human operator. These machines can also be upgraded with robotic arms that can automatically pick up bags and insert them onto the fill nozzles, leaving the operator to simply ensure that the bags are in supply in the pickup area.

Traditionally, composite paper/plastic bags, due to their built-in venting (either valves or perforations), have been best suited for bagging mining aggregates, especially those involving fine powders such as silica. For certain applications, a newer more advanced machine category exists called the form-fill-seal (FFS) system (Figures 7.14 and 7.15).

With an FFS system, plastic rather than paper bags are used. These plastic bags are supplied to the machine in the form of a continuous roll, stored on a spooling spindle. The bags are threaded into the machine, re-oriented via a set of roller mechanisms, and presented in a vertical fashion to the separator (knife) and then to the fill nozzles. Finally, they are ejected onto a waiting conveyor. The entire system is under the control of one programmable logic system, from the bag feeding to the final conveyance.

With an FFS system, the manual operator is typically not replaced but is instead freed to ensure that the machine is kept loaded with spools of plastic bags and that the process has not become hindered by any mechanical or electrical malfunction. FFS technologies have thrived where very high throughput is necessary and plastic bags can be used. Historically, these technologies have not been as reliable on ultra-fine powders, but there are installations successfully working on frac sands and even amorphous powdered silicas. As with any bagging system, it is still critical to supply the necessary local exhaust ventilation to the fill hopper to ensure that significant airborne concentrations are not released throughout the plant.

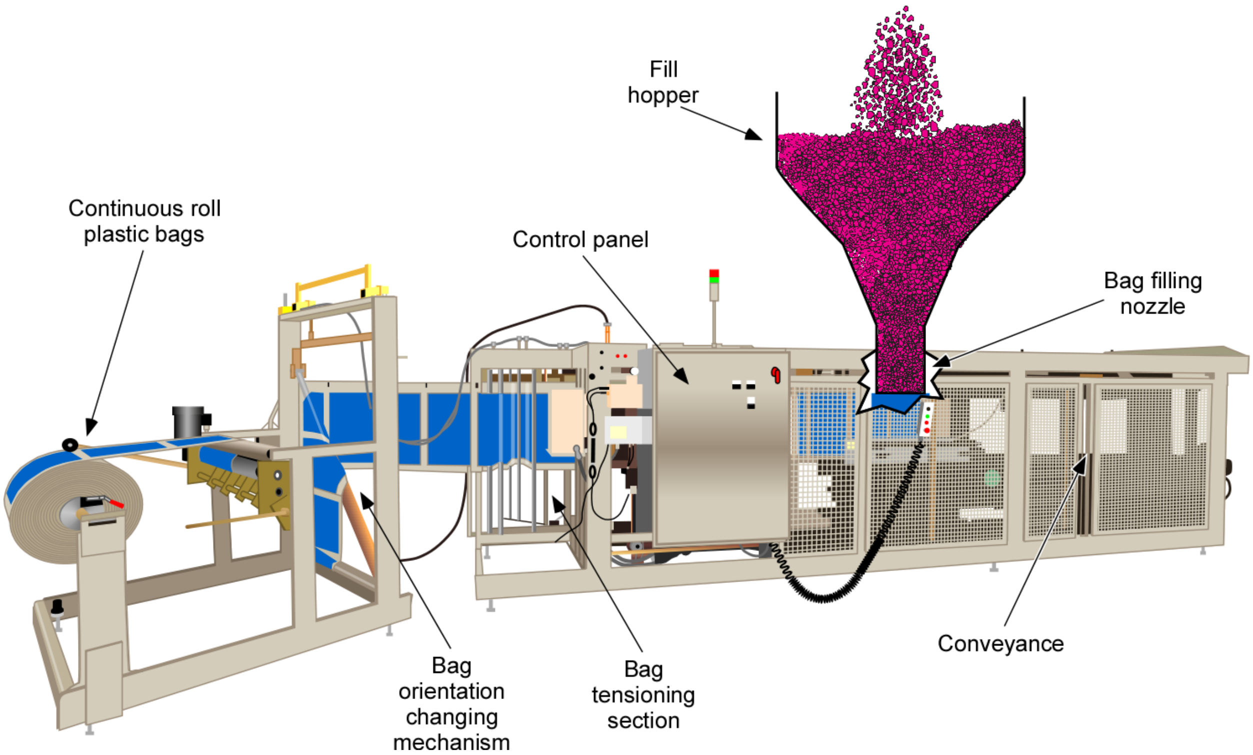


Figure 7.14. Illustration of a form-fill-seal (FFS) machine. The process moves from left to right, starting with the bag supply, re-orientation and tensioning, fill hopper, and belt transfer to the stacking area. (LEV system not shown.)

Photos by NIOSH

Figure 7.15. FFS system in service loading larger-grain play sands.

CONTROL TECHNOLOGIES FOR CONVEYING AND PALLETIZING 50- TO 100-POUND BAGS

Bag and Belt Cleaning Device

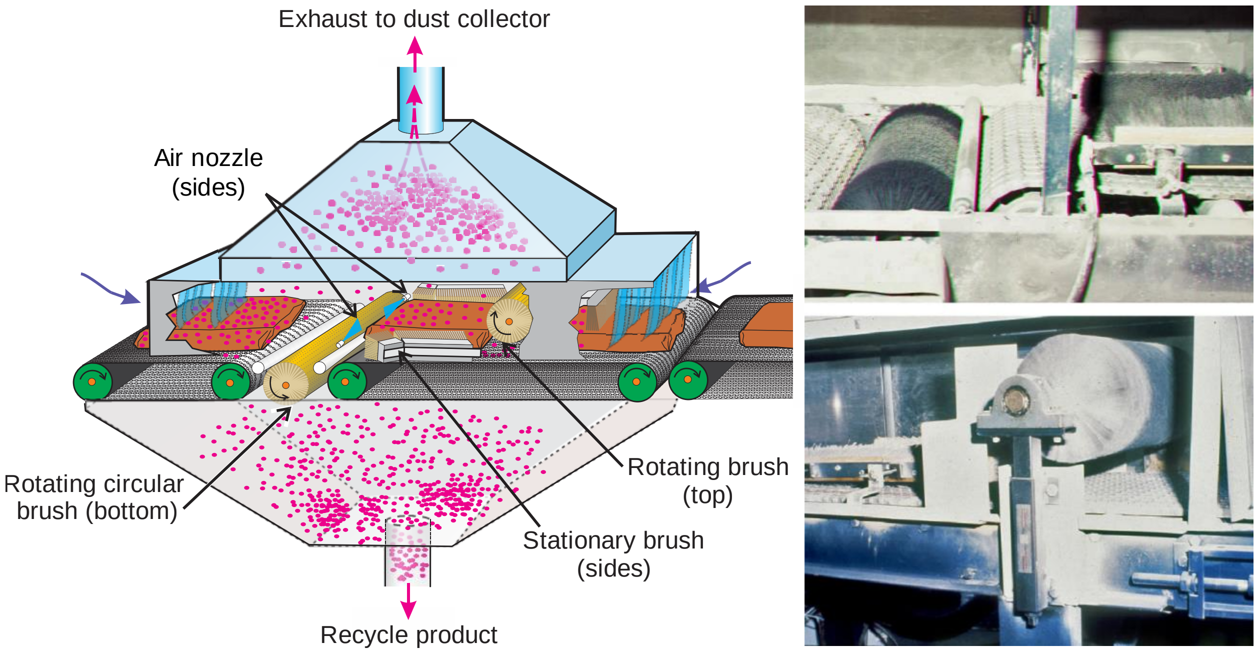
The bag and belt cleaning device (B&BCD) is designed to reduce the amount of dust escaping from bags as they travel from the bag loading station to the stacking/palletizing area. This device reduces the dust exposure of all workers involved in and around the conveying process, as well as anyone handling the bags once they are filled at the loading station.

These systems are applicable to any mineral processing operation that loads product into 50- to 100-pound paper bags. This system should be located in-line on the conveyor at the closest available position to the filling station.

In one particular application, the B&BCD was 10 feet long and used a combination of brushes and air jets to clean all sides of the bags (Figure 7.16). Initially, the bags enter the B&BCD through a curtain made of clear, heavy-duty, flexible plastic stripping to seal it from the plant air. The bags then travel past a stationary brush on a swing arm that cleans the front and top of each bag. Next, the bags go through a second set of plastic stripping and into the main cleaning chamber. The bags then travel under a rotating circular brush that further cleans the top of each bag. The sides are cleaned by a stationary brush located on each side of the bag, and an air jet located at the end of these brushes provides additional cleaning. The side of the unit facing the valve uses a higher volume (velocity) air jet to provide the maximum amount of cleaning of the valve area. After passing through the air jets, the bag travels over a rotating circular brush beneath the bag, which cleans the bottom of the bag. Finally, the bag exits the device by traveling through another air lock chamber with flexible plastic stripping.

A chain conveyor is used for the entire length of the device to allow product removed from the bags during cleaning to fall into a hopper. Product collected in this hopper is then recycled back into the process, normally using a screw conveyor. Once exiting the B&BCD, both the bags of product and the conveyor belt should be essentially dust-free.

During the evaluation of this specific B&BCD at two mineral processing plants, the device showed very favorable results in lowering respirable dust levels. The most relevant data from this testing was the amount of dust removed from the surface of the bags, with a 78 to 90 percent range of reduction [Cecala et al. 1997; USBM 1995].



Photos by NIOSH

Figure 7.16. Illustration and photo of a bag and belt cleaning device. The left illustration shows the overall device design, with the magenta arrows indicating a closed system under negative pressure. The right photos show stationary (top) and rotating (bottom) brushes in actual service.

Another common instance of dust generation and liberation from bags is during the bag flattening process. In operations that use bag flatteners, this task could be performed within the B&BCD to capture the dust released during this process.

Although this section describes one particular B&BCD system, there are numerous types that can be purchased from manufacturers, fabricated in-house by mineral processing plants, or fabricated by a local engineering firm. One key factor for a system is to be self-supporting so it can be implemented anywhere along the conveyor belt line. It is more logical to place a B&BCD in the closest possible proximity to the filling station to eliminate the dust hazards as quickly as possible. These devices normally need electricity and compressed air to power the cleaning unit and the blow-off nozzles, respectively.

One last critical aspect is that a B&BCD must be under sufficient negative pressure to ensure that any dust removed from the bags or conveyor belt does not leak from the cleaning unit into the plant. Refer to Chapter 2—Fundamentals of Dust Collection Systems—for the specifics on negative pressure and local exhaust ventilation systems.

Semi-Automated Bag Palletizing Systems

Semi-automated systems use workers in conjunction with an automated system to perform the bag stacking process. These can include a vast array of different setups and types of systems. In one case, a worker performs the bag stacking task manually, but is assisted by a hydraulic lift table. This lift table allows the height for stacking the bags to remain constant throughout the entire pallet loading cycle. The lift table is set to approximately knuckle-height for the worker, which is the most ergonomic loading height (Figure 7.17). A push-pull ventilation system is used on either side of this pallet to capture the dust liberated during the bag stacking (palletizing) process [Cecala and Covelli 1990]. This system is composed of a low-volume, high-velocity blower operating at approximately 120 cfm to direct a stream of air over the top layer of bags on the pallet. The blower system is composed of two three-inch air jets (approximately 1,200 fpm velocity) directed toward an exhaust system on the opposite side of the pallet. As these air jets travel approximately 10 to 12 inches above the top of the pallet, they entrain the dust generated during bag stacking. The exhaust ventilation system pulls approximately 2,500 cfm of air and dust through the exhaust hood. This exhaust air can then be dumped into an LEV system.

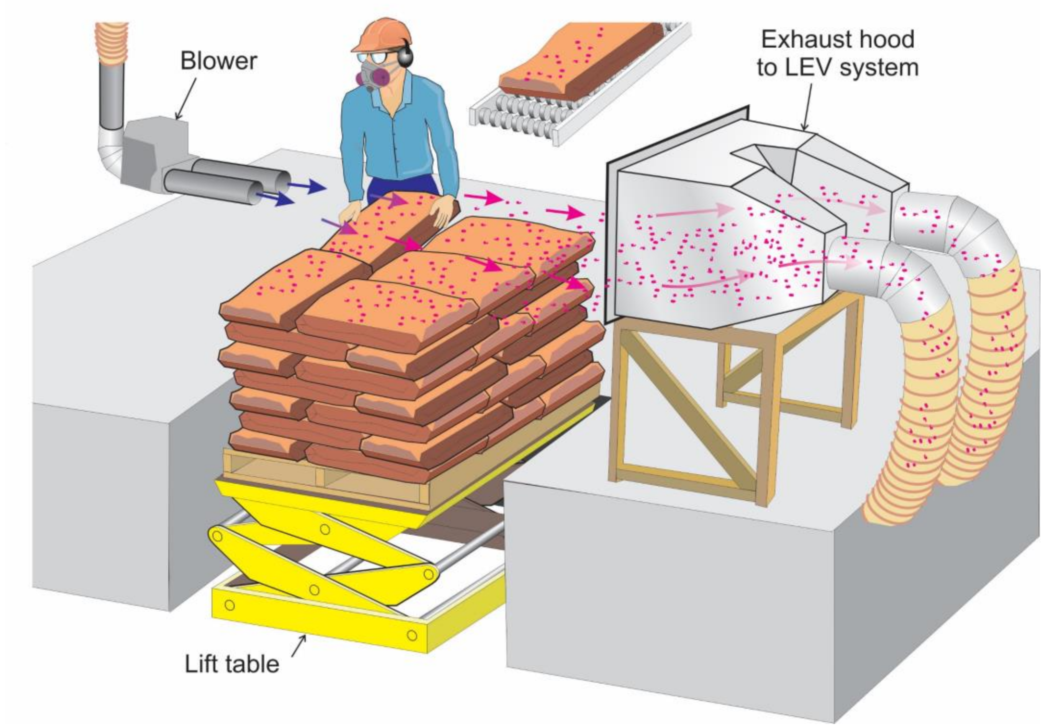


Figure 7.17. Illustration of a semi-automated bag palletizing system. This system provides ergonomic improvements to the bag stacking process with a push-pull ventilation system used to capture the dust generated.

In other cases involving palletizing systems, the worker slides the bag of product on an air table one layer at a time, but the actual stacking of the bags onto the pallet is performed automatically. Since back injuries represent such a major potential lost-time injury for bag stackers, this design significantly reduces back stress by eliminating the need to manually lift any bags of product.

One problem with an air slide device is that it can cause dust to be blown from the bags of product into the worker’s breathing zone. An OASIS (see this chapter’s earlier “Overhead Air Supply Island System” section) can work very effectively in conjunction with an air slide device.

In addition to the OASIS, an exhaust hood was also used next to the air slide area to capture the dust blown from the bag (Figure 7.18) [Cecala et al. 2000]. With this setup, or any other industrial application using an exhaust hood, one area of concern for overexposure is when a worker positions himself or herself between the dust source and the exhaust hood. In this application, if the worker leans out over the air slide, he or she will be exposed to any dust being blown off the bags by the air slide as it is pulled into the exhaust hood.

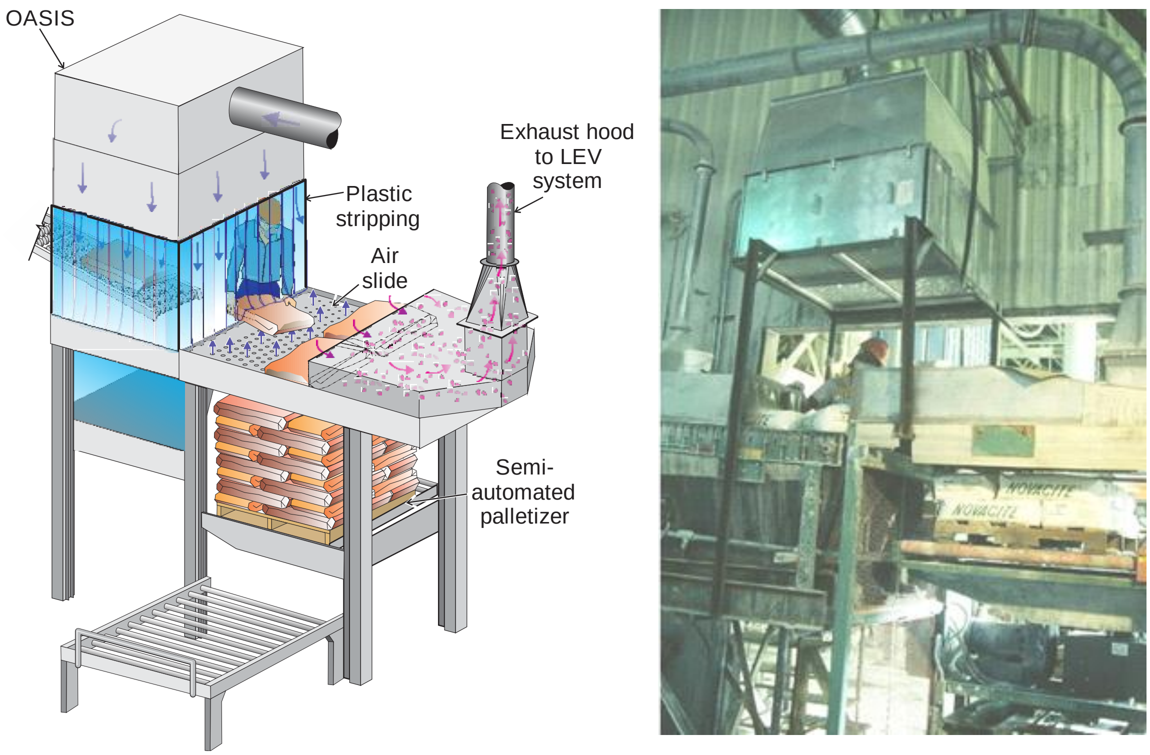


Photo by NIOSH

Figure 7.18. Illustration and photo of a semi-automated bag palletizing system. As shown in the left illustration, in this system, a worker removes bags from a conveyor and lifts and positions each layer on an air slide before automated loading onto the pallet. The right photo shows a worker using a semi-automated bag palletizing system, but without plastic stripping. Both an OASIS and an exhaust ventilation system are used to lower the worker's dust exposure during this bag palletizing process.

Automated Bag Palletizing Systems

Various manufacturing companies have developed advanced designs for automatic palletizing equipment that utilize either the traditional high-level pallet loading technology or a low-level pallet loading technology. With high-level pallet loading systems, the pallets enter the automated palletizer system near the floor and are then raised to perform bag loading. When the pallet is completely loaded, the full pallet is then lowered back down to near the floor level before being delivered to a plastic pallet wrapping system or loadout area.

With these high-level pallet loading systems, the bags arrive at the unit from the filling station via a conveyor belt. Once at the unit, the bags are guided onto a stripper plate that is composed of a series of rollers. Bags are arranged onto the stripper plate in a predetermined pattern as programmed into the unit by the worker overseeing the automated unit. Once a full layer of bags is positioned, the system stripper plate is automatically opened and the entire layer of bags is loaded onto the previous layer. The stripper plate then closes, allowing another layer of bags to begin loading in a prearranged pattern. Each layer of bags is loaded in an opposite pattern than the previous layer, typically by way of any manually or automated pallet loading system. Each time a full layer of bags is completed, the stripper plate is opened and the new layer of bags is stacked onto the pallet. When the predetermined number of layers of bags is achieved, the full pallet is lowered down near the floor level, which ends the automated pallet loading process.

Figure 7.19 shows a typical high-level automated bag palletizing system. There are many different manufacturers of these types of systems, with each system having its own specialized design.

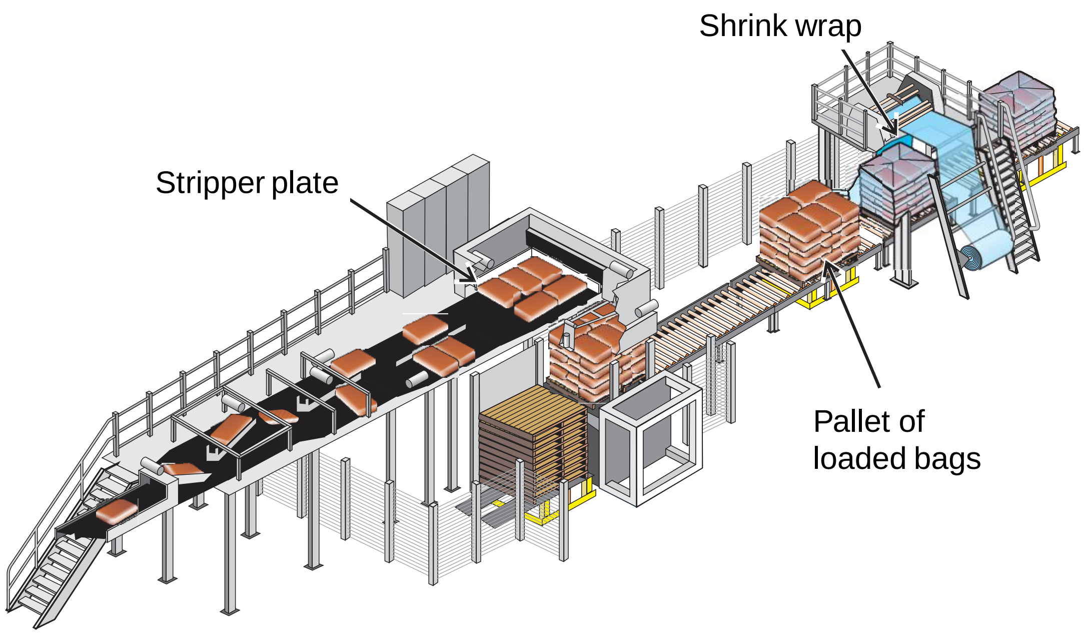


Photo by NIOSH

Figure 7.19. A typical high-level automated bag palletizing system. The top illustration shows an overhead view of the overall design. The bottom photo shows an automated high-level palletizing process in use.

With low-level automated pallet loading systems, the pallets are located near the floor and remain stationary throughout the entire loading process. A mechanical device takes the loaded bags and places them directly onto the pallet. The use of a robotic mechanical arm palletizer is the most common type of automated low-level system.

The robotic arm automatic palletizer illustrated in Figure 7.20 has become very popular due to its productivity and lower maintenance costs compared to the in-line/high-level palletizer. Filled bags travel from the bagging station to the palletizing area via a conveyor belt. At the palletizing area, a photocell detects that a bag has arrived and is ready to be loaded onto a pallet. Each bag is grasped by the fingers of the robotic arm, and then taken and gently placed onto the pallet in a programmed pattern established by a worker overseeing the automated unit. The arm can be programmed to close tolerances to prevent the bag from being dropped onto the pallet, which would cause dust to be emitted from the bag valve. The robotic arm can also stack bags onto two separate pallets and at a high rate of speed to increase productivity.

The robotic arm automatic palletizers are proving themselves to be the preferred method for palletizing bags because they are much simpler, and thus more cost effective, by comparison to the high-level pallet loading systems. With these systems, operating costs, breakdowns, and maintenance are greatly minimized [Case History 2006b]. They also require much less space and minimize dust generation and liberation potential compared to high-level pallet loading systems.

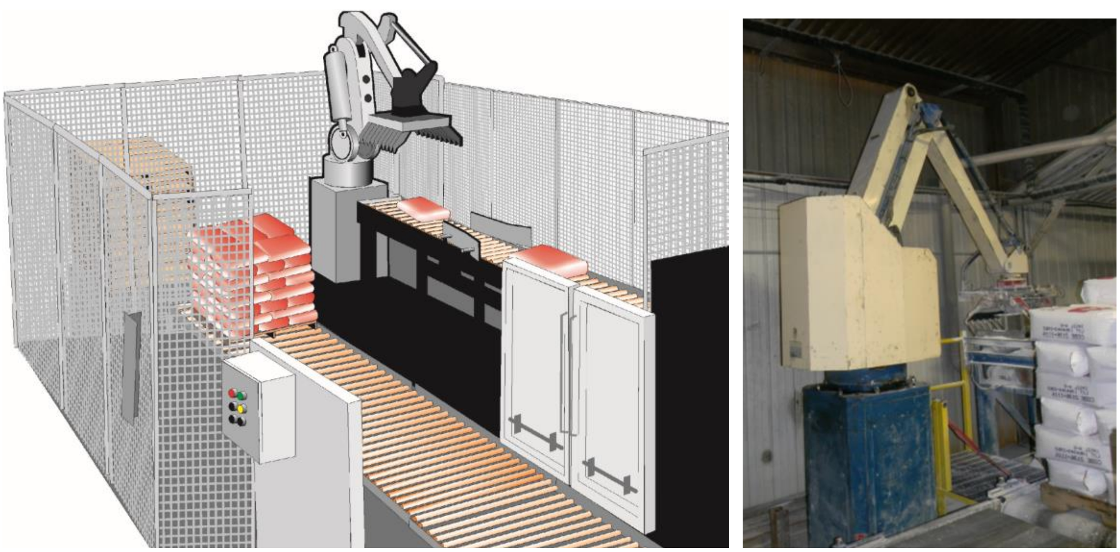


Photo by NIOSH

Figure 7.20. Illustration and photo of a robotic arm automatic palletizer. The left illustration shows a low-level pallet loading process using a robotic arm device with a safety fence. The right photo shows an actual installation (with fencing present, but not within the image).

Importantly, any automated system should provide adequate guarding to protect workers from entering automated work areas while these units are operating, or even when activated but idle. Because of the operating speeds and the mass of the unit in robotic arm systems, the swing pattern can span significant distances and the mechanical arm can cause severe injury, or even death, if it strikes a worker.

When combining these automated palletizing systems with automated bag placers, in-line bag cleaning devices, automatic bag weighing systems, printing systems, and plastic pallet wrapping systems, the worker is removed from the work processes. This in turn substantially reduces the worker's dust exposure potential, and the worker has more of an oversight responsibility to ensure that the system is working properly. Another significant benefit over and above the dust exposure reduction is the elimination of MSD bag stress injuries common to performing these various tasks manually.

It should be stressed that when using automated systems, there is still a concern for dust. The amount of respirable dust generated and liberated from automated systems still needs to be evaluated and controlled to ensure that it does not flow into the surrounding plant areas and contaminate the breathing atmosphere of workers. This is normally achieved by enclosing the dust generation areas with plastic stripping and using an LEV system to exhaust the respirable dust.

Plastic Pallet Wrapping Systems

The final consideration for dust control in the palletizing of paper bags is plastic pallet wrapping systems. The purpose of plastic pallet wrap is to contain product and dust leakage from bags loaded onto full pallets from becoming airborne while also providing protection from torn or ruptured bags during the pallet transportation process. Currently, there are two types of plastic pallet wrapping systems being used: (1) spiral stretch wrap and (2) shrink wrap/stretch hoods. Both systems are commonly used in the mineral processing industry, and they can be used in both manual and automated applications. The size of the packaging system will normally dictate which pallet wrapping system is most practical.

A consideration when using plastic pallet wrapping systems is that the bags should be completely void of entrapped air before the plastic wrap is applied. If a protective plastic coating is applied before the bags have been deflated, it will become loose and thus ineffective. In operations where entrapped air is a problem, a pallet press should be used to squeeze the excess air from the bags immediately before the plastic wrap is applied.

Spiral stretch wrap was one of the first types of plastic wrapping techniques developed and used in the industry. This technique can be performed through either a manual or automated process. For manual operations, the full pallet is placed in an open area and a worker manually walks around the pallet, unwinding spiral stretch wrap over the pallet. Once completing multiple revolutions to the point that the pallet is adequately covered, the worker cuts the stretch wrap from the roll and connects the cut end to the pallet.

In the automated process, the full pallet of bags is placed on a rotating table. As this table spins the pallet round and round, a roll of stretch plastic is continually wrapped around the pallet while slightly moving up and down at a predetermined wrap tension (Figure 7.21). After enough revolutions occur that the pallet is completely sealed, a mechanical device cuts the plastic wrap from the roll.

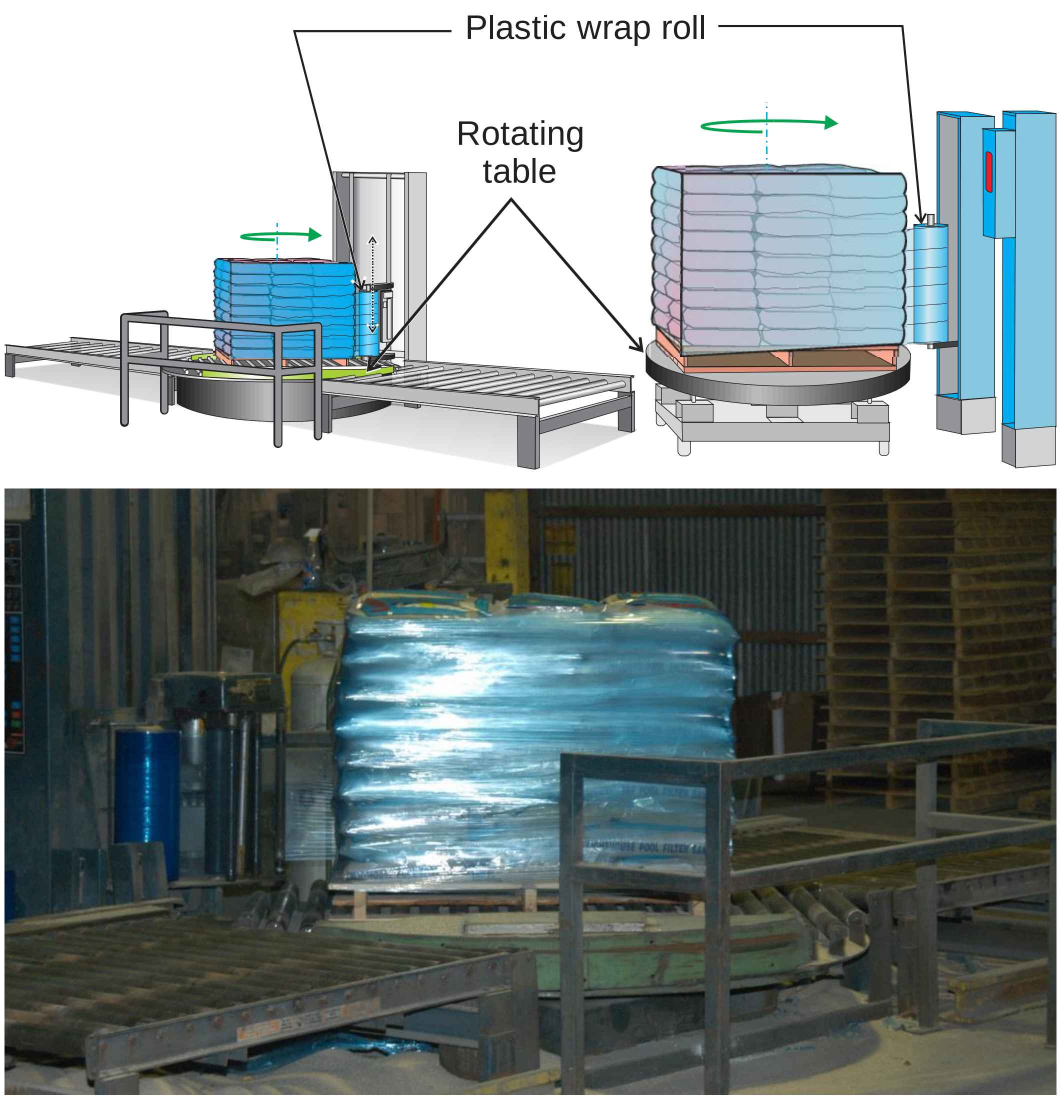


Photo by NIOSH

Figure 7.21. Illustration and photo of a plastic pallet wrapping system. The top illustration shows an automated spiral stretch wrap machine. The bottom photo shows the wrapped product on a rotating table.

For many years, this plastic wrapping technique was the best and least expensive method of protecting loads for shipment [Packaging system eases mineral dust problems 1978]. One shortcoming with the spiral stretch wrap is that the top of the pallet is not normally sealed and dust can be liberated from this top area. In addition, when the pallets are outside, rain or moisture can get down in and saturate the bags of product. To correct this shortcoming, a top sheet can first be placed over the top of the pallet before the process is started, but this normally has to be performed manually by a worker, which increases the time and the cost of performing this process.

Another method to perform this technique is through the use of shrink wraps or stretch hoods. A single sheet of plastic is placed over the entire pallet and then heated to cause it to shrink tightly down and completely around the pallet of bags. This technique can also be performed manually by a worker or through the use of an automated system. When using this technique, pallets can be stacked and stored outside without worrying about water damage during storms. Finally, stretch-hooded pallets are safer than shrink wrapped pallets because the pallets are more stable and easier to handle [New Installations 2006].

FLEXIBLE INTERMEDIATE BULK CONTAINERS

Flexible intermediate bulk containers (FIBCs), also called “bulk bags,” “semi-bulk bags,” “mini-bulk bags,” and “big bags,” have become more popular over the recent years for shipment of product material. They are often more cost effective than the 50-, 80-, or 100-pound bags for both the mineral producer and the end user. The most effective method to control the dust liberated during filling of FIBCs is by using an expandable neoprene rubber bladder in the fill spout of the bagging unit. This bladder expands against the interior of the FIBC loading spout and completely seals it, eliminating any product and dust escaping from the spout during loading (Figure 7.22). When using this expansion bladder, the feed spout must also incorporate an exhaust ventilation system to exhaust the excess pressure from the FIBC during loading (Figure 7.23).

Photo by NIOSH

Figure 7.22. Expandable neoprene rubber bladder used in the fill spout of the bagging unit for flexible intermediate bulk containers.

If dust is still being liberated, another effective technique is to isolate the bag loading area from the rest of the plant. A worker can enter this area to manually attach the empty bag onto the loading device. The worker then leaves the area and, once outside, remotely activates a start button to begin the bag filling cycle. The area is under negative pressure by virtue of being tied into an LEV system, and any dust generated will be exhausted and not allowed to contaminate the operator’s work space. Once the FIBC loading is completed, the worker re-enters the area, removes the bag for shipping, and begins the process again.

A cautionary note is made here regarding work habits of employees performing the sealing of the filled FIBC spout. Most FIBCs have a fabric fill spout that requires cords to be tied or secured in some manner. In this case, to avoid dust exposure, it is very important that the operator “point” the position of the spout away from the body to avoid the dust-laden exhaust air exiting the bag from being directed toward the operator’s breathing zone.

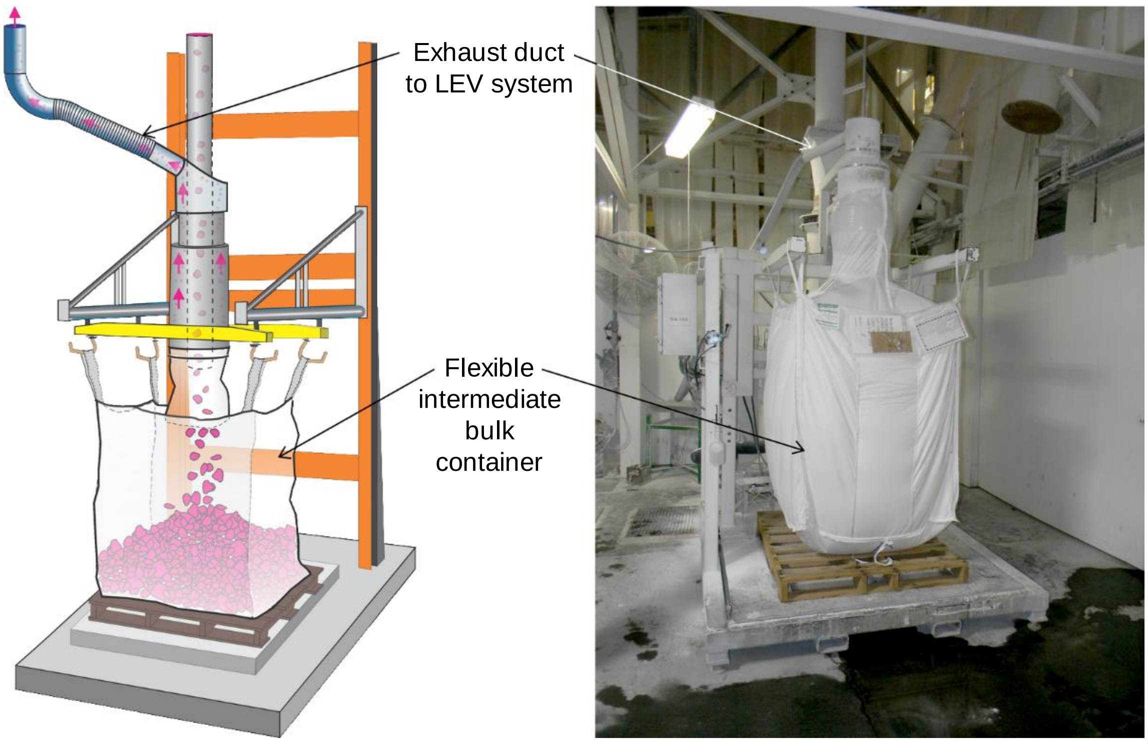


Photo by NIOSH

Figure 7.23. Illustration and photo of exhaust ventilation system being used during the loading of flexible intermediate bulk containers.

MAINTAINING CLEAN FLOORS IN BAG LOADING, PALLETIZING, AND WAREHOUSE LOCATIONS

Pallets loaded with 50- to 100-pound bags or bulk bags are normally moved by a forklift or tow motor directly to trailer trucks or railcars, or they are stored in a warehouse location until a later time when they are then loaded into a transportation vehicle. As these forklifts and/or tow motors move around plant and warehouse locations, they can stir up significant amounts of dust if floors are not kept in a clean condition. The two most common floor cleaning techniques in mineral processing plants are washing with water and through the use of floor cleaning units.

To serve as an effective cleaning technique, hosing down floors with water needs to be built into the structure right from the beginning. Floors need to be sloped toward floor drains to be truly effective and to minimize the amount of standing water. Typically, hosing down floors needs to occur on a shift-by-shift basis to be effective.

For floor cleaning units, there are many different manufacturers and companies that produce and sell a vast array of units. For more information on floor cleaning units and related best practices, refer to “Reducing Dust Exposure Through Improved Housekeeping Practices” in Chapter 9—Controls for Secondary Sources.

ENCLOSING DUST-LADEN AREAS WITH PLASTIC STRIPPING AND USING AN LEV SYSTEM

Many of the different dust control techniques discussed in the chapter for bagging and palletizing operations can be further improved by enclosing the dust-laden air zone with clear plastic stripping and using an LEV system to capture and remove the dust. This “enclose and capture” technique has a number of benefits. The plastic stripping contains the dust within the job process and minimizes the possibility of it being liberated throughout the entire plant. It also provides a visual indication for the plant personnel of the boundary of the dust-laden air zone. Workers know not to enter the dust-laden air zone while the job processes or functions are operating.

Another benefit of the boundary area created by the plastic stripping is that it allows the LEV system to perform more effectively. Since the capture efficiency of exhaust ventilation systems in an open environment is not very efficient, the plastic stripping barrier allows the exhaust system to operate much more effectively than without one in place. From an economic standpoint, plastic stripping is relatively inexpensive compared to other types of dust control techniques.

One last area to consider when using clear plastic stripping is that it allows workers to see through the curtain for safety reasons. This technique has numerous applications, not only in the bagging and palletizing area but throughout the entire mineral processing operation. When evaluating the correct connection technique for the LEV system, as well as recommended exhaust airflow quantities, refer to Chapter 2—Fundamentals of Dust Collection Systems.

WORK PRACTICES TO MINIMIZE DUST EXPOSURES FROM BAGGING AND PALLETIZING

The following list of best practices should be considered by operations wishing to minimize respirable dust exposures to workers performing bagging and palletizing.

- Use slides or chutes whenever possible to minimize the distance that product free-falls in open areas.
- Keep floors as clean as possible to minimize dust liberation as forklifts and tow motors travel around the area transporting bag material and other items.
- Maintain the work area such that there are no sharp edges at bag drop-off locations, turning points, and/or conveyor lines that could tear bags of product material.
- Maintain material flow cut-off valves at bagging machines to minimize product dribble from fill nozzles and fill chutes.
- Determine the optimal bag construction and bag valve type for the material being processed and bagging machine being used.
- Minimize product blowback and product “rooster tail” during bag filling and ejection from the fill station. Both of these dust sources can also cause extensive dusting on the outside of bags, as well as increase the overall demand on the LEV system.
- Consider using ventilated filling spouts as discussed in the “Dual-Nozzle Bagging System” section to remove product from the fill nozzle and bag valve areas after bag filling is completed.

- Slow bag filling rates when necessary to minimize the amount of product blowback.
- Carefully place loaded bags onto pallets. Throwing or dropping bags onto conveyors or pallets increases the potential for dust generation and bag breakage.
- Use a hydraulic lift table to minimize dust generation and MSDs among workers during bag loading onto pallets by keeping the loading height at knuckle height as described in the “Semi-Automated Bag Palletizing Systems” section. This allows for a push-pull ventilation system to more effectively capture any dust generated during bag palletizing.
- Use dust-free empty bags manufactured to flexible intermediate bulk container standards. Many reusable FIBC bags are returned with clean interiors, but dust is often trapped in the fabric on the bag exterior. This dust is then expelled during handling of the bag.
- Store all empty bags in a clean environment and keep them covered to prevent dust from settling on them.
- When tying or sealing the spout of a filled FIBC bag, the operator should always hold the flexible loading spout away from his or her breathing zone to minimize the escaping dust.
- Avoid positioning the bag operator or the bag palletizer between any dust source and the pickup point of an LEV system. When this is not done, dust will be drawn directly over the worker, significantly increasing the worker’s dust exposure.
- Consider using a mechanically assisted bag handling system to avoid filled bags being dropped onto pallets. These systems also greatly reduce the potential for MSDs among workers.
- Consider the use of a bag cleaning device prior to bag palletizing, as discussed in the “Bag and Belt Cleaning Device” section. Mechanical brushes and air nozzles can be used successfully to perform this cleaning. Brushes need to be adjusted or replaced often due to high wear potential. It is also critical to capture the dust removed from the bags with an LEV system.
- Develop and implement a plan for dealing with broken bags that minimizes manual handling. This can include a vacuuming system or a ventilated waste hopper device. Every effort should be made to eliminate plant personnel from manually handling any broken bags.
- Enclose bagging and palletizing areas from the general plant environment through the use of clear plastic stripping. If entry is not necessary, a solid type curtain could be used. These enclosed areas should be under negative pressure through an LEV system to prevent dust from migrating to other areas of the plant.
- Collect dust at the source through an LEV system rather than trying to redirect or dilute it with ventilation fans. The use of freestanding fans only circulates the air and dust and does not remove it from the plant.
- When using an OASIS, periodically clean and replace filters and ensure that clean filtered air is evenly distributed down over the worker. Significant airflow reductions can occur from dust-laden filters.
- Check and lubricate bearings on LEV systems, including the OASIS, and check power transmission belts. In addition, consider the use of a pressure differential gauge or monitor to indicate system problems or when maintenance needs to be performed.
- Ductwork to the LEV system should be examined and cleaned periodically to ensure that the system is working properly. Capture velocities at the face of shrouds and hoods should be monitored periodically to ensure proper functioning.

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Chapter 8 Bulk Loading

CHAPTER 8: BULK LOADING

As the product stream falls from the loadout discharge point to the transport carrier (truck, railcar, barge, or ship) during bulk loading, particle separation, air entrainment, and increased particle velocity occur. Dust contained within this product stream can be liberated and emitted into the ambient air [Heitbrink et al. 1992], potentially exposing workers to respirable dust and creating nuisance dust problems. When the product stream impacts the targeted carrier, the product stream compresses and liberates additional dust into the air [Sutter et al.1982; Biere et al. 2010].

A number of factors impact the severity of dust liberation during bulk loading, including the following:

- the type and size distribution of the product;
- the moisture content of the product;
- the volume of the product being loaded and the loading rate;
- the falling distance;
- environmental factors, such as wind velocity, humidity, and rain; and
- the physical configuration of the receiving vessel (e.g., open top vs. enclosed).

The first two factors represent the physical characteristics of the product being loaded and may be defined by the process or by customer specifications. Past research has shown that larger particle size distributions and higher moisture contents typically result in less airborne respirable dust liberation. As a general rule, a moisture content of 1 percent by weight is recommended as a starting point for adding moisture to a crushed product for dust control [NIOSH 2003]. Chapter 3—Wet Spray Systems—provides a detailed discussion on using water to reduce dust liberation.

The last four factors represent the characteristics of the loading process. Past research has shown that dust liberation increases as loading rate increases [Heitbrink et al. 1992]. Similarly, dust liberation increases as falling height increases [Cheng 1973; Cooper and Arnold 1995] and with higher wind velocities. Engineering controls can be implemented to minimize the impact of these factors. For example, the falling distance can be reduced, and physical barriers can be installed to protect against high winds.

To mitigate dust during bulk loading, the following controls have been implemented in the mining industry and will be discussed in this chapter:

- loading spouts,
- conical loading hoppers, and
- enclosures.

LOADING SPOUTS

Loading spouts are designed to transfer product from a plant or storage area into carriers that will be used to transport the product. These spouts can be simple fixed tubes mounted to silos or telescoping units. Telescoping spouts have the capability of extending down to the vehicle being loaded and then retracting to provide clearance for the vehicle to move away from the loading station. A review of several loading spout manufacturer specifications shows that these telescoping spouts can travel as little as a few feet or extend up to 100 feet in other installations. As shown in Figure 8.1, these loading spouts are equipped with a series of telescoping cups or pipes that extend and retract through a cable system. This figure also shows that the spout typically has an outer shroud, which encases the product transfer section of the spout. This outer shroud shields the product from the elements (rain, wind, etc.) and helps to contain any dust that is liberated during loading.

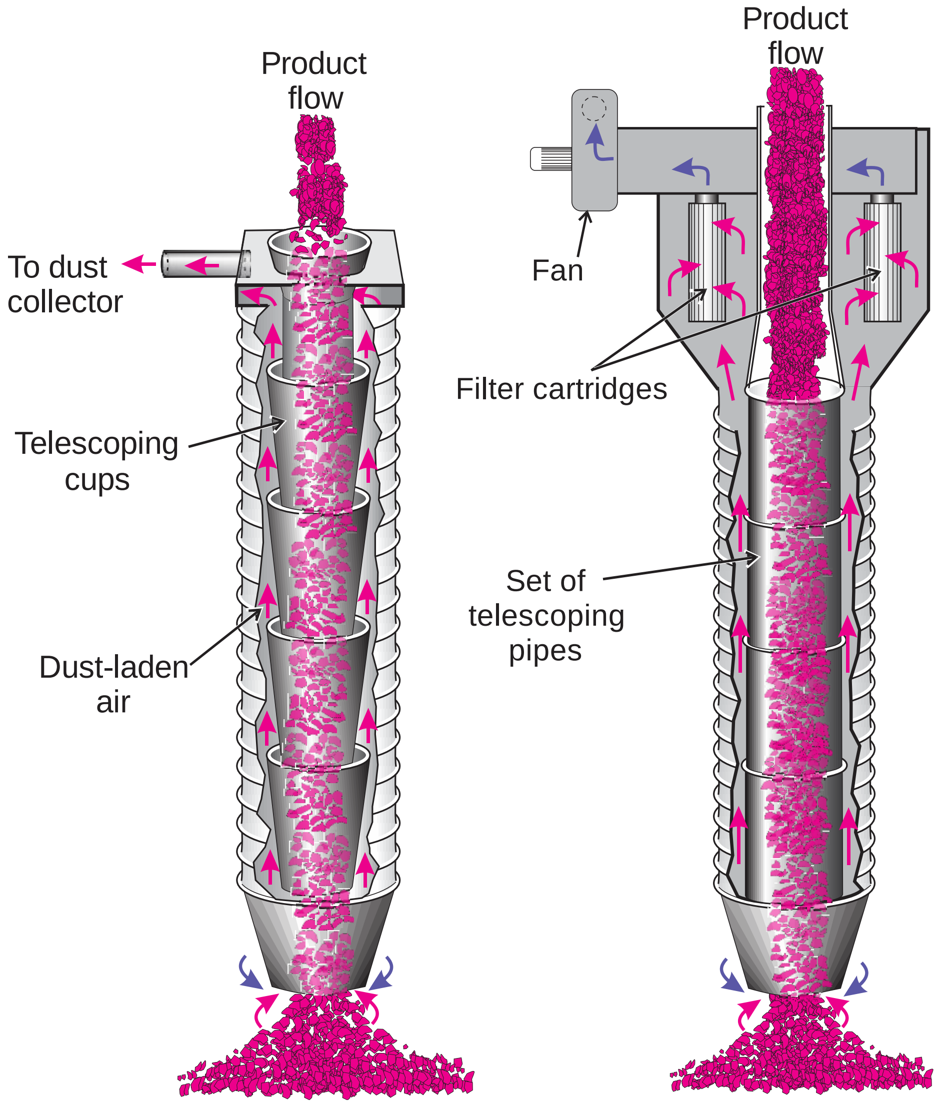


Figure 8.1. Illustration of loading spouts designed with telescoping cups or pipes and dust collection capabilities.

For receiving vehicles that are enclosed and equipped with round loading hatches (i.e., pneumatic trailers or railcars), the spout discharge can be specially designed to seal against the loading port to reduce dust escape. Typically, the spout discharge is cone-shaped, as shown in Figure 8.2, to partially enter and seal against the vehicle loading port. If the vehicle has multiple loading ports, only the ports being actively loaded should be opened. Inactive ports should remain closed to prevent dust escape, as shown in the right photo in Figure 8.2. For railcars equipped with elongated loading hatches (trough hatches), one manufacturer has designed a hatch adapter that covers the open area and is equipped with neoprene rubber to seal against the car and reduce dust escape [Vortex Global 2018].

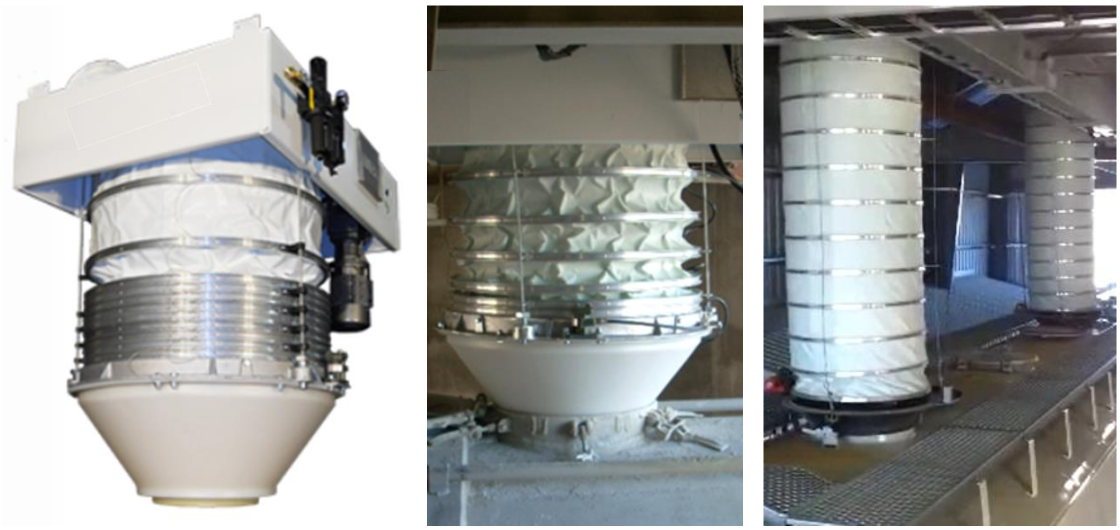


Photo by Midwest International Photo by Midwest International Photo by PEBCO

Figure 8.2. Photos of loading spout discharge cones designed to seal against the loading port of closed vehicles to minimize dust liberation.

In order to realize the benefits of the discharge cone, the loading spout must be properly positioned within the vehicle loading port to minimize the chance of dust escaping into the ambient air. This can be accomplished through the use of single- or dual-axis positioners, articulated positioners, or rotating positioners. Depending on the type used, positioners can move the loading spout side to side or forward and back, or can rotate the spout through an arc to ensure that the spout discharge is located in the optimum position in the vehicle port to minimize dust liberation and product spillage. The operator can control these adjustable loading systems from a control room or from a pendant station near the loading site. Figure 8.3 shows three different spout positioners.

Photo by Vortex Global Photo by Vortex Global Photo by DCL

Figure 8.3. Three types of loading spout positioners. The left photo shows a dual-axis positioner, the center shows a rotating positioner, and the right shows an articulating arm positioner.

When loading into open-top vehicles, the discharge end of the loading spout can be equipped with a skirt or apron that can form a seal against the product pile in an effort to minimize dust liberation from the impacting product stream. The skirts are typically fabricated from conveyor belting or heavy-weight fabric and flare out as the loaded material builds up. For the most effective dust control and to prevent clogging of the loading spout, it is important that the spout position be periodically raised as the height of the loaded material increases. To automate this procedure, the loading spouts can be equipped with tilt sensors that are suspended vertically from the spout. As the loaded material builds up, it moves these sensors from their vertical orientation (e.g., 15 degrees or more), which activates the automatic raising of the loading spout. Examples of these discharge skirts and tilt sensors are illustrated in Figure 8.4.

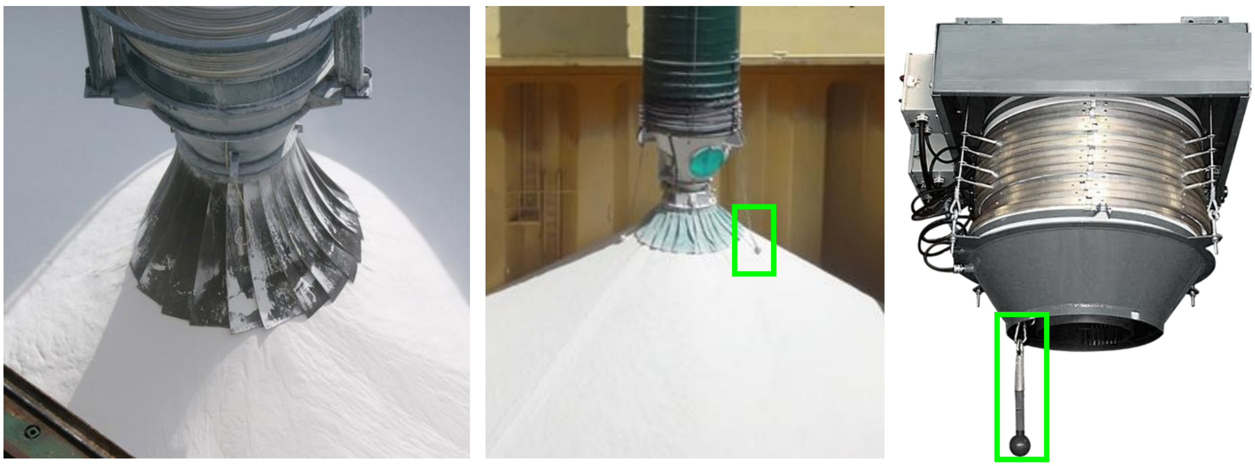


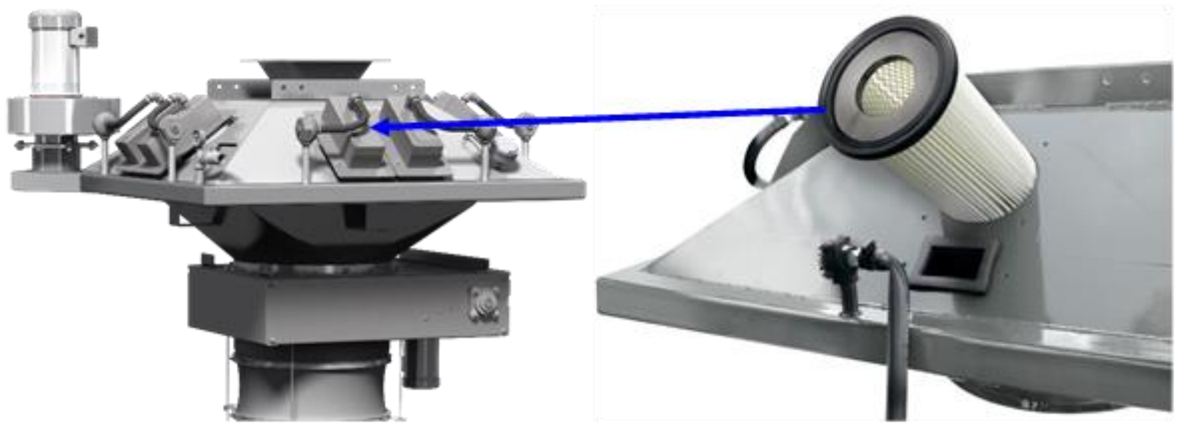
Photo by PEBCO Photo by Cleveland Cascades Photo by Vortex Global

Figure 8.4. Skirts installed on the discharge end of loading spouts to help reduce dust emissions along with tilt sensors. The left and center photos show the skirts and the green rectangles show the tilt sensors.

Dust Collection Systems and Loading Spouts

As material falls through the loading spout, airflow is induced, which can entrain dust liberated from the product. As the falling product hits the vehicle floor or previously loaded material, the material is compressed and the induced air is driven off, creating entrained dust. As the falling distance increases, the induced air is driven off with a higher velocity, which creates larger amounts of dust [Biere et al. 2010]. Chapter 2—Fundamentals of Dust Collection Systems—discusses and illustrates air induction and dust generation for falling material. When a given volume of material is loaded into a receiving vehicle, an equal volume of air in the vehicle is displaced, which can carry liberated dust with it. Equation 5.1 in Chapter 5—Crushing, Milling, and Screening—can be used to calculate the quantity of air displaced by falling material.

To address the above dust emissions during bulk loading, a common control measure is to equip the loading spout with a fan-powered dry dust collection system. These dust collection systems induce airflow in the annular region between the outer shroud and the inner loading portion of the spouts to entrain airborne dust, as shown in Figure 8.1. As the dust-laden air exits the top of the loading spout, it can be carried through ductwork to a remote dust collector (baghouse), as shown on the left in Figure 8.1. Another option is to have filter cartridges incorporated into a collection unit mounted on the top of the loading spout, as shown on the right in Figure 8.1. The right photo of Figure 8.3 and the left photo of Figure 8.5 illustrate top-mounted dust collectors. This configuration provides ready access to the filter cartridges as shown in Figure 8.5, right. Airborne dust is captured by and accumulates on these filter cartridges. Compressed air is periodically introduced to backflush the filters cartridges to dislodge captured dust and return this dust to the product stream.



Photos by Vortex Global

Figure 8.5. Photos of a top-mounted dust collection unit and an expanded view to show filter cartridge access.

A review by the handbook authors of various loading spout manufacturers' specifications indicates that dust collection systems are recommended with exhaust air volume capacities ranging from approximately two to five times the rated loading volume of the spout [SLY 2018; PEBCO 2018]. Equation 2.2 in Chapter 2—Fundamentals of Dust Collection Systems—can be used to calculate a recommended exhaust air volume based upon material feed rate, height of free-fall, product size, and feed open area. It should also be noted that if the exhaust airflow is too high, product can be pulled into the dust collection system or excessive negative pressure can potentially collapse the loading spout, as shown in Figure 8.6, left. An acceptable level of exhaust flow (negative pressure) may suck in the flexible fabric of the outer shroud but not impact the support rings, as shown in Figure 8.6, right.

Photos by Midwest International

Figure 8.6. Photos of loading spouts under different levels of negative pressure. The photo on the left shows excessive exhaust flow collapsing the spout while the photo on the right shows an acceptable level of exhaust pulling the outer shroud fabric but not collapsing the spout.

Cascading Loading Spouts

As mentioned earlier, free-falling product streams can promote dust entrainment and liberation into the ambient air during the loading process. Cascading-type loading spouts are designed with a series of inclined cones that do not permit the product to free-fall through the spout. The goal is to minimize product velocity and induced airflow movement by allowing the product to flow smoothly from one cone to the next. Figure 8.7 illustrates a loading spout designed with cascading cones.

Cascading loading spouts were originally designed to reduce product degradation. The cascading action was also thought to have the potential to lower dust emissions by reducing product velocity and promoting mass flow [Maxwell 1999]. Improved mass flow of the product allows the particles to maintain greater contact with one another and thus reduces the release of small dust particles into the air. Product flow rates can be regulated by altering the cone size, spacing, and inclination.

Typically, cascading loading spouts are not equipped with dry dust collection systems. Instead, wind shrouds and discharge skirts are the primary dust control devices utilized in these designs. Also, since there is more contact between the product and the cones than found in free-falling spouts, abrasion-resistant liners are frequently utilized inside the cones.

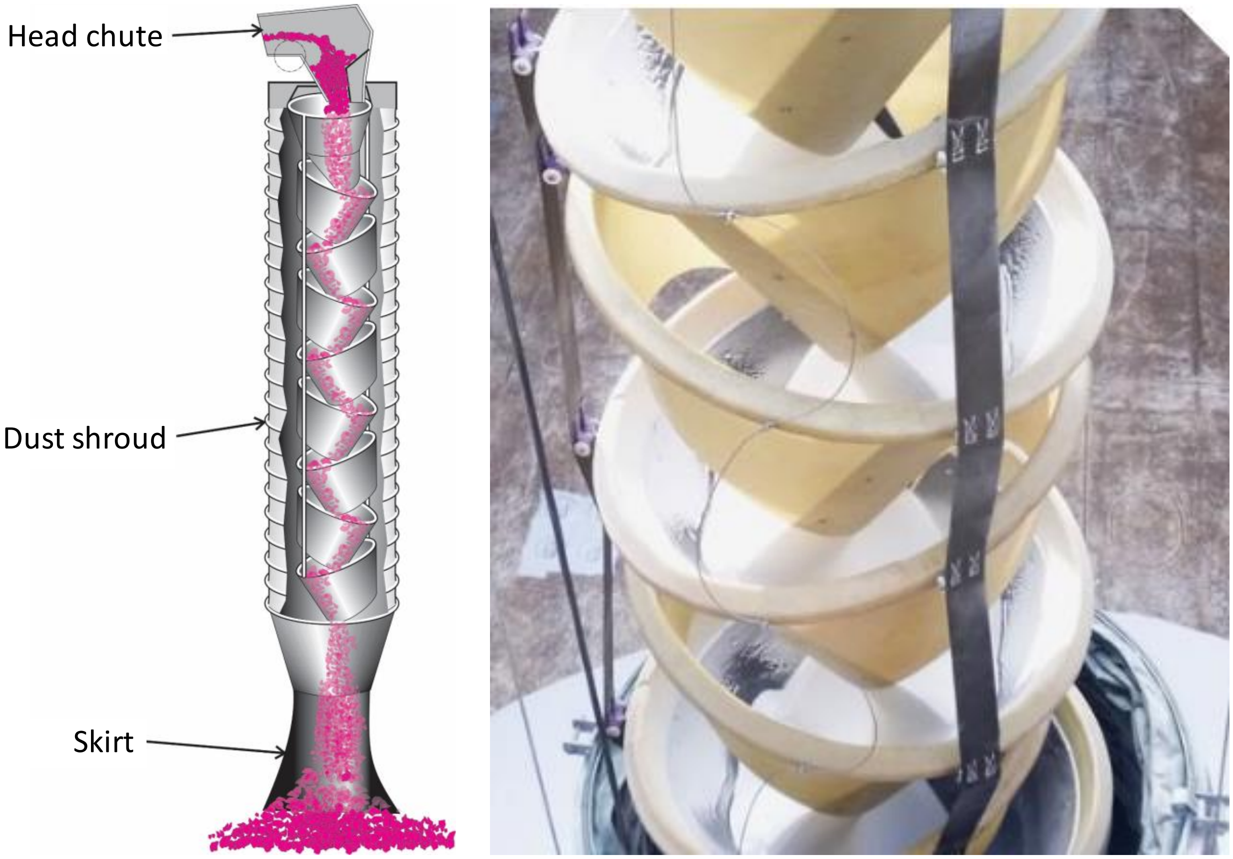


Photo by Cleveland Cascade

Figure 8.7. Illustration and photo of a cascade loading spout.

CONICAL LOADING HOPPERS

Another option that is available to potentially reduce dust emissions during bulk loading is the utilization of the Dust Suppression Hopper (DSH). The DSH is a conical-shaped hopper installed at the product discharge point and is designed to provide a simpler method to minimize dust liberation during bulk loading [Powder & Bulk Solids 2014]. The DSH is equipped with a stationary plug centered in the conical hopper. The hopper is suspended from the top frame by multiple springs that hold the hopper closed against the plug until sufficient product mass has accumulated to overcome the spring tension and lower the hopper [DSH Systems 2018]. Material then flows from the hopper in more of a solid column, as shown in Figure 8.8, rather than in a free-falling unconsolidated stream.

Based upon the stated design principle, this mode of operation provides two benefits from a dust control point of view. As product mass builds in the hopper, the pressure resulting from this increasing mass causes air trapped within the loaded product to be forced out, thus reducing air and dust liberation from the product stream when it lands in the loading vessel. In addition, when the product is discharged from the hopper, it flows in a consolidated column, which minimizes air entrainment and dust liberation during the fall to the vessel.

Photos by NIOSH

Figure 8.8. Demonstration of how a conical-shaped hopper installed at the product discharge point can minimize dust liberation during bulk loading. The left photo shows the Dust Suppression Hopper discharging a consolidated product stream versus an unconsolidated stream from a rigid spout in the right photo.

Research was conducted by NIOSH at two silica sand plants to evaluate the performance of the DSH [Colinet et al. 2018]. Results show that airborne respirable dust levels during area sampling were reduced by 88 percent compared to dust levels observed with a rigid loading spout at Plant A. Dust reductions of 40 percent to 85 percent were observed at Plant B, depending upon the product size being loaded, compared to dust levels observed with a retracted telescopic loading spout.

ENCLOSURES

During bulk loading, the preferred method of dust control is to prevent dust from becoming airborne. However, if dust is released into the ambient air, efforts must be made to keep the dust from reaching the breathing zone of surrounding workers. This can be accomplished by enclosing the dust-generating process or enclosing the worker. Both of these methods are discussed and illustrated below.

Enclosed Loadout

The goal of enclosing the loadout area is to contain and capture the airborne dust so that it cannot reach the breathing zone of nearby workers or contaminate the surrounding environment.

Typically, this type of control will be used for the loading of trucks or railcars. Essentially, a physical barrier is constructed that confines the dust that is generated as loading occurs. The barrier also minimizes the impact of environmental factors, such as high wind velocities.

Barriers can be permanent walls with flexible plastic stripping, belting, or curtain used to provide a seal at the vehicle entry and exit points. Alternatively, flexible plastic stripping or curtains can be used to construct the entire enclosure, as shown in Figure 8.9. In either case, the individual pieces of flexible material should overlap one another to provide a more effective barrier against the possibility of dust escaping.

To further prevent dust escape, the enclosure should be supplemented with a dry dust collection system. Equation 5.2 in Chapter 5—Crushing, Milling, and Screening—can be used to calculate an initial exhaust volume for the dry dust collector. If dust is seen escaping the enclosure, it is an indication that an effective seal is not being maintained, that the exhaust air quantity is not sufficient, or both.

Photo by Unimin

Photo by Dust Control Technologies

Figure 8.9. Two options for enclosing a loadout area to contain and capture airborne dust. The left photo shows plastic strips enclosing a railcar loadout. The right photo shows wind fence material enclosing a truck loading area at a plant.

During loading and until all liberated dust is cleared, personnel should not be allowed to enter the enclosed loading area. Therefore, the loading process should be designed so that it is not necessary for personnel to enter the enclosure. The following issues should be considered when designing the loading process and the loadout area.

- Vehicle hatches should be opened and closed outside of the enclosure.
- Cameras can be installed to assist the operator in properly positioning the loading spout to minimize dust generation and spillage.
- Automatic level sensors should be installed to signal to the operator when the vehicle is fully loaded or to automatically shut off the feed. Several types of sensor technologies are available and include tilt, pressure, capacitance, and infrared. This automation allows the operator to maintain a more remote position from the area where dust might be generated.

- The loading spout can be raised automatically after the vehicle is loaded to a predefined height, which allows the vehicle to move away without the spout being fully retracted. This ensures that sufficient clearance is available and reduces the time required to begin the loading of the next vehicle. Level sensors and limit switches can be used to help accomplish this automation effort.
- If personnel must enter the enclosure, dust concentrations within the enclosure should be quantified in order to ensure that appropriate respiratory protection is provided and utilized.

Operator Booths/Control Rooms

One of the most effective means of protecting a worker associated with a dust-generating operation can be the utilization of a booth/control room that provides filtered air to positively pressurize the inside of the enclosure. Previous research has shown that properly operating filtration systems installed on enclosed compartments can provide over 90 percent reductions in respirable dust exposures [NIOSH 2008]. Another advantage of these booths is that they can be equipped with air-conditioning and heating systems to make the work environment more comfortable for the operator. Figure 8.10 shows interior and exterior views of enclosed operator booths.

From a dust control engineering standpoint, the goal is to provide a well-designed operator booth that is positively pressurized with filtered air. The positive pressure within the booth prevents dust that may be present outside of the booth from leaking in and exposing the worker. Chapter 10—Filtration and Pressurization Systems for Environmental Enclosures—provides detailed information regarding the design and operation of filtration/pressurization systems for operator compartments.

Photo by Unimin

Photo by NIOSH

Figure 8.10. Two views of an environmentally controlled operator booth to protect the worker from dust exposure. The left photo shows an interior view of a booth. The right photo shows an exterior view.

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Chapter 9: Controls for Secondary Sources

CHAPTER 9: CONTROLS FOR SECONDARY SOURCES

This chapter discusses various types of secondary dust sources frequently found in industrial minerals and mining processing facilities that may have a significant impact on workers' respirable dust exposures. In some cases, workers' personal respirable dust exposure can be more significant from secondary sources than from exposures resulting from their primary job functions. Due to this potential impact, these dust sources need to be recognized, identified, assessed, and controlled.

The use of video exposure monitoring (VEM) was discussed in Chapter 1—Overview of Dust Exposure Assessment and Control—as a viable method to assess how, when, and where workers are being exposed to respirable dust [Gressel et al. 1988; McGlothlin 2009; NIOSH 1992, 2014; Rosen and Lundstrom 1987; Rosen and Andersson 1989; Rosen et al. 2005]. Numerous studies have highlighted advancements and strides using VEM assessment techniques, including the Helmet-CAM and EVADE (Enhanced Video Analysis of Dust Exposures) software developed by the National Institute for Occupational Safety and Health (NIOSH) to quickly perform assessments and identify common tasks, areas, and sources of elevated respirable dust exposures in industrial mineral mining and processing operations [Cecala et al. 2017; Haas and Cecala 2017; Haas and Cecala 2015; Cecala et al. 2015; Cecala and O'Brien 2014; Cecala et al. 2013; Joy 2013]. The following list provides common examples identified in these studies of the sources that exposed workers to elevated levels of respirable dust.

- Dusty work clothing, hands, and gloves.
- Dust-laden cloth seats and chairs in mobile equipment, light utility fleet vehicles, labs, various work locations, and break rooms.
- Lack of general ventilation within facilities and structures.
- Lack of filtration and pressurization of air for labs, enclosed areas, and rooms.
- Changing and cleaning of screens used for product sizing.
- Poor housekeeping practices—e.g., spraying or hosing down areas around the plant site using a forceful water spray jet.
- Using or maneuvering dust-laden items while performing tasks—e.g., opening handles, bolts, installing new items stored on location in cardboard boxes, stacking bags, tying bulk bags (flexible intermediate bulk containers), as well as using open-cell foam padding to work or kneel on while performing a variety of tasks.

The remainder of this chapter discusses common secondary dust sources and provides available technologies to lower workers' respirable dust exposures. In some cases, a short initial introductory section is provided to indicate the potential magnitude of the respirable dust exposure that has been identified with the secondary dust sources.

CLEANING CONTAMINATED WORK CLOTHING

Background

A significant area of respirable dust exposure to workers in all types of industries is from contaminated work clothing [Abelmann et al. 2017; Bohne and Cohen 1985; Chan et al. 2000; Chiaradia et al. 1997; Cohen and Positano 1986]. It must be noted that once clothing becomes contaminated, it is a continual source of dust exposure to the miner until the clothing is either changed or cleaned.

A study from many years ago identified that the level of contamination from dust-laden work clothing can be significant, and in one reported case, a 10-fold increase in a worker's respirable dust exposure was documented [USBM 1986]. In another more recent example, contaminated work clothing was again identified, but in this case, there was a comparison of two miners working side by side [Cecala et al. 2017]. Since outside temperatures were low during this assessment, both maintenance workers were wearing very similar cotton "hoodie" type sweatshirts. A VEM analysis showed that one worker's respirable dust exposure was significantly higher than that of his coworker even though they were working side by side in a contained area performing the same task. Footage from the VEM revealed that the source of the elevated exposure was the worker's sweatshirt, which had not been recently laundered and was visibly dusty. As this worker performed his normal work duties, respirable dust was being liberated from his dusty sweatshirt and was significantly increasing his exposure.

In further analysis, a 12-minute time segment was analyzed for both miners working inside the same baghouse dust collector changing tubular bags. From this comparison, it was determined that the respirable dust exposure for the worker wearing the dust-laden sweatshirt was approximately three times higher than that of his coworker, with an average respirable dust exposure of 73.58 $\mu g/m^3$ compared to 26.50 $\mu g/m^3$, respectively.

Figure 9.1 is a screenshot from the EVADE software showing both worker's videos and respirable dust exposures during this time period. Both examples indicate the significant impact that contaminated work clothing can have on miners' respirable dust exposures.

Currently in the U.S., except for when a petition for modification for a variance is granted through the Mine Safety and Health Administration (MSHA) for an alternative solution,[19] the only approved method for cleaning work clothes in the mining industry is to use a vacuuming system that uses a high-efficiency particulate air (HEPA) filter. This makes the clothes cleaning effort both time-consuming and unlikely to be performed effectively. It is very difficult for a worker to effectively vacuum his or her clothing, particularly in hard-to-reach areas of the back, including the backs of legs and arms.

The use of compressed air to remove dust from work clothing is prohibited by MSHA; however, because the vacuuming method is very time-consuming and ineffective, workers may attempt to use this prohibited method of a single compressed air hose to blow the dust from their clothing. Although this is a slightly more effective cleaning method than the vacuuming technique, it is

[19] See, for example, Petition—Docket No. M-2007-009-M, at https://www.msha.gov/regulations/rulemaking/petitions-modification/petition-docket-no-m-2007-009-m.

also time-consuming and the worker still has difficulty cleaning the same hard-to-reach areas. The primary concern with the blowing technique is that it creates a dust cloud, elevating respirable dust levels for both the worker and coworkers in the same work environment [Pollock et al. 2005].

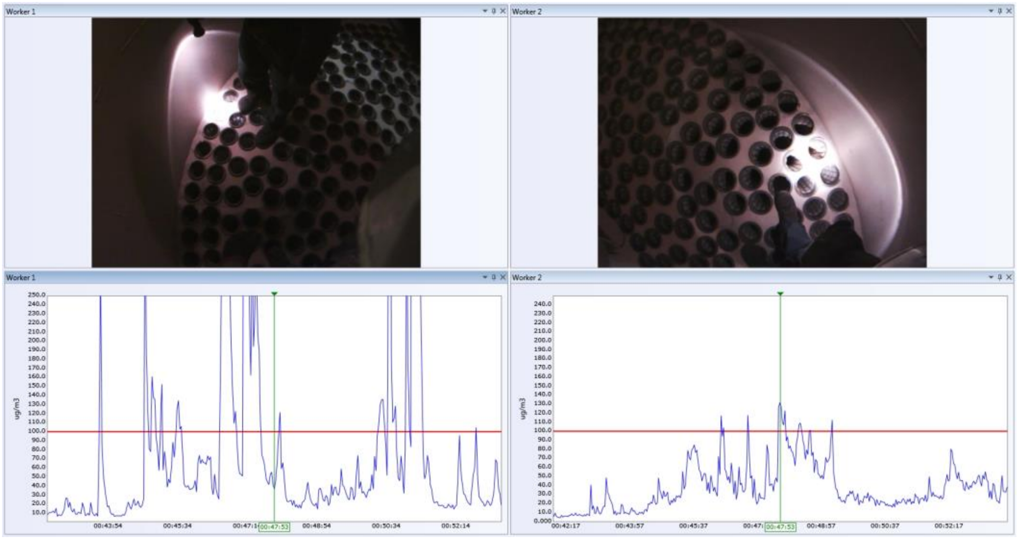

Figure 9.1. Screenshot from the EVADE software showing video stills and respirable dust exposures for two coworkers. The video stills and graphs show respirable dust exposures for Worker 1 (left) and Worker 2 (right) while changing filter canisters inside the same local exhaust ventilation system at the same time (i.e., in the same confined space). Note that the respirable dust exposure of Worker 1, who was wearing a contaminated sweatshirt, was three times higher than that of Worker 2.

Once a worker's clothing becomes contaminated, dust is continually emitted from the material as the worker performs normal work activities and the clothing moves and flexes. Since workers are exposed to multiple dust sources throughout the day that contaminate their clothing, the most effective solution is to change the contaminated clothing with clean clothing. Although this is theoretically possible, it is not a viable option in most instances for many reasons—time and expense being two of the most obvious.

Another well-known solution used in some industries is the use of disposable coveralls. However, due to a plethora of issues, including heat retention, inconvenience, and costs, disposable coveralls are not typically used in industrial minerals and mining applications.

One last area investigated over the years has been the use of new and improved clothing materials that are less susceptible to dust retention. Once again, however, these have been shown to be costlier, and the vast majority of miners continue to wear standard work clothing (typically denim cotton material) [Langenhove and Hertleer 2004; Hartsky et al. 2000; Salusbury 2004].

To address the issues described above, a quick, safe, and effective method was developed that allows workers to clean their dust-contaminated clothing periodically as necessary throughout the workday.

Technology for Cleaning Dust from Work Clothing

A cooperative research effort between Unimin Corporation and NIOSH led to the development of a clothes cleaning booth system technology.[20] This technology was not intended to eliminate the need to launder work clothing, but to provide an interim solution that allows workers to safely remove dust from their work clothing periodically throughout the day until laundering can be performed.

The clothes cleaning system developed under this cooperative research effort consists of four major components: (1) a cleaning booth, (2) an air reservoir, (3) an air spray manifold, and (4) an exhaust ventilation system. Figure 9.2 represents the design of the clothes cleaning system.

To perform the clothes cleaning process with this system, a worker wearing personal protective equipment (respirator, eye, and hearing protection) simply enters the cleaning booth, activates a start button, and rotates in front of the air spray manifold while dust is blown from the clothing via forced air. After a short time period (18 seconds), the air spray manifold is electronically deactivated, and the worker can exit the booth with significantly cleaner work clothing.

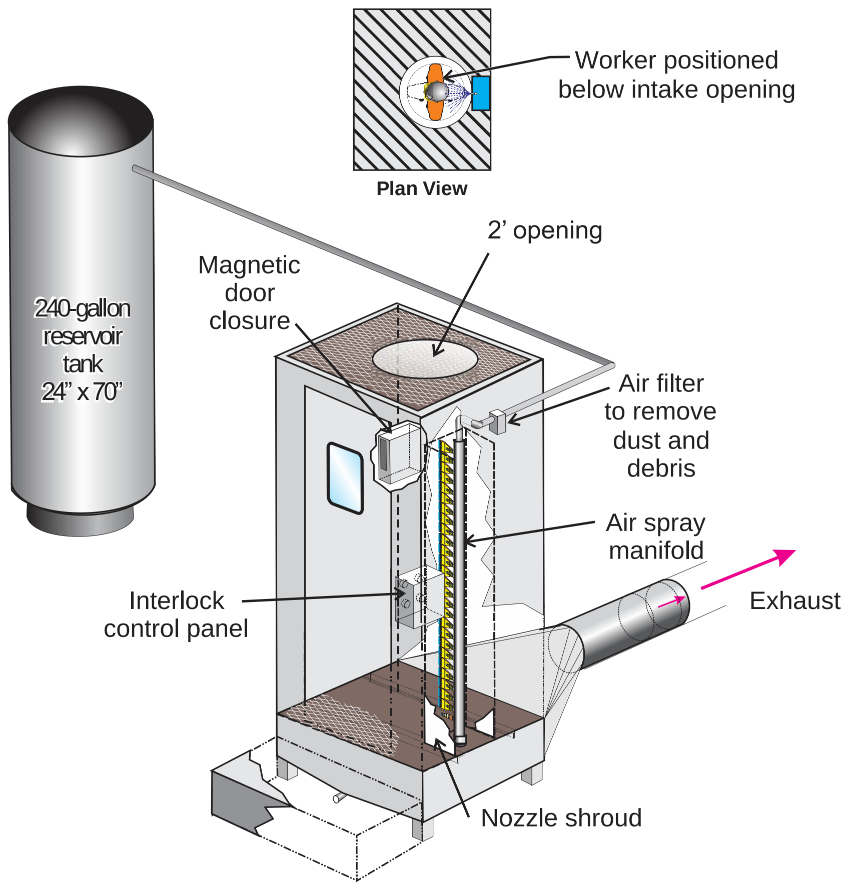

Figure 9.2. Illustration of the overall design of a clothes cleaning system.

[20] Clothes Cleaning Systems, SK Bowling, Inc. http://clothescleaningsystems.com/.

Clothes Cleaning Booth

The cross section of the clothes cleaning booth is 48 by 42 inches, providing the worker with sufficient space to rotate in front of the air nozzles to perform the cleaning process. Intake air enters the booth through a 2-foot circular opening directly above where the worker typically stands, and then the air flows down through the enclosure before exiting through grating over the entire floor area. As this intake air flows through the booth, it entrains dust removed from the worker's clothing during the cleaning process and forces it down toward the air plenum and away from the worker's breathing zone. The exhausted dust-laden air then travels from this air plenum at the base of the booth to the exhaust ventilation system.

Air Reservoir

The air reservoir is necessary to supply the required air volume to the air nozzles used in the spray manifold. The size requirement for the reservoir was calculated based upon the design of the manifold. Either a 120- or 240-gallon reservoir should be used, depending on the number of workers needing to clean their clothes in sequence. The average cleaning time required during field testing was about 18 seconds, and the 120-gallon reservoir provides approximately 22 seconds of air capacity. If multiple individuals will be using the booth one after another, then the 240-gallon reservoir should be used. This reservoir should be pressurized to at least 150 pounds-force per square inch gauge (psig), and it should be located close to the cleaning booth and hard-piped to the air spray manifold located in the booth. A pressure regulator must be installed immediately before the air spray manifold to regulate the nozzle pressure to a maximum of 30 psig.

Air Spray Manifold

Figure 9.3 represents the air spray manifold design, which is composed of 26 spray nozzles spaced two inches apart. The bottom nozzle is located six inches from the floor and is a circular-designed nozzle for cleaning the worker's boots. This nozzle is used in conjunction with an adjustable ball-type fitting so that it can be directed downward. The other 25 air spray nozzles are flat fan sprays, which lab testing proved to be the most effective for cleaning at close distances. The air spray nozzles deliver slightly less than 500 cubic feet per minute (cfm) of air.

Based upon an MSHA request, the original air spray manifold was designed for a worker being 5 feet 10 inches—the average height of a male worker in the U.S. For shorter workers, a sliding mechanism is used to cover the top air nozzles to prevent discharged air from directly hitting the individual's face.

An in-line filter should also be incorporated between the compressed air supply and the air spray manifold. This filter substantially reduces the potential for foreign material, such as a metal burr or rust particle, to be blown from an air spray nozzle during cleaning.

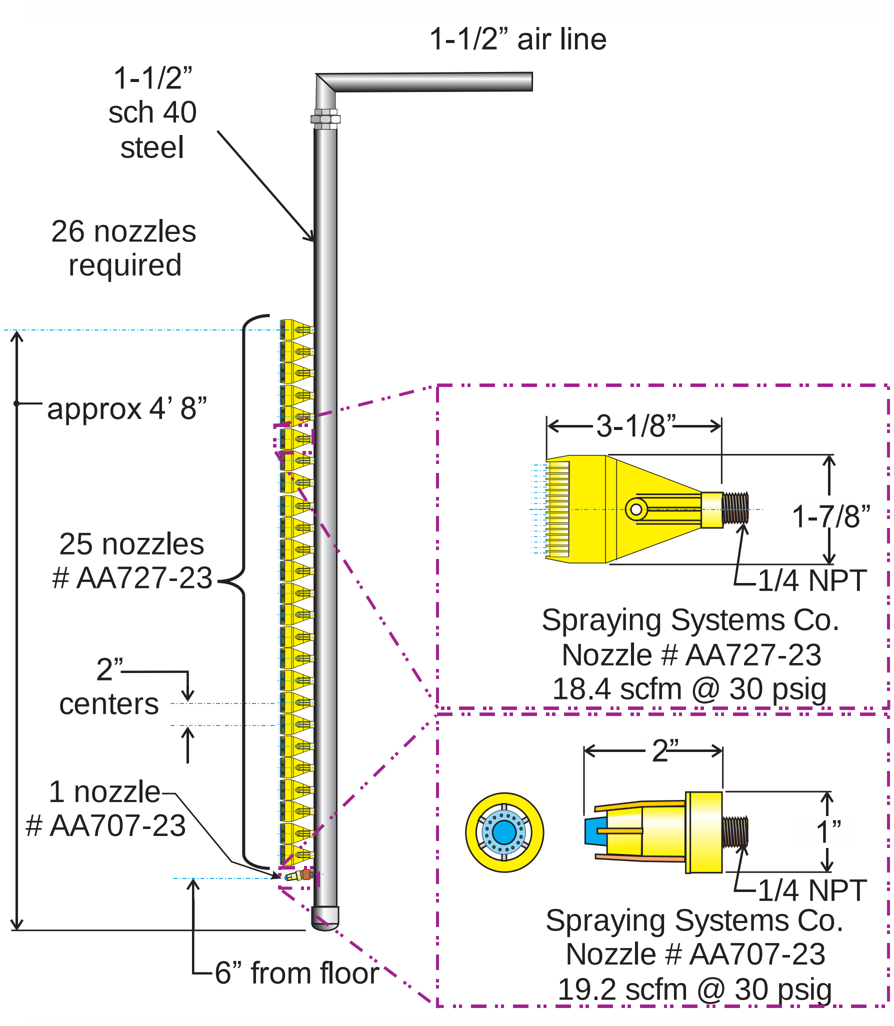

Figure 9.3. Air spray manifold design with 26 nozzles spaced two inches apart.

Exhaust Ventilation

For effective dust removal, it is critical that the cleaning booth be continually under negative pressure to prevent any dust removed from the clothing to escape the booth and enter the work environment. In the design stage of this technology, testing validated that an exhaust volume of 2,000 cfm was sufficient to maintain a negative pressure throughout the entire clothes cleaning cycle. A pressure control switch is also incorporated into the system, which will not allow the air spray manifold to activate unless an acceptable negative pressure is maintained within the cleaning booth.

To exhaust the dust-laden air from the cleaning booth, there are three recommended methods, as described below.

1. The dust can be filtered through a HEPA filter before being directed back into the structure or outside. If this method is used, a safety measure should be in place to ensure that the HEPA filtering method is working properly and not delivering dust back into the work environment.

2. The dust can be vented to a dust collection system—e.g., via a baghouse [see Cecala et al. 2007b].
3. The dust can be vented to an area outside the plant where it will not contaminate other workers nor be entrained back into the plant [Cecala et al. 2008]. There are many dust sources outside all mineral processing plants, and the amount of dust-laden air ducted outside for this application is minor in comparison to other sources.

Safety Issues

All personnel entering the cleaning booth must wear personal protective equipment, including an approved fit-tested respirator with filters that are acceptable for the material being processed as well as hearing and eye protection. In addition, based upon the pressure regulation mandated by the Occupational Safety and Health Administration (OSHA), the air pressure at the air spray manifold must be regulated to a maximum of 30 psig before being directed toward the individual performing the clothes cleaning process. In addition, in order for MSHA to grant a petition of modification to use this method, the system's air pressure regulator must be contained in a lock box with the key controlled by the plant manager to prevent regulator tampering.

Effectiveness of Clothes Cleaning Technology

During development, the clothes cleaning technology was compared to both the MSHA-approved vacuuming approach and a single handheld compressed air hose. In this testing, several 100-percent cotton and cotton/polyester blend coveralls were soiled with limestone dust before the worker entered the clothes cleaning booth. Table 9.1 shows the three cleaning methods, their effectiveness in cleaning dust off the two types of coveralls, and the time it took the worker to perform the cleaning task. Clearly, the clothes cleaning system was much more effective at removing the dust than the other two approaches and required only a fraction of the time—17 to 18 seconds compared to an average of 372 seconds for vacuuming and an average of 178 seconds for the handheld compressed air hose. Table 9.1 also shows that the polyester/cotton blend coveralls were cleaned more effectively than the 100-percent cotton coveralls. To further demonstrate the effectiveness of the clothes cleaning system, Figure 9.4 depicts a worker before and after entering the clothes cleaning booth.

Table 9.1. Amount of dust remaining on coveralls after cleaning and the cleaning time for 100 percent cotton and polyester/cotton blend coveralls

	100% Cotton		**Polyester/Cotton Blend**	
Cleaning method	Dust remaining on coveralls, grams	Cleaning time, seconds	Dust remaining on coveralls, grams	Cleaning time, seconds
Vacuuming	63.1	398	45.5	346
Air hose	68.8	183	48.4	173
Clothes cleaning booth	42.3	17	21.9	18

Photos by NIOSH

Figure 9.4. Test subject wearing polyester/cotton blend coveralls before and after using the clothes cleaning booth.

More recent research conducted by NIOSH at a number of industrial mineral mine sites continued to show the validity of the clothes cleaning technology [Haas and Cecala 2017]. For example, one worker's contaminated work clothing was evaluated from pre- and post-dust VEM exposure assessments, which documented that the clothes cleaning booth technology reduced the worker's respirable dust exposure peaks by approximately 88 percent. Though this represents a dramatic reduction in dust exposure, it is important to emphasize that this engineering control must be used by workers consistently to have a cumulative effect on health outcomes.

Status of Clothes Cleaning Technology Usage

Regulations

In the United States, two federal regulations exist that impact the clothes cleaning process and that needed to be addressed to successfully develop the clothes cleaning booth, as cited and described below.

> *MSHA standard 30 CFR 56.13020*: “At no time shall compressed air be directed toward a person. When compressed air is used, all necessary precautions shall be taken to protect persons from injury” [Use of compressed air, 2018]. In the clothes cleaning booth, a deflector mechanism was incorporated into the air spray manifold, which allows the top air nozzles to be covered over when shorter individuals are performing the cleaning process. This only allows the nozzles to impact the worker’s clothing and not the worker’s face.
>
> *OSHA standard 29 CFR 1910.242(b)*: “Compressed air shall not be used for cleaning purposes except where reduced to less than 30 psig and then only with effective chip guard and personal protective equipment” [OSHA 2018]. This regulation established the 30-psig limit for the maximum air pressure for the air spray manifold used in the clothes cleaning booth.

Because of these federal standards, mining operations must file a petition of modification through their MSHA District Office to obtain approval to install and use a clothes cleaning system at their facilities. Since this system has already been approved by MSHA for use at many mining operations throughout the country, it is a simple and straightforward approval process.[21]

Commercial Manufacturers of Clothes Cleaning Technology

There are a number of known companies selling clothes cleaning systems to remove dust and contaminants from workers clothing. To date, two companies[22] are offering units that appear to be very similar to the cleaning technology outlined above (see Figure 9.5). All of the key elements of these systems are similar to the technology developed through the NIOSH/Unimin cooperative research effort and should provide similar clothes cleaning results as tested by NIOSH.

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[21] For any operations interested in assistance with this MSHA approval process, contact the Industrial Minerals Association–North America at http://www.ima-na.org.

[22] These units are the Tempest WindDraft, sold by Clothes Cleaning Systems (http://clothescleaningsystems.com/models.html), and the Bat Booth, sold by Mideco (https://www.mideco.com.au/personnel-de-dusting-booth).

Photo by Clothes Cleaning Systems

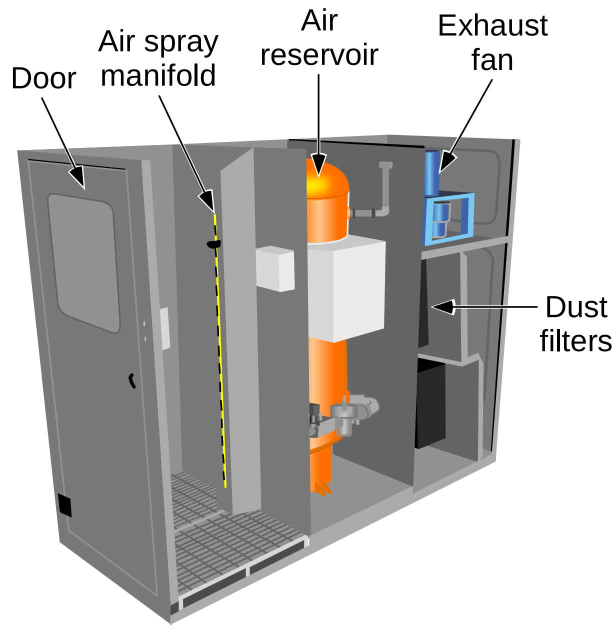

Illustration based on Mideco design.

Figure 9.5. Two clothes cleaning systems using compressed air at 30 psig to remove dust from work clothing.

Other Companies Offering Clothes Cleaning Technology

There are also two other companies[23] offering clothes cleaning systems that are similar to those described above but that use a completely different method for supplying air to the cleaning nozzles (see Figure 9.6). In both applications, the cleaning process occurs in a similar-sized cleaning booth, and the airflow direction in the booth is downward and exhausts from the floor in an effort to minimize contaminants in the user's breathing zone.

The major difference in these two applications compared to the NIOSH/Unimin design is that the actual clothes cleaning is not provided from a series of compressed air nozzles at the 30-psig pressure, but instead via air nozzles at high velocities delivered from a blower fan. This eliminates the need for a 120- or 240-gallon air reservoir to house the air volume necessary for the multiple air nozzles. In these applications, the air delivery from the blower flows directly to the nozzle or nozzles. Since blower systems are only capable of achieving air pressures up to approximately 10 psig, this represents a significant difference from the original NIOSH/Unimin design. In the original design, the clothes cleaning is from approximately 500 cfm of air directed through 26 sprays nozzles at 30 psig. In these two applications, the clothes cleaning is from a high-velocity air nozzle or nozzles at approximately 10 psig.

Although this specific air delivery application has not been tested or compared to the cleaning effectiveness of the NIOSH/Unimin design, this technology has been used for many years and

[23] These units are the Personnel-Cleaning Booth, which uses a single blow-off nozzle, sold by Air Control Industries (https://www.aircontrolindustries.com/us/products/dust-removal-systems/cleaning-booths/), and the "BOB" Blow Off Booth, sold by Filter-1 Air Filtration Engineering and Manufacturers (http://filter-1.com/products/bob-decontamination-blow-off-booths/).

has wide application throughout a number of industries. Because this technology has not been tested in a comparative study to the NIOSH/Unimin technology, the information provided comes with the caveat that it might not provide as effective cleaning at the lower air pressure values.

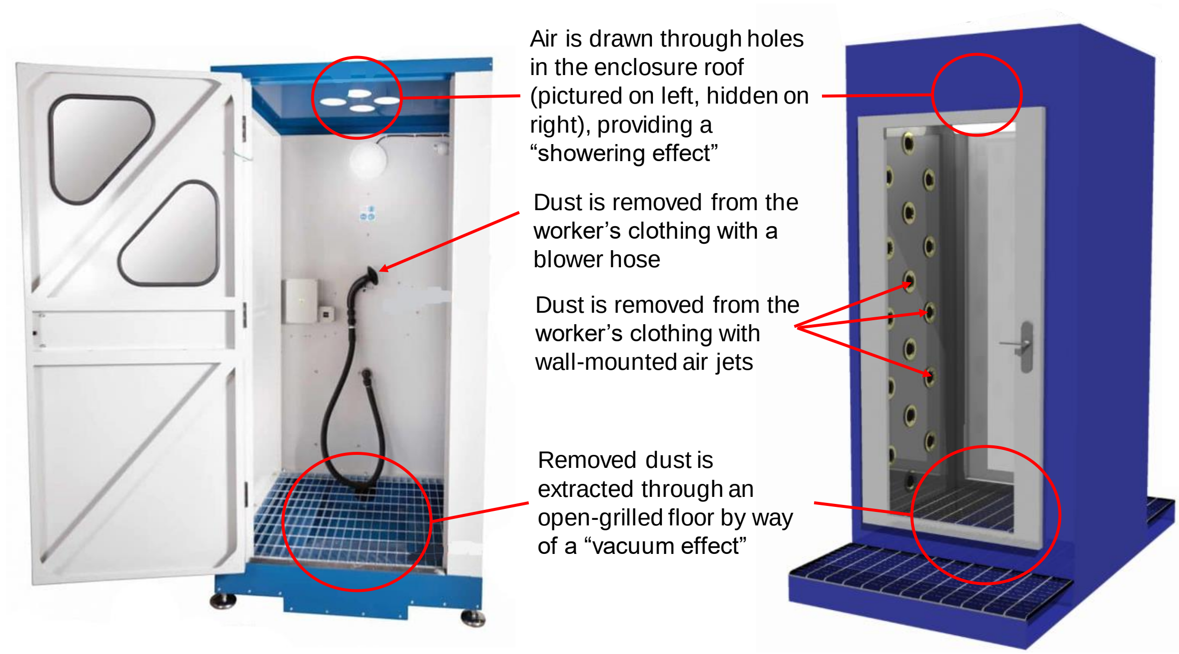

Photo by Air Control Industries   Illustration based on Filter-1 Air Filtration Engineering and Manufacturers design

Figure 9.6. Two clothes cleaning systems using high-velocity air through a blower system for removing contaminants from work clothing. Though these systems are made by different manufacturers, they have some common features, as noted in the labels.

CLEANING CONTAMINATED HANDS AND GLOVES

Background

One area that was unexpected in relation to workers' consistent respirable dust exposure from NIOSH's VEM assessments was the impact from contaminated hands or work gloves. One example of this was from a lab worker who constantly wiped his hands on his work shirt throughout the day as he was processing and analyzing work samples. This personal work habit significantly increased this worker's respirable dust exposure from the actual hand-wiping process, as well as from the impact of contaminated work clothing. As discussed earlier, once the worker's shirt became dust-laden, this was a constant source of respirable dust exposure throughout the day as dust was released from the worker's movements.

A second very common occurrence identified was workers clapping their hands or work gloves together to remove dust accumulation throughout the workday and not realizing the impact of this practice on their exposure. The example shown in a screenshot from the EVADE software in Figure 9.7 shows the impact to the worker from this event. In this case, the worker descended a flight of stairs while holding onto the handrails, which is the recommended work practice from a safety standpoint. Once reaching the landing, the worker clapped and rubbed his hands to remove the dust. Since the worker continued to walk while doing this, he walked right through the small dust cloud created from this event. In this example, the worker's respirable dust exposure was less than 10 µg/m^3 within a few seconds from the occurrence but then spiked at 1,933 µg/m^3 from clapping and rubbing his hands. When this worker observed his exposure using the EVADE software, he commented that he does this constantly throughout the workday without realizing the impact it has on his personal respirable dust exposure.

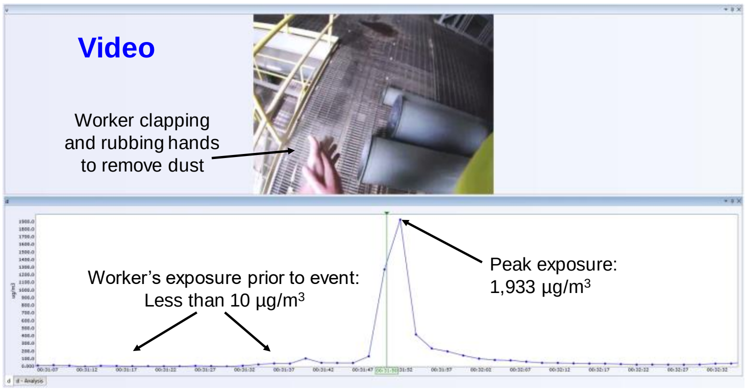

Figure 9.7. EVADE 2.0 screenshot with labels added to indicate respirable dust exposure to a worker from clapping hands to remove dust after holding handrails while going down steps.

Another area of contamination generated from hands or gloves and identified from VEM assessment technology occurred when a worker was climbing down a ladder within a facility. As the worker descended the ladder, dust was liberated from the ladder as the worker grabbed onto each rung during descent. This liberated dust then fell directly over the worker's breathing zone and thus increased the worker's respirable dust exposure, as seen in Figure 9.8. There would be a similar respirable dust exposure whether the worker was climbing or descending the ladder.

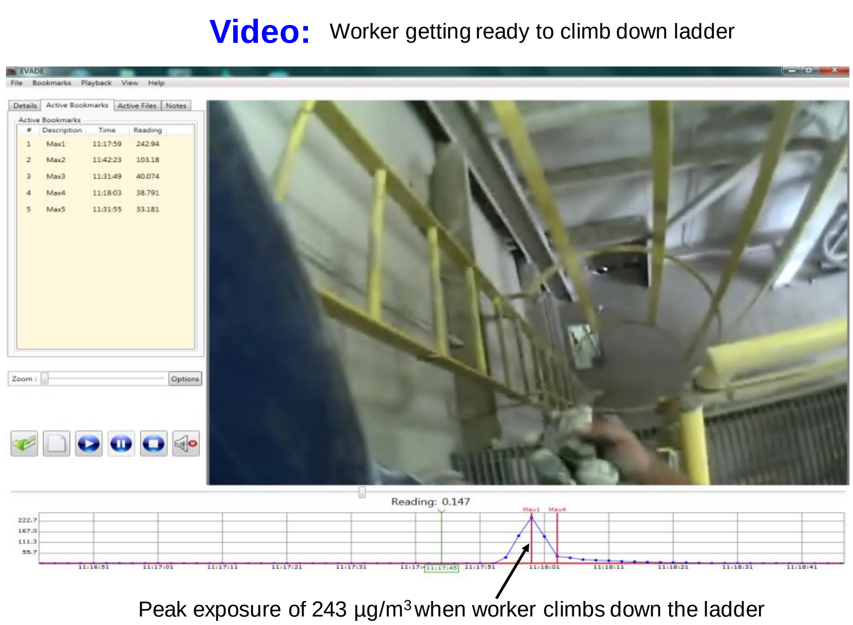

Figure 9.8. EVADE screenshot with labels added to indicate respirable dust exposure to a worker from climbing down a ladder and exposure from dust released from ladder rungs.

Solution

The best solution to reduce the dust exposure from contaminated hands or gloves is by performing good housekeeping at the end of each shift so the new crew begins with a clean work environment—thus attempting to minimize the amount of dust at the facility that gets onto workers' hands or gloves. Regardless, workers' hands or gloves will ultimately become contaminated throughout the workday. Therefore, to eliminate the respirable dust exposure from clapping and rubbing dust-laden hands or gloves, this personal work habit needs to be eliminated. When gloves are not used, it is recommended that cleaning be done simply by washing one's hands. Wearing cotton gloves or any fabric gloves that absorb and retain dust should be avoided, and it is recommended that non-absorbent material or leather gloves always be used. When using these types of gloves, the recommended cleaning method is with a moist cloth. Once again, wiping contaminated hands on one's shirt or clapping or rubbing hands to remove dust and contaminants should be avoided as a personal work practice.

To reduce dust exposure while climbing or descending from a dust-covered ladder, the best method is good housekeeping (hosing down) to minimize this respirable dust accumulation. Another engineering control is to replace the vertical ladder with traditional stairs or a very inclined device referred to as "alternating tread stairs"[24] (Figure 9.9). Both of these options provide ergonomic benefit while potentially lowering the respirable dust exposure to the worker. Although the worker is still releasing dust accumulated on the handrails from hand movement, this liberated dust does not enter the worker's breathing zone to the same extent as would occur from climbing up or down a vertical ladder, in which case the dust released from hand movement on the upper ladder rungs falls directly into the worker's breathing zone.

When space is not an issue, traditional stairs should always be the first option. When floor space is limited, the alternating tread stairs should be considered because they offer a much smaller footprint while still providing some of the ergonomic and safety advantages of traditional stairs. In one study, alternating tread stairs were perceived to be safer and more comfortable to use.[25] It must also be noted that with the alternating tread stairs, MSHA requires per 30 CFR 56/57.11011 that workers have both hands free to grasp the handrails and that they must ascend and descend in the forward-facing direction.[26]

[24] As one example, see "Alternating Tread Stairs," Lapeyre Stair, P.O. Box 50699, New Orleans, LA 70150. Phone: 504-733-6009; https://www.lapeyrestair.com/alternating-tread-stair.

[25] This study compared alternating tread stairs with the conventional ladders used on ships. For the full article, see "Performance, Perceived Safety and Comfort of the Alternating Tread Stairs," available at https://www.sciencedirect.com/science/article/pii/0003687089900057?via%3Dihub.

[26] See the MSHA presentation, "Ladder Safety Standards: Metal and Nonmetal Mine Safety and Health," available at https://www.msha.gov/sites/default/files/Alerts%20and%20Hazards/LadderSafety21B.pdf.

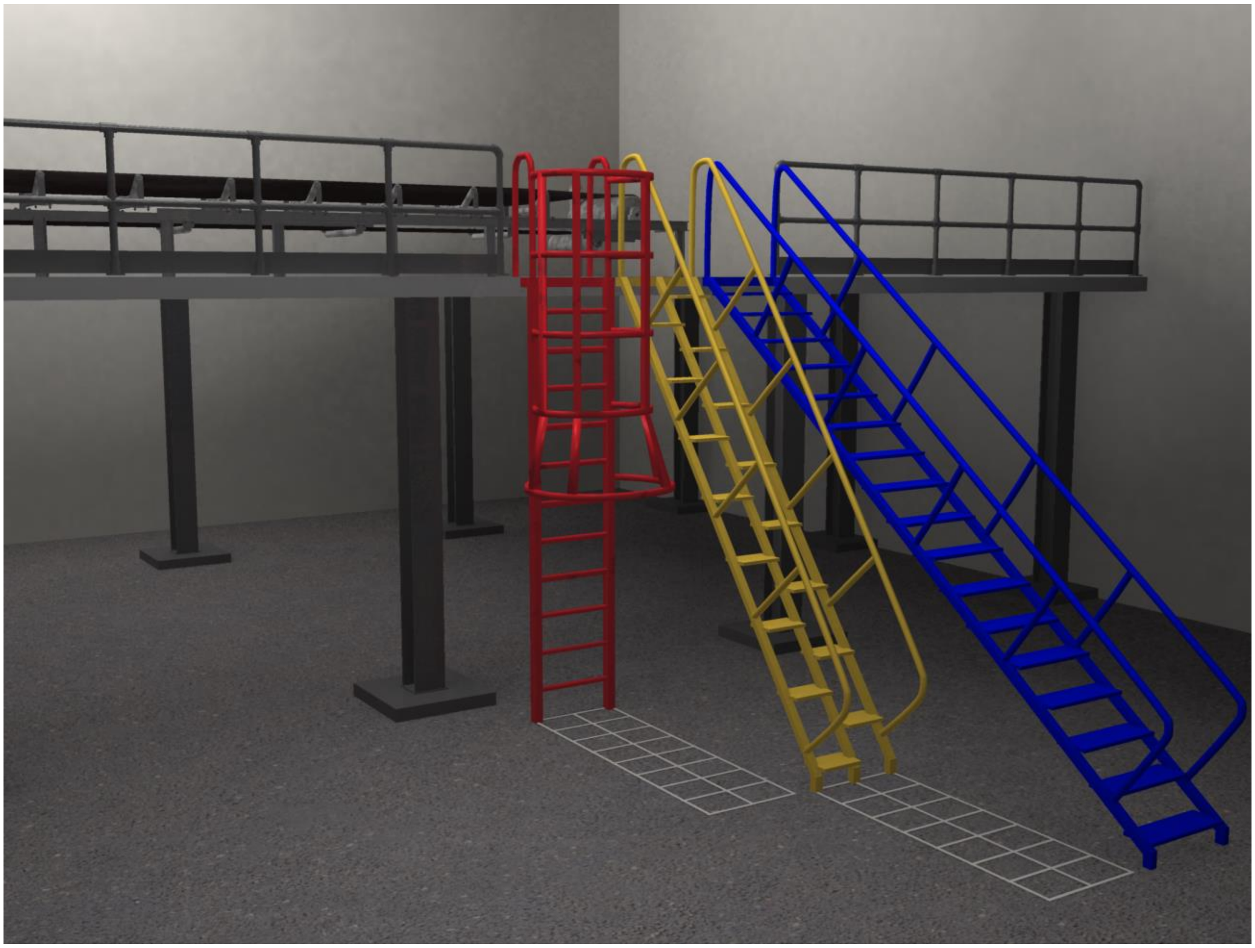

Figure 9.9. Three types of ladder designs. On the left is a vertical ladder, in the center is a ladder with alternating tread stairs, and on the right is a traditional stair design at a mine. The grids on the floor represent the relative footprints of the ladders in comparison to each other. Both the alternating tread and traditional stairs provide ergonomic advantages while also lowering workers' respirable dust exposure compared to a vertical ladder.

CLEANING DUST FROM CLOTH CHAIRS AND SEATS

Background

At many locations throughout mining operations, workers are required to sit in chairs to perform their job functions. This includes all mobile equipment operators, control room operators, crusher operators, some bag loading operators, bulk loading operators, fork lift operators, and lab workers, as well as many other site-specific applications. In addition to these workers, there are many other locations—for example, break rooms, lunch rooms, offices, conference rooms—where workers sit throughout the workday to perform various job functions or simply to take a break.

When one considers all the seats and chairs at mining facilities, there is a vast assortment of different types as well as a variety of materials and wear conditions. Two examples of seating material and wear can be seen in Figure 9.10. The photo on the left shows a seat that is so old that the seating material is completely worn away, with only the padding left behind, which is typically an open-cell foam material. Seats in this condition are the worst from a dust liberation standpoint because the open-cell foam material absorbs significant quantities of dust, and then every time a worker sits on the seat or moves around, respirable dust is liberated. The photo on the right shows a new seat in very good condition; however, any type of cloth material also absorbs and holds dust, and this material will liberate dust in a similar fashion as previously stated, although to a lesser degree than an extremely worn seat or chair.

Photo by Fotolia Photo by NIOSH

Figure 9.10. Two examples of seats that absorb and hold dust and then liberate this dust each time a worker sits or moves around. This occurs whether the seats are extremely worn (left) or new (right).

Similar occurrences were identified when open-cell material was used for padding for mechanics in shop areas, where the workers would kneel to perform tasks or lean into the engine compartment while performing repair or maintenance work. Additionally, this issue was also identified for an array of maintenance workers performing similar kneeling or leaning work in various mine work areas.

A similar problem can occur when acoustical material is used in enclosed cabs, control rooms, operator compartments, or other similar types of enclosures to minimize noise exposures to workers. When this acoustical material gets old and the outer covering deteriorates, the acoustical dampening foam becomes exposed and is typically an open-cell foam material. This then becomes a source of dust accumulation and exposure to workers, just as with cloth or exposed foam in seats or chairs. However, acoustical material is located on the walls and ceiling, so the liberation of respirable dust typically occurs because of vibrations in the enclosed cabs of mobile equipment, crusher booths, control rooms, and similar types of enclosures.

Solution

One way to remove this significant secondary dust source is to replace cloth seating material with hard molded plastic chairs or seats, leather or vinyl chairs or seats, or chair or seat coverings made of leather or vinyl. However, even with leather or vinyl seats or coverings, once the material deteriorates to a point where the foam padding is exposed, it needs to be changed with new material.

IMPLEMENTING TOTAL STRUCTURE VENTILATION DESIGN

Background

The first strategy to lower dust exposures in any structure is to have an effective primary dust control plan that captures dust at the point of origin, before it is allowed to escape out into the plant and contaminate workers. Most mineral processing plants control the dust by using standard engineering controls, such as local exhaust ventilation systems, water spray applications, scrubbers, and electrostatic precipitators (refer to Chapter 2—Fundamentals of Dust Collection Systems). These engineering controls are effective at reducing and capturing the dust generated and liberated from the primary sources at mineral processing plants; however, they do not address the continual buildup of dust from background sources, such as the following:

- product residue on walls, beams, and other equipment that becomes airborne from plant vibration or high-wind events;
- product that accumulates on walkways, steps, and access areas and may thus be released as workers move through the plant and by plant vibration;
- leakage or falling material from chutes, beltways, and dust collectors;
- lids and covers of screens that are damaged or must be removed for inspection and cleaning; and
- product released because of imperfect housekeeping practices.

Since most mineral processing structures can be considered closed systems, the background dust sources listed above, along with numerous other unnamed sources, can cause dust concentrations to continually increase as the day or shift progresses inside these closed buildings. In order to keep dust levels at safe and acceptable levels, a method needs to be used to control these background dust sources. The most effective way to achieve this is to use a total structure ventilation system.

Principles of Total Structure Ventilation

The basic principle behind the total structure ventilation design is to use clean outside air to sweep up through a building to clear and remove the dust-laden air. This upward airflow is achieved by placing exhaust fans at or near the top of the structure and away from plant personnel working both inside and outside the structure. The size and number of exhaust fans is determined based upon the initial respirable dust concentration and the total volume of the structure. All the processing equipment within a plant generates heat, which produces a thermodynamic “chimney effect” that works in conjunction with the total structure ventilation design [Cecala and Mucha 1991; USBM 1994; Cecala 1998; Cecala et al. 1995]. Figure 9.11

demonstrates the concept of the total structure ventilation design. To be effective, the total structure ventilation design must meet three criteria: a clean makeup air supply, an effective upward airflow pattern, and a competent shell structure.

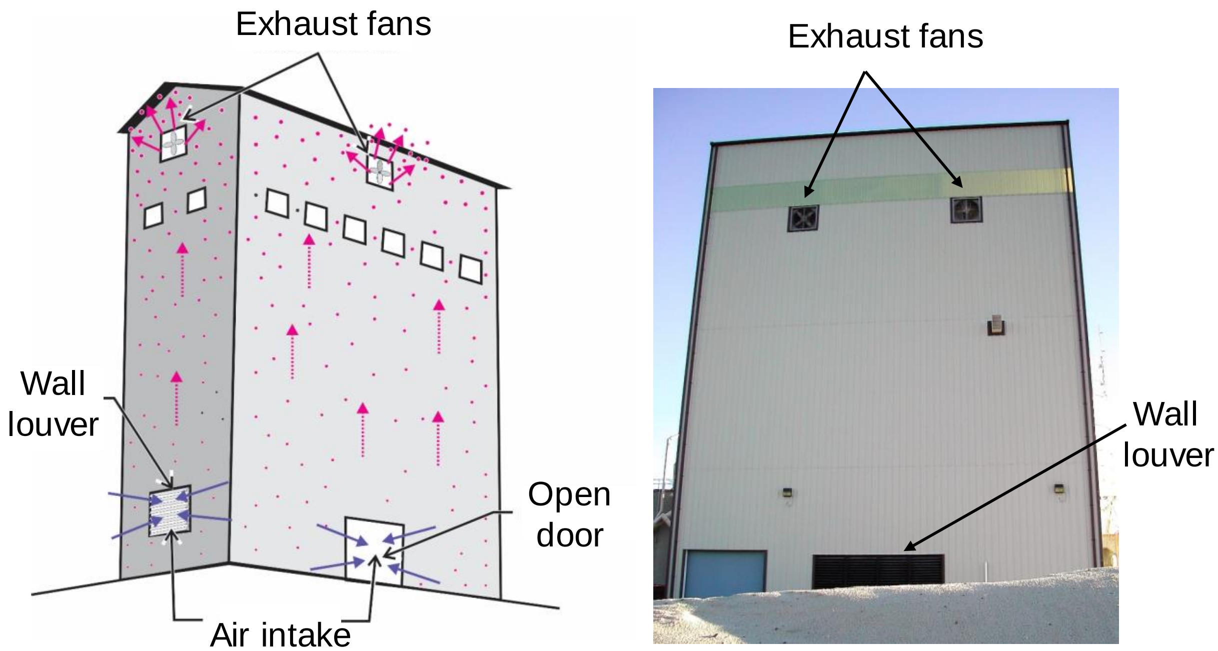

Photo by NIOSH

Figure 9.11. Illustration and photo showing the basic design of a total structure ventilation system.

Clean Makeup Air Supply

Intake air needs to be brought in at the base of the structure by strategically located wall louvers or open plant doors. It is imperative that this air be free from outside dust sources, such as bulk loading activities, high-traffic areas, etc., which could cause the dust-laden air to be drawn into the structure and would ultimately increase respirable dust levels. By using wall louvers or closing doors, the intake air locations could be changed based upon the outside dust conditions.

Effective Upward Airflow Pattern

The system must provide an effective upward airflow pattern that ventilates the entire structure by sweeping the major dust sources and work areas. Strategic positioning of both exhaust fans (high in the walls or roof) and makeup air intakes (at the base) creates the most effective airflow pattern for purging the entire building. It is important to note that total structure ventilation is not applicable to buildings with multi-story solid floors, since solid floors do not allow the air to flow up through the structure.

Competent Shell of Structure

A competent outer shell of the structure is necessary because the ventilation system draws the makeup air through the points of least resistance. Therefore, the structure's outer shell must be free of open or broken windows, holes, cracks, and openings, especially in the vicinity of the exhaust fans. The exhaust fans create negative pressure, and if the building is not structurally competent, air will be brought in from unwanted dust sources and will not allow for an effective airflow pattern for purging the building.

A normal range of airflow for a total structure ventilation design is in the 10–35 air changes per hour (acph) level and is dependent on baseline respirable dust concentration levels within the structure. During the development of the total structure ventilation design concept, two different field studies were performed to document its effectiveness. In the first study, with a 10 acph ventilation system, a 40 percent reduction in respirable dust concentrations was achieved throughout the entire structure. In the second study, the total structure ventilation system provided 17 and 34 acph. Average respirable dust reductions throughout the entire structure ranged from 47 to 74 percent for the two exhaust volumes, respectively [Cecala et al. 1995].

Variables Affecting Total Structure Ventilation

The direction of the prevailing wind is a variable that needs to be considered when initially designing a total structure ventilation design because of its impact on exhausting and possible re-entrainment of contaminants from the building. When roof exhausters are used, the impact is minor, but when wall-type exhausters are used, fans should not be placed in locations where the prevailing winds will work against them. The ideal design is to have the fan or fans exhaust with the prevailing wind direction; this also minimizes the possibility of dust being recirculated back into the plant through the makeup air.

Importantly, a total structure ventilation system increases the vulnerability of plant freeze-up problems during times of extremely low outside temperatures and must be taken into consideration. The makeup air can be heated to avoid this problem, but this is an extremely expensive proposition. A more affordable and realistic approach is to lower the ventilation volume during freeze-up air temperatures. This can be achieved by using variable-speed control fans or selectively turning off fans in a multiple-fan design. When lowering the ventilation volume is not an option, operations may want to consider providing localized heating to individual work areas.

Costs

The total structure ventilation design has proven to be one of the most cost-effective systems to lower respirable dust concentrations throughout an entire closed mineral processing structure. Not only is the initial cost of this technique inexpensive when compared to other engineering controls, but its operation and maintenance are also minimal. Operations can install all the components for this system in-house to reduce their costs.

OPEN STRUCTURE DESIGN

The outside ambient environment can be an effective source of ventilation to dilute and carry away dust generated and liberated within a structure. Therefore, in some cases, an open structure design can be used as an optimal way to provide for whole structure ventilation. In a study that compared three different building types—masonry, an open structure design, and a steel-sided design—respirable dust concentrations were significantly lower in the open structure building

[Cecala et al. 2007a; NIOSH 2006]. The open design is similar to the total structure ventilation design in that it has the potential to be a global approach to lower dust levels throughout an entire building or structure. In the open structure design, the natural environment dilutes and carries away dust liberated during operations in mineral processing structures. No dust plume should ever be visible with an open structure design. As with the total structure ventilation system, the first goal is to capture dust at the point of origin before allowing it to escape out into the plant and contaminate the work environment. The open structure design is a secondary technique to control the residual dust not captured at the source.

Figure 9.12 shows a conceptual drawing of a typical open structure design with a roof compared to an identically sized walled processing facility. If an open structure design is considered for an operation, several issues need to be addressed, as described below.

- Product residue that becomes airborne from plant vibration or high-wind events can accumulate on walls, beams, and other equipment.
- Because an open structure design must be considered a secondary design, engineering controls are still needed to eliminate the major points of origin before dust is liberated into the plant and contaminates the work environment.
- Additional effort must be made to provide safety railings and guards to minimize the potential for any personnel falling from the structure.
- Obviously, a roof provides more protection from the natural elements than a totally open design. Therefore, equipment and personnel must be protected from environmental elements, such as rain, snow, sleet, and hail. One possibility to minimize this concern would be to design a structure with a roof and sufficient overhang.
- Equipment freeze-up problems can happen when low outside air temperatures occur.

From a federal standard basis, an important consideration is the Environmental Protection Agency (EPA) opacity dust measurement [EPA 1993], which is a qualitative measurement that requires a permit. This measurement is assessed by a federal regulator based on the presence of a visible dust plume. If any plumes are visible from an operation using an open structure design, primary dust control methods need to be implemented to control the problem.

In addition to lowering dust levels throughout an entire building or structure, the open structure design can also lower workers' noise exposure because it reduces the reverberation effects by comparison to a closed structure. In a closed structure, reverberation is made up of the reflections that come from within the space—e.g., from the walls, ceiling, and objects—which depend on the dimensions of the room, absorptive properties of the space, and directivity of the noise source. In an open structure, the reverberation effects from walls and ceilings would be reduced, which could also lower workers' noise exposure.

When building new facilities, the open structure design is more cost effective because it lowers material and construction costs. Some companies may also want to consider modifying their existing structure with a more open design to further reduce dust and noise levels.

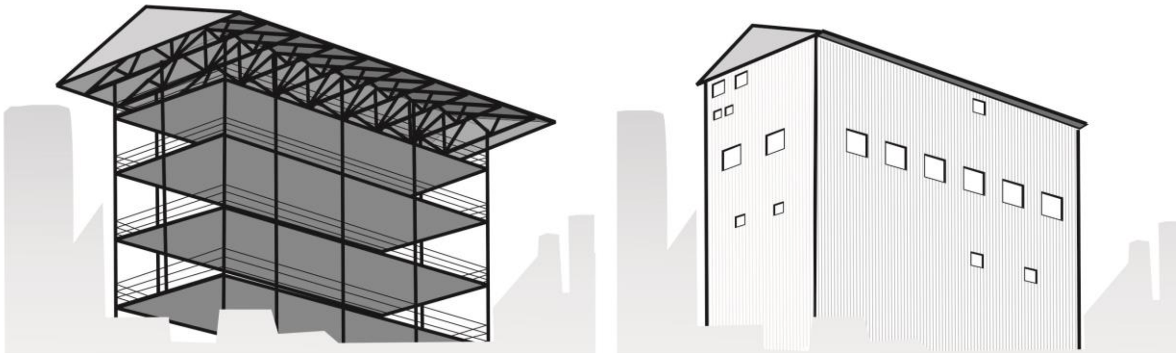

Figure 9.12. Illustration of an open structure design compared to a standard walled structure.

Federal and State Environmental Regulations

Regarding both total structure ventilation systems and open structure designs, operations need to be aware of both federal and state regulations/standards that govern discharging contaminants from industrial facilities into the environment. The federal Clean Air Act (CAA), first established in 1975, was the first comprehensive federal law that regulated emissions from both stationary and mobile sources into the environment. The CAA was amended in 1977 and 1990 to set additional goals and establish a framework to address air pollution throughout the country. Section 112 of the CAA addresses emissions of hazardous air pollutants and first required the issuance of technology-based standards. Standards developed pursuant to Section 112 of the CAA are known as the National Emissions Standards for Hazardous Air Pollutants (NESHAP). For major sources, these standards must be based on maximum achievable control technology (MACT).[27]

After the promulgation of the initial NESHAP, Section 112(d) of the CAA requires the EPA to review these technology-based standards and revise them as necessary—taking into account developments in practices, processes, and control technologies—at least every eight years. Furthermore, Section 112(f) of the CAA requires the EPA to review the remaining risks eight years after the MACT standards are promulgated. The first step in this risk review process is to determine if remaining risks are acceptable. If risks are determined to be unacceptable, the EPA must revise the standards to achieve acceptable risks, regardless of costs. If risks are acceptable, the EPA evaluates whether the standards provide an ample margin of safety to protect public health considering costs and other relevant factors.

These federal mandates were designed to be coupled with state and local governing air pollution agencies to provide those agencies with the authority to monitor for quality, inspect facilities, and enforce the standards established in the CAA. The state and local agencies oftentimes also have other rules or requirements that apply to air pollution sources to help achieve National Ambient Air Quality Standards (NAAQS) or for other reasons.

When considering the various techniques described above to minimize and control dust emissions, operators should consult with their state and local governing bodies to determine the exact standards for their facilities. As stated earlier, if both a total structure ventilation system

[27] See the Environmental Protection Agency's NESHAP page at https://www.epa.gov/stationary-sources-air-pollution/national-emission-standards-hazardous-air-pollutants-neshap-9.

and an open structure design are viewed as secondary dust control techniques, the level of contaminant should be minor and there should be no issue complying with the CAA or any state or local standards.

CLEANING THE AIR IN LABS, CONTROL ROOMS, BOOTHS, AND OTHER ENCLOSURES, INCLUDING LUNCH AND BREAK AREAS

Background

A common source of elevated respirable dust exposure to miners can be from working in areas such as sample prep labs, control rooms, operator booths, lunch and break rooms, and other similar enclosures without proper ventilation. The problem occurs when there are dust sources in these enclosed areas without any designed airflow or filtration incorporated to address the sources. The fundamental issue is similar to that described above on the total structure ventilation system but on a much smaller scale. Since these areas are closed systems, any dust sources within the lab, room, or area cause respirable concentrations to continually increase as the day or shift progresses. These dust emissions also deposit inside of the enclosure, and can therefore cause additional dust exposure problems.

One noteworthy example identified from a NIOSH VEM assessment was in a break room with cloth seats and chairs that absorbed product and dust. As multiple workers came into the break room and sat down, and then went to microwaves, vending machines, and refrigerators, they were constantly liberating dust from the chairs as well as releasing small quantities of dust that were on their shoes and work clothing. Since there were a significant number of individuals in this break room, all liberating small levels of dust, and since there was no clean air provided, respirable dust levels continually rose and were even higher than general levels out in the plant. Similar examples were found in other labs, control rooms, operator booths, and comparable enclosures throughout mining sites. In order to keep dust at safe and acceptable levels, a method must be implemented to provide clean and/or filtered air to these areas.

Methods to Lower Exposures

To control respirable dust in enclosed areas, the following viable options should be considered:

1. Provide clean air from some other areas outside to continually dilute any dust liberated with new and clean air.
2. Restrict entry to certain authorized workers to minimize dust being brought into the area.
3. Require workers with contaminated clothing to clean themselves via clothes cleaning booth systems or other similar methods, or have workers remove dust-laden outer garments before entering these areas.
4. Provide a filtration and pressurization system to filter and clean the air before workers enter these enclosed areas. This approach is outlined in detail in Chapter 10—Filtration and Pressurization Systems for Environmental Enclosures. Refer to this chapter for a detailed explanation on recommended filtration and pressurization systems for providing clean filtered air for these areas.

LOWERING DUST DURING SCREEN CLEANINGS AND CHANGES IN SCREENING AREAS

Background

NIOSH has conducted numerous VEM assessment studies to evaluate respirable dust exposures to workers who are cleaning and changing screens, and it is common knowledge in the industry that workers in these areas can experience high dust exposures. In one study, contributing factors to workers' elevated respirable dust exposures were identified as low local exhaust ventilation (LEV) airflow volumes to the screens; poor total structure ventilation air volumes in the building; and poor housekeeping practices overall, which included improper storage of the new screens before use and the storage of old screens before removal from the area for disposal (Figure 9.13) [Cecala et al. 2017]. These new screens were in cardboard boxes from the manufacturer and located near the screening machines. Over time, these boxes accumulated a significant coating of dust, which was then liberated when the screens were removed for installation by the workers, thus significantly increasing their exposure. The same was true for the storage of old screens before they were removed from the building for disposal.

In another building at this same facility, it was determined from a VEM assessment that short-term exposures to multiple workers were above 1000 $\mu g/m^3$ during the process of unclipping and removing old or damaged screen from the screen housing. Again, this is a common source of respirable dust exposure to all workers performing this task throughout the industry.

Photos by NIOSH

Figure 9.13. Examples of poor housekeeping practices with screens. The left photo shows old screens being stored before disposal. The right photo shows new screens in boxes before use.

Methods to Lower Exposures

General Principles

The following list provides general principles to minimize miners' respirable dust exposure during screen cleanings and changes as well as in screening areas in general.

- Ensure that proper LEV system ventilation is provided to each screen to achieve negative pressure and not release dust into the work environment.
- Ensure the plant building has a sufficient total structure ventilation system (a minimum of 10 air changes per hour) to keep general plant dust levels at a minimum.
- Improve general housekeeping efforts and pay special attention to the storage of new screens enclosed in cardboard boxes. Keep these boxes in a contained location as close as possible to the screening area, but do not allow them to be exposed and coated with a layer of general plant dust while waiting to be used.
- Immediately remove old screens from the screening area and the building for disposal. Allowing used screens to be stored in the area for later removal from the building allows additional dust accumulation and causes greater exposure to workers when they are ultimately removed.

During one particular VEM assessment study, after these recommendations were implemented, two workers' respirable dust exposure showed a 99 percent reduction while they were changing screens as well as an average post-respirable dust exposure averaging 50 µg/m^3 while they were working in this area [Cecala et al. 2017].

Vacuuming Screens and Using Segmented Panels

The following techniques have been found to be effective in lowering workers' respirable dust exposure during screen cleanings and changes:

1. Vacuuming the exterior cloth fabric material around the screening clips as well as the screen housing bracket before removal.
2. The use of a new design called a "segmented panel" screen, which is composed of three different panels that clip together on both ends.

Testing workers with VEM assessment at a screening facility provided insights into the reduction in workers' respirable dust exposure using both of these techniques. Workers' baseline respirable dust exposures averaged 166 µg/m^3 with peak levels over 1000 µg/m^3 during screen changes. When the workers vacuumed the screen housing brackets and the exterior fabric material around the screening clips—with the aid of both a high-pressure total plant structure vacuuming system and a portable shop-vac system before removing the screen—their respirable dust exposure averaged 66 µg/m^3 with peak levels around 410 µg/m^3. This represents a 60 percent reduction in the workers' exposure. One company[28] recently developed a screen technology called a "segmented panel" made up of three different panels that clip together on both ends. When testing this new design in the same study, the workers' respirable dust exposures were 63 µg/m^3,

[28] Rotex Global LLC, Cincinnati, Ohio.

representing a slight improvement over vacuuming, with a 62 percent reduction in their respirable dust exposure [Cecala et al. 2017].

Figure 9.14 shows a worker vacuuming a regular screen design and a worker removing a new segmented panel screen. Although it is not known if companies or workers will be willing to regularly perform this vacuuming process because of the additional time requirement, the segmented panel design and other similar future improvements to screening technology show great promise.

Photos by NIOSH

Figure 9.14. Photos of a worker vacuuming a regular screen and a worker removing a new segmented panel screen. The left photo shows the worker vacuuming exterior cloth fabric material around the screening clips and screen housing bracket. The right photo shows a "segmented panel" screen design made up of three different panels that clip together.

REDUCING DUST EXPOSURE THROUGH IMPROVED HOUSEKEEPING PRACTICES

Although good housekeeping practices might seem to be a minor or obvious issue, ultimately, housekeeping has a significant impact on miners' respirable dust exposures. When housekeeping is performed properly and on a scheduled time frame, it can be a key factor in minimizing respirable dust exposures to workers. On the other hand, when neglected or executed improperly, it can have just the opposite effect. Housekeeping should be performed at the end of each shift so that workers coming on to the next shift start with a clean work environment. When housekeeping is performed at the beginning of a shift, it increases the potential for worker clothing to become contaminated, which will increase the worker's personal dust exposure throughout the work shift.

The importance of housekeeping was documented in one study when a worker was dry sweeping the floor with a push broom. In this case, the average exposure of a coworker working one floor up from the person sweeping the floor increased from 0.03 mg/m^3 before sweeping to 0.17 mg/m^3 during and immediately after sweeping (Figure 9.15). Dry sweeping is prohibited by

OSHA [Part 1926.1153(f)(1)][29] and is discouraged as a viable cleaning technique because of the dust generated and liberated into the work environment [USBM 1986].

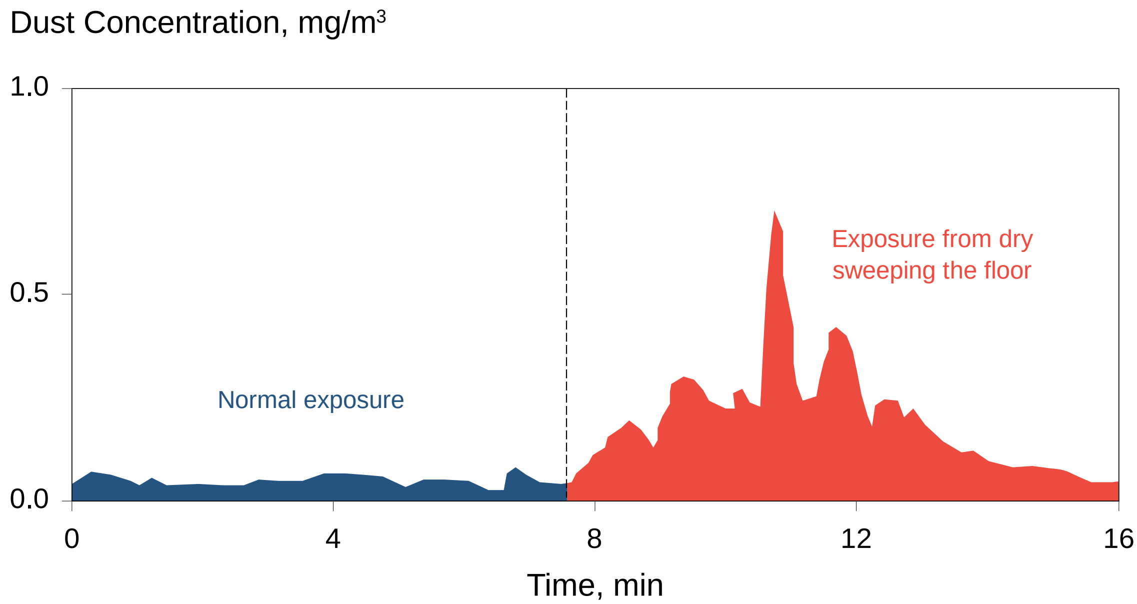

Figure 9.15. Graph showing an increase in a coworker's dust exposure one floor up from floor sweeping.

Spills of product material are a common occurrence at processing operations and, when they occur, the initial removal of material is most often performed with a scoop, with a skidsteer, or by way of a worker using shovels. It is critical that appropriate respiratory protection be worn by workers when removing spills manually.

Hosing Practices and Spray Patterns

In a building such as a plant, once the bulk of accumulated material is removed, or for general housekeeping, it is very effective to wash down the facility with water on a regular basis. Ideally, this option should be incorporated into the building design during construction so that drains are installed and the floor is sloped correctly to ensure that the water runs to the drains. Although washing down is very effective, it can unintentionally increase respirable dust levels during the hosing process if performed incorrectly. This increase occurs when a concentrated stream of water strikes piles of accumulated fine material, causing dust to be liberated into the air. Consequently, it is important to have the worker performing this housekeeping task to do so in a conscientiousness manner (e.g., being attentive to the spray pattern and by starting at the top and working down through the building). The worker needs to start by attempting to slowly wet surfaces and especially any piles of product accumulation. Once everything is wet, a more forceful spray pattern can be used to move the product more quickly to the floor drains. It may also be useful to test different types of nozzles and spray patterns that support workers' reduction in exposure during routine spraying in plant buildings and other locations (see Figure 9.16).

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[29] OSHA, CFR 1926.1153(f)(1): "The employer shall not allow dry sweeping or dry brushing where such activity could contribute to employee exposure to respirable crystalline silica unless wet sweeping, HEPA-filtered vacuuming or other methods that minimize the likelihood of exposure are not feasible."

When washing down is being used as a housekeeping technique, it should be done shift by shift, or at least daily, to keep product from accumulating.

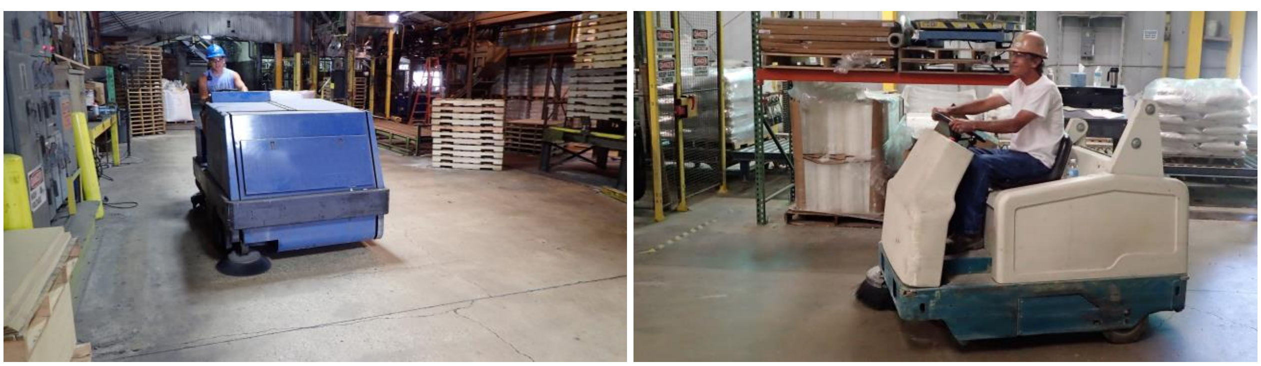
Photos by NIOSH

Figure 9.16. Worker using different spray nozzles during housekeeping.

Floor Cleaning Devices and Vacuum Systems

In addition to washing down, the next most common housekeeping techniques are the use of floor cleaning devices and vacuum systems, although both of these techniques are costlier than washing down. Floor sweeping units can be especially effective in high-trafficked areas, such as those in forklift truck routes and even outside the plant to prevent liberated material from being tracked inside or otherwise.

When considering floor cleaning options, there are many different manufacturers and companies that sell a variety of units. These units vary from ones that workers ride to smaller units that they walk behind (see Figure 9.17). One area that should be closely investigated is the disposal of the contaminated material once it has been collected. It would be counterproductive if the unit is efficient during the floor cleaning process but employees are contaminated when cleaning the unit or disposing of the accumulated material.



Photos by NIOSH

Figure 9.17. Photos of two types of riding floor sweeping units used to clean dust-laden floors. The left photo shows a larger unit with an employee operating from behind. The right photo shows a more compact unit designed for the employee to ride. The size of the unit chosen is based upon plant layout.

Some operations also clean roadways throughout the plant by way of street cleaning units, as shown in Figure 9.18. This roadway cleaning unit typically vacuums dust and debris first before applying a wet spray.

Photo by NIOSH

Figure 9.18. Sweep truck cleaning an outside roadway, typically used at plants and mills.

In addition, there are many different types of vacuuming units. These can range from high-capacity in-plant vacuuming systems with multiple collector pickup locations to portable tank-type units. Some operations contract this work to independent companies that bring in high-powered exhaust trucks to perform the vacuuming process. In almost all cases, a worker uses an exhaust system collector device to manually exhaust the product and dust into the collector system (Figure 9.19). This is very time-consuming and can be difficult to perform in areas that are not easily accessible in the plant. Therefore, this cannot be performed on a shift-by-shift or daily basis because it is so labor intensive. One safety issue with these vacuuming devices is from static electricity charges that can be created while performing this cleaning technique. Using a nonconductive or grounded hosing material should eliminate the risk of this safety issue.

Figure 9.19. Illustration of a portable system used to vacuum product.

In addition to hosing with water, sweeping, or using mechanical devices to clean the floors at mineral processing facilities, one last option is to use a floor sweeping compound. Although this practice is not commonly used throughout an entire facility, some operations use a floor sweeping compound in high-traffic or extremely dusty areas to assist in minimizing the dust generated. Since there are many different manufacturers selling floor sweeping compounds, operations may want to consider evaluating different types of material in some problem areas to determine the effectiveness of sweeping compounds in relation to material type within their facilities.

One final aspect of effective housekeeping is proper upkeep and maintenance of plant equipment and processes. When product builds up on floors, it indicates that some function or process is causing the leakage. In some cases, visible dust can be seen leaking from holes or damaged equipment, and this must be quickly corrected to minimize dust leakage. In addition, repetitive dust leaks should not simply be “patched”; instead, the underlying cause should be determined and corrective action taken to both fix the leak and prevent future reoccurrences.

Each process or function within mining and mineral processing operations should have a standard operating procedure (SOP) that includes routine inspections, maintenance, and cleaning schedules. When equipment is cleaned and maintained on a routine basis, it can have a significant impact on minimizing dust generation and liberation.

ADDRESSING OTHER SECONDARY DUST SOURCES

The following are a few examples that were documented in actual field studies and will demonstrate the impact that secondary dust sources can have on a worker’s respirable dust exposure [Cecala and Thimons 1987; USBM 1988; Cecala and Thimons 1992].

Dust from Outside Sources Traveling Inside Structures

When dust from outside sources travels into structures, every worker inside the structure is impacted. Most bagging operations at mineral processing plants use an exhaust ventilation system to draw the dust generated from the bagging process down into the fill hopper and away from the breathing zone of the bagger (refer to Chapter 7—Bagging). It is important that the air being drawn into this exhaust ventilation system, commonly called makeup air, be clean air. At one operation, the makeup air was drawn directly from the bulk loading area outside the plant. The dust generated from this bulk loading process traveled through an open door into the plant, substantially contaminating the workers inside. During periods when bulk loading was not performed, the bag operator’s average dust exposure was 0.17 mg/m^3. As trucks were loaded at the bulk loading area, the worker’s average exposure increased to 0.42 mg/m^3 due to this contaminated air (Figure 9.20). As this study demonstrates, if outside air is used as makeup air, it must be from a location where the air is not contaminated.

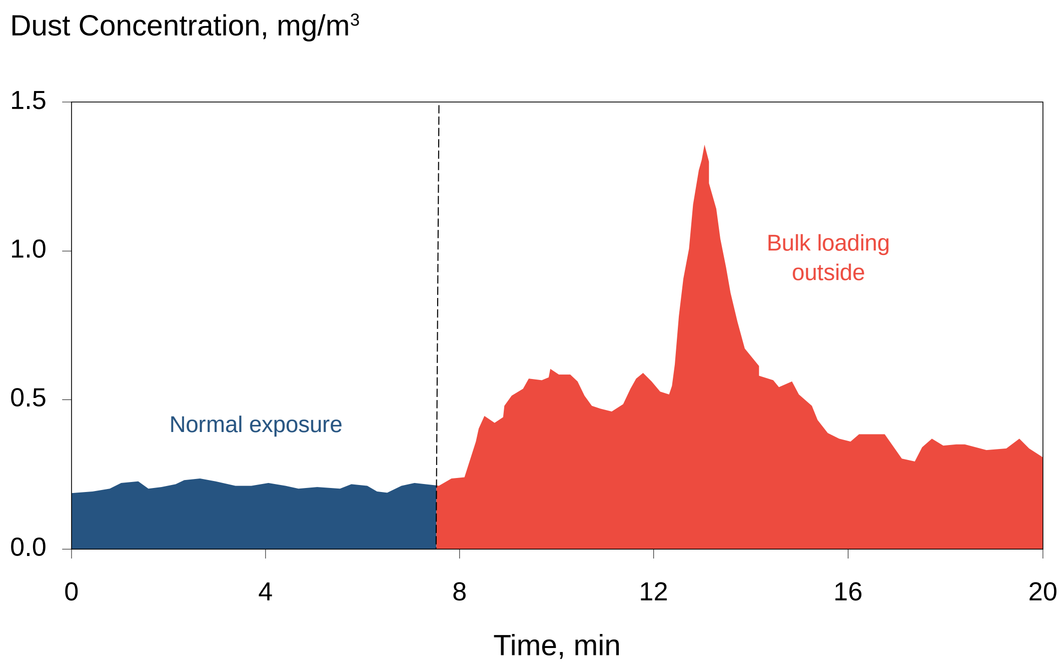


Figure 9.20. Graph showing the increase in a worker's respirable dust exposure inside a mineral processing facility while bulk loading was being performed outside.

Personal Dust Exposure from Differences in Job Function Work Practices

During an evaluation of four different dust control systems at a mineral processing operation, it was determined that substantial variations occurred in the respirable dust exposure of two workers based upon their personal work practices in performing their same job function. In this case, these two workers were loading bags of product on a bag filling machine and then manually removing the bags and placing them onto a conveyor belt. Figure 9.21 shows a comparison of the respirable dust exposure of these two workers while performing the same job function when different control techniques were implemented (System Type 1–4 on the x-axis). The point to be highlighted from this testing is that regardless of the system being evaluated, Worker #2's respirable dust exposure was always significantly less than that of his coworker (Worker #1). The main reason for these differences was that Worker #1 performed his job function in a rough manner relative to Worker #2, who performed the exact same tasks in a careful manner. Ultimately, this resulted in Worker #2's respirable dust exposure being approximately 70 percent less than that of his coworker.

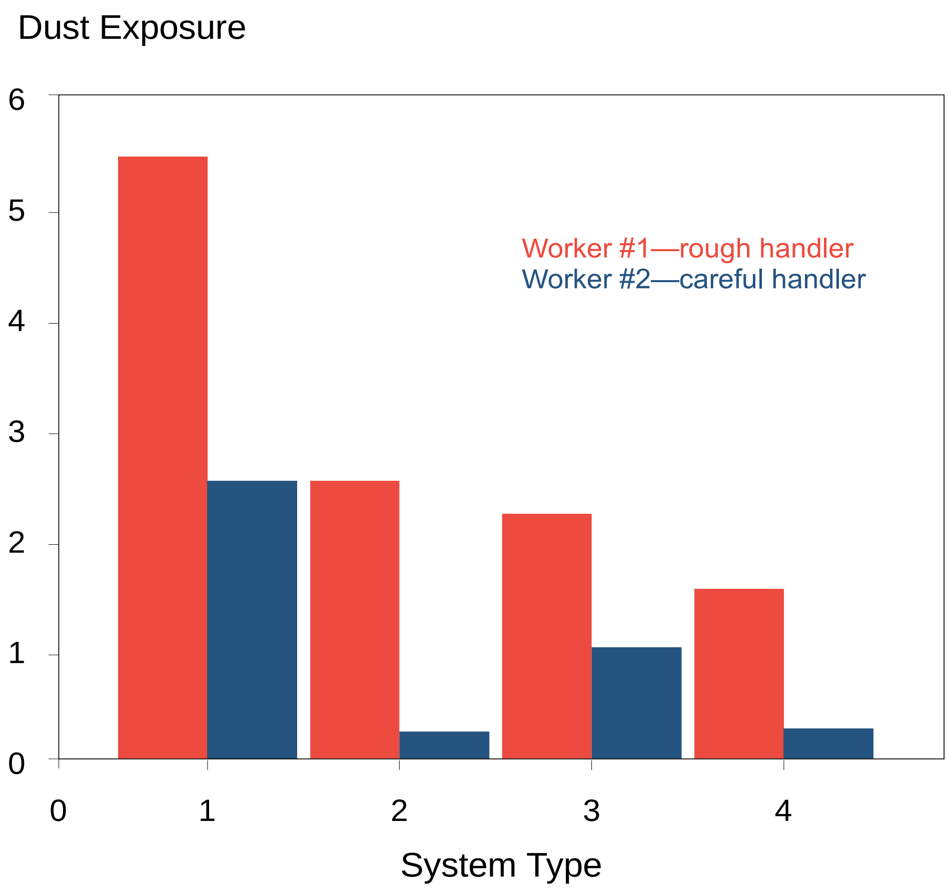


Figure 9.21. Bar chart comparing two workers' respirable dust exposure while performing their jobs with different control techniques being implemented.

One key element in how Worker #2 performed his tasks was the way he manually squeezed the bag valve closed with his hand as he removed the bag from the fill station and transferred it to the conveyor (Figure 9.22). This technique was believed to be instrumental in lowering the worker's respirable dust exposure. Comparing the difference between these two workers indicates the impact that individuals can have on their dust exposure based upon how they perform their jobs.

Photo by NIOSH

Figure 9.22. Worker squeezing the bag valve closed with his hand as he removes the bag from the fill nozzle, significantly reducing his dust exposure.

Broken Bags of Product and Bag Sealing

In most cases, bag breakage occurs because of flaws in the bags delivered from the bag manufacturer. At one operation, a bag operator’s average dust exposure went from 0.07 mg/m^3 before a bag break to 0.48 mg/m^3 afterward. Since the bag broke during the conveying process and not directly in front of the worker, the dust substantially contaminated the surrounding plant air, which in turn, flowed over the bag operator (Figure 9.23). This occurred because the exhaust ventilation system in the bag loading area creates a negative pressure that draws background air from the contaminated plant air.

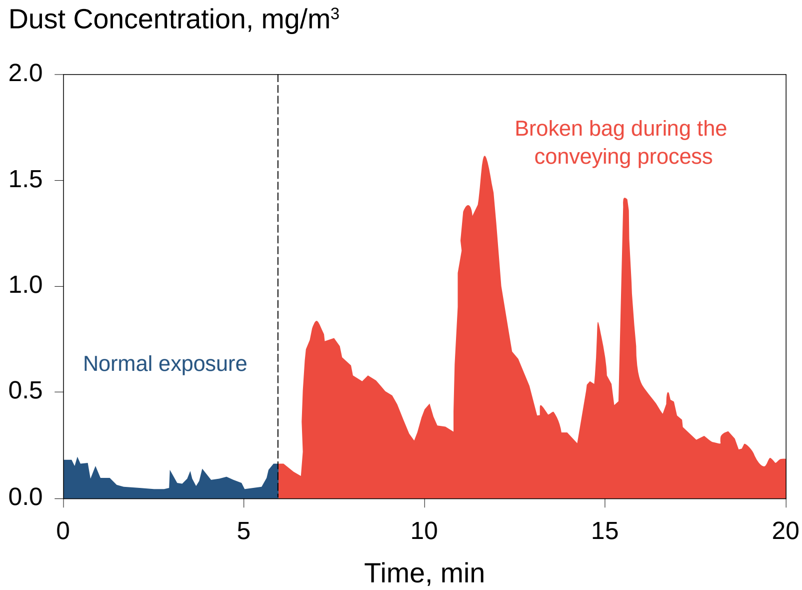


Figure 9.23. Graph showing the increase in a worker's respirable dust exposure from a broken bag during the conveying process.

Tying of Collar on Flexible Intermediate Bulk Containers

One area of common elevated respirable dust exposure is when workers manually tie the collars closed on flexible intermediate bulk containers (FIBCs) (Figure 9.24). Although additional research is still needed in this area, recent NIOSH research confirmed a simple work practice that workers can perform to significantly reduce their exposure. At one site, it was documented that when a worker changed his bag tying practices by folding the bag collar away from him rather than toward him, his exposure reduced significantly [Haas and Cecala 2017].

Photos by NIOSH

Figure 9.24. Photos representing how a worker's method for tying a bag collar on a flexible intermediate bulk container can significantly impact respirable dust exposure.

Dirty Work Boots

As with dust-laden work clothing, dirty work boots can also be a source of background dust exposure to workers. This occurs when a worker walks through wet product, overburden, or mud and it adheres to his or her boots. Obviously, wet conditions are common at mining and mineral processing operations from precipitation or any wet plant processes. Once a worker's boots are soiled with product, it is then tracked everywhere the worker goes until it either all falls off or the boots are cleaned. Figure 9.25 shows product tracked onto the floor of a piece of mobile equipment. It is easy to understand the amount of dust that can be generated when this level of material is accumulated on the floor.

Photo by NIOSH

Figure 9.25. Product tracked onto the floor of a piece of mobile equipment from dirty work boots.

In cases where a substantial amount of dust and product gets carried and tracked into a work area, housekeeping should be performed on a daily or shift basis. When the contamination is not as significant, housekeeping could be done on a more infrequent basis, but it is critical that this contamination is addressed to minimize the source of dust to workers.

One strategy that was tried and shown to be effective in reducing the amount of dust generated from dirt and product on the floor was by using sweeping compounds. A study was conducted to determine the effectiveness of using a gritless nonpetroleum sweeping compound in enclosed cabs on two drills [NIOSH 2001]. Figure 9.26 shows the average respirable dust concentrations measured inside the two enclosed cabs for three to five shifts for both test conditions (baseline and sweeping compound). The respirable dust levels were reduced from 0.18 and 0.68 mg/m^3 to 0.07 and 0.12 mg/m^3, respectively, for the cabs. These results indicate that the sweeping compound had a positive effect on suppressing dust when it was able to make direct contact with and bind up the dirt on the steel and rubber floor mats.

It should be noted that before any sweeping compound is used, companies should examine the Safety Data Sheet (SDS) to ensure there are no ingredients that would cause problems in an enclosed area. The sweeping compound should also be changed and disposed of properly once it has reached a state where it is no longer containing the dust.

In other cases, an operation may want to consider installing a boot washing or boot cleaning device to minimize the negative effects of dirty work boots. These boot cleaning stations are relatively inexpensive and can be placed at various locations around an operation.

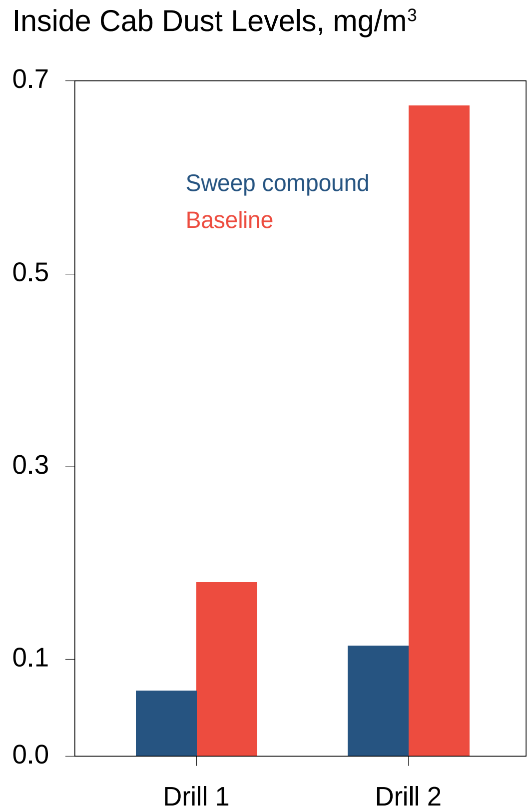


Figure 9.26. Bar chart showing respirable dust concentrations inside the enclosed cabs of two different pieces of equipment with and without the use of a gritless nonpetroleum-based sweeping compound.

MAINTENANCE

Maintenance of dust control systems is critical to ensure continuing worker protection [USBM 1974]. Preventive maintenance schedules should be established based on observed component wear, system performance measures, and exposure sampling results.

Work Practices to Reduce Dust Exposure during Maintenance Activities

Workers performing maintenance can be exposed to higher-than-normal dust concentrations because the maintenance task may involve working in areas where dust controls are not functioning effectively, working on highly contaminated equipment, or working on tasks that must be performed in unusual nonroutine operating conditions. The following list provides effective techniques for lowering workers' respirable dust exposures while performing maintenance activities.

- Clean equipment and work areas when needed by washing or vacuuming before and during maintenance work. Working in dusty work areas results in increased dust exposure to maintenance workers.
- Maximize the use of remote-access fittings such as extension grease lines. This practice lessens the potential for dust exposure to maintenance workers from having to remove guards, covers, and other items of equipment that may have surface dust or exposed dusty areas.
- Keep outside intake air and recirculating air dust filters clean and replace when necessary in mobile equipment, cabs, control rooms, and operator booths. Proper attention must be given to the filter efficiency when filter changes are necessary. Refer to Chapter 10—Filtration and Pressurization Systems for Environmental Enclosures—for more information.
- Provide travelways to routine maintenance sites. This eliminates dust exposure from climbing in and around equipment to access maintenance sites.
- Provide lifting and mechanical handling equipment to reduce worker handling of dust-laden equipment.
- Clean dust-laden work clothing immediately following the completion of maintenance work activity using a clothes cleaning booth system or another approved technique. (Refer to the "Technology for Cleaning Dust from Work Clothing" section earlier in this chapter.) In addition, disposable coveralls made of dust-blocking material, such as Tyvek or Kleenguard, can be worn to greatly reduce dust contamination of work clothing and the transfer of dust to clean work areas or to the worker's home.
- When gloves are worn, a nonporous material that does not retain dust should be used. Using an open-weave fabric material that holds the dust is discouraged because of its ability to increase the worker's dust exposure.
- Where feasible, wash down mobile equipment prior to entering maintenance bays for conducting maintenance work.
- Avoid the use of compressed air to clean surfaces.
- Periodically clean the inside of mobile equipment, control rooms, and operator booths to remove accumulated product, dust, and debris.

Through the use of one or a number of these techniques, respirable dust exposure to maintenance workers can be significantly reduced.

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Chapter 10: Filtration and Pressurization Systems for Environmental Enclosures

CHAPTER 10: FILTRATION AND PRESSURIZATION SYSTEMS FOR ENVIRONMENTAL ENCLOSURES

Environmental enclosures, such as operator booths, control rooms, and enclosed cabs, have been used for many years to isolate workers from dust sources in mining and mineral processing operations, as well as in construction, oil and gas, and agricultural operations and facilities. When they are properly designed, installed, and maintained, they can provide a safe work environment that supplies clean and acceptable air quality to the worker.

In the mining industry, environmental enclosures, including enclosed cabs, operator booths, and control rooms, have distinctive aspects and parameters that must be considered when designing an optimal filtration and pressurization system. Enclosed cabs on mobile equipment are unique in that the equipment is constantly moving and working in different mining areas, and therefore they are subjected to vastly different dust conditions. In addition, because of the movement of the equipment in undulating and rough terrain, there is a constant stress that compromises the integrity of the cab enclosure. Operator booths and control rooms do not experience this constant stress from movement but can be affected by significant vibration from nearby work, such as the primary dumping of a large volume of product. In addition, operator booths and control rooms can be large in volume, allowing for ingress and egress by multiple workers.

In short, mine workers in environmental enclosures are surrounded by dynamic working conditions that have highly variable dust sources. These enclosures create a microenvironment where workers can be either more protected or more vulnerable to respirable dust and other contaminants. Filtration and pressurization systems are the primary engineering control to reduce worker exposure to airborne dust in enclosed cabs, operator booths, and control rooms.

This chapter provides a detailed summary of the development and advancement of effective design strategies for filtration and pressurization systems for environmental enclosures, including effectiveness terminology, results from field and lab studies, and mathematical modeling of use to design engineers. The chapter concludes with a summary of the key components to ensure optimal air quality in environmental enclosures.

EFFECTIVENESS TERMINOLOGY

When evaluating a pressurization and filtration system—i.e., comparing outside and inside respirable dust concentrations—a number of descriptors can be used to provide a numerical value that ranks the system’s effectiveness. The following three descriptors are commonly used for this purpose:

$$Protection\ factor\ (PF) = \frac{c}{x};\ (ratio)$$

$$Efficiency\ (\eta) = \frac{c - x}{c};\ (fractional, or\ multiplied\ by\ 100\ for\ percent\ value)$$

$$Penetration\ (Pen) = 1 - \eta;\ (fraction)$$

where *c* = outside respirable dust concentration and *x* = inside respirable dust concentration.

A comparison of these descriptors can be provided by the following equation:

$$PF = \frac{c}{x} = \frac{1}{1-\eta} = \frac{1}{Pen} \tag{10.1}$$

The higher the value for both *protection factor* and *efficiency* and the lower the value for *penetration*, the better the air quality inside the operator booth, control room, or enclosed cab. Table 10.1 shows a comparison of the three different descriptors.

Table 10.1. Comparison of three different terms to describe effectiveness at providing clean air to an enclosed cab, operator booth, or control room

Protection Factor	Efficiency, %	Penetration
2	50	0.50
5	80	0.20
10	90	0.10
100	99	0.01
1,000	99.9	0.001

For this chapter, the term *protection factor* (PF) will be used when discussing the effectiveness of environmental enclosures.

STUDIES ON FILTRATION AND PRESSURIZATION SYSTEMS

Researchers have put forth a substantial effort in studying filtration and pressurization systems over the past two decades, identifying and correcting problems and determining critical components necessary for an effective design and system. Among the numerous laboratory and field studies, many have been cooperative partnerships between mining companies; original equipment manufacturers (OEMs); after-market manufacturers of filtration and pressurization systems; OEMs of heating, ventilation, and air-conditioning (HVAC) systems; and government agencies. These synergistic efforts have reduced respirable dust and improved the air quality inside many different types of environmental enclosures. To lay the foundation for design considerations, this section summarizes the key studies that have been completed, including field studies, lab testing, and mathematical modeling.

A health screening study performed during the mid-1990s in central Pennsylvania identified a significant number of silicosis cases attributed to operators of mobile mining equipment in enclosed cabs that were not providing an acceptable level of protection [CDC 2000]. In this study, surface drill operators had the greatest number of cases of silicosis, although workers in other types of mechanized equipment, including dozers, loaders, and haul trucks, were also being overexposed to respirable crystalline silica and respirable dust. An alarming aspect with this study was that in a number of cases, relatively young workers with relatively little mining experience were being diagnosed with the disease due to the high exposure levels.

Since this time, there has been a substantial work effort to better understand the problem and to improve the air quality and protect workers in enclosures. This work has included both installing retrofit systems on older pieces of equipment and developing prototype designs for new OEM machinery. The results of a number of these different field studies at mining operations can be seen in Table 10.2, which shows the average respirable dust concentrations as measured by gravimetric sampling and the resulting protection factors. As observed in this table, the shift-to-shift time-weighted average (TWA) dust concentrations and protection factors can range significantly based upon operational and work practice variations. The lowest protection factor shown for some of these studies resulted from the outside concentrations not being high enough during some shifts to accurately establish the cabs' effectiveness.

Table 10.2. Summary of respirable dust sampling results of retrofitted cab filtration systems on mine vehicles

Vehicle Cab Tested (*No. of Shifts*) [Case study reference]	Mining Type	Cab Pressure, inches wg	Inside Cab Dust Level, **Average** (*Range*) mg/m^3	Outside Cab Dust Level, **Average** (*Range*) mg/m^3	Protection Factor, **Average** (*Range*)
Rotary drill (*4*) [Organiscak et al. 2004]	Surface	None detected	**0.08** (*0.02 to 0.17*)	**0.22** (*0.12 to 0.46*)	**2.8** (*2.0 to 7.9*)
Haul truck (*3*) [Chekan and Colinet 2003]	Underground/ Surface	0.01	**0.32** (*0.23 to 0.43*)	**1.01** (*0.92 to 1.07*)	**3.2** (*2.4 to 4.0*)
Front-end loader (*6*) [Organiscak et al. 2004]	Surface	0.015	**0.03** (*0.01 to 0.07*)	**0.30** (*0.09 to 0.47*)	**10** (*2.1 to 50*)
Rotary drill (*7*) [Cecala et al. 2009]	Surface	0.10–0.40	**0.16** (*0.06 to 0.21*)	**2.85** (*0.68 to 4.20*)	**18** (*3.7 to 42*)
Rotary drill (*3*) [Cecala et al. 2004]	Surface	0.20–0.40	**0.05** (*0.03 to 0.07*)	**2.80** (*0.73 to 6.25*)	**52** (*24 to 89*)
Rotary drill (*7*) [Cecala et al. 2005]	Surface	0.07–0.12	**0.07** (*0.02 to 0.13*)	**6.25** (*0.25 to 31.8*)	**89** (*3.6 to 245*)

These studies highlighted some very important factors relevant to improving the air quality in enclosed cabs and ultimately protecting the workers. Cab integrity, and the related ability to achieve positive pressurization, was found to be a critical component. As seen in the first two studies listed in Table 10.2, when there was very little to no cab pressure detected, there was minimal improvement in the cab's air quality. In fact, similar filtration and pressurization systems were installed on the rotary drill and front-end loader (Rows 1 and 3), with the PF varying from 2.8 to 10. One notable difference between these two systems was that a small amount of pressurization was achieved in the front-end loader, whereas it was not possible to achieve any pressurization in the rotary drill. This table also shows there was a positive correlation between those enclosed cabs with higher positive pressures and improved air quality (i.e., lower respirable dust), as measured by the PF.

Another critical factor studied has been the quality and effectiveness of the filtration system. Various studies indicate substantial improvements in the interior air quality from effectively removing the dust particles from the outside air and delivering this clean filtered air into the enclosed cab. When sufficient pressurization was achieved along with an effective filtration system, very good air quality was obtained in these cabs, as indicated by the significant PFs.

Another recent study tested a new primary crusher booth installed at an underground mine. When testing this OEM crusher booth, respirable dust levels inside the enclosure were approximately 12 times higher when the ventilation system was on compared to when the ventilation system was off (with no intake/outside air being mechanically blown into the booth). It was determined that these elevated levels were caused by the dust plume created when haul trucks dumped into the primary crusher at this underground location. When the system was turned off, the enclosure somewhat shielded or buffered a portion of the dust from entering the booth until the mine ventilation airflow was able to direct the dust cloud away from the area and from entering the enclosure. Since there was no filtration on the OEM's ventilation system, the dust generated and liberated by the dumping process was blown directly into the crusher booth when the ventilation system was on. Later, an aftermarket filtration and pressurization system was installed and significantly improved the respirable air quality by a factor of 18.7 times [Patts et al. 2017].

Importantly, in the above study, although respirable dust and contaminant levels, including diesel particulate matter (DPM), were lower inside the booth when the OEM's ventilation system was off, turning off an enclosure's ventilation system is definitely not a recommended practice. Another study documented that workers in these enclosures can also be more vulnerable to in-cab dust sources (floor heaters, dirt on floors/walls, operator's clothing, etc.) and exposed to elevated carbon dioxide levels. The threshold limit value (TLV) for carbon dioxide (CO_2) was established in 1983 at 5,000 ppm and at 30,000 ppm for a 15-minute short-term exposure limit [ACGIH 2009; ASHRAE 2007]. In environmental enclosures, it may not take long for a worker to show signs of health concerns from CO_2 exposure without fresh air being delivered.

Mathematical modeling of enclosure filtration systems has been used to examine the key design parameters influencing system performance to improve the air quality in enclosures. The first mathematical model was developed in 2008 and was derived in conjunction with lab testing of an enclosure to determine and evaluate all the components and parameters involved in an effective system (Figure 10.1). From this study, it was determined that the key filtration parameters are intake filter efficiency, air leakage around the intake filter, intake filter loading, recirculation filter usage, and wind infiltration [NIOSH 2008a]. This first mathematical model formulation was based on a time-dependent mass balance model of airborne substances within a control volume. This model was a differential equation that converged to a steady state solution for ease of use [NIOSH 2008a; Organiscak and Cecala 2009]. To simplify mathematical derivation of other filtration system models, a node analysis technique was utilized to illustratively assist with the algebraic formulation of these models at steady state conditions [Organiscak et al. 2014].

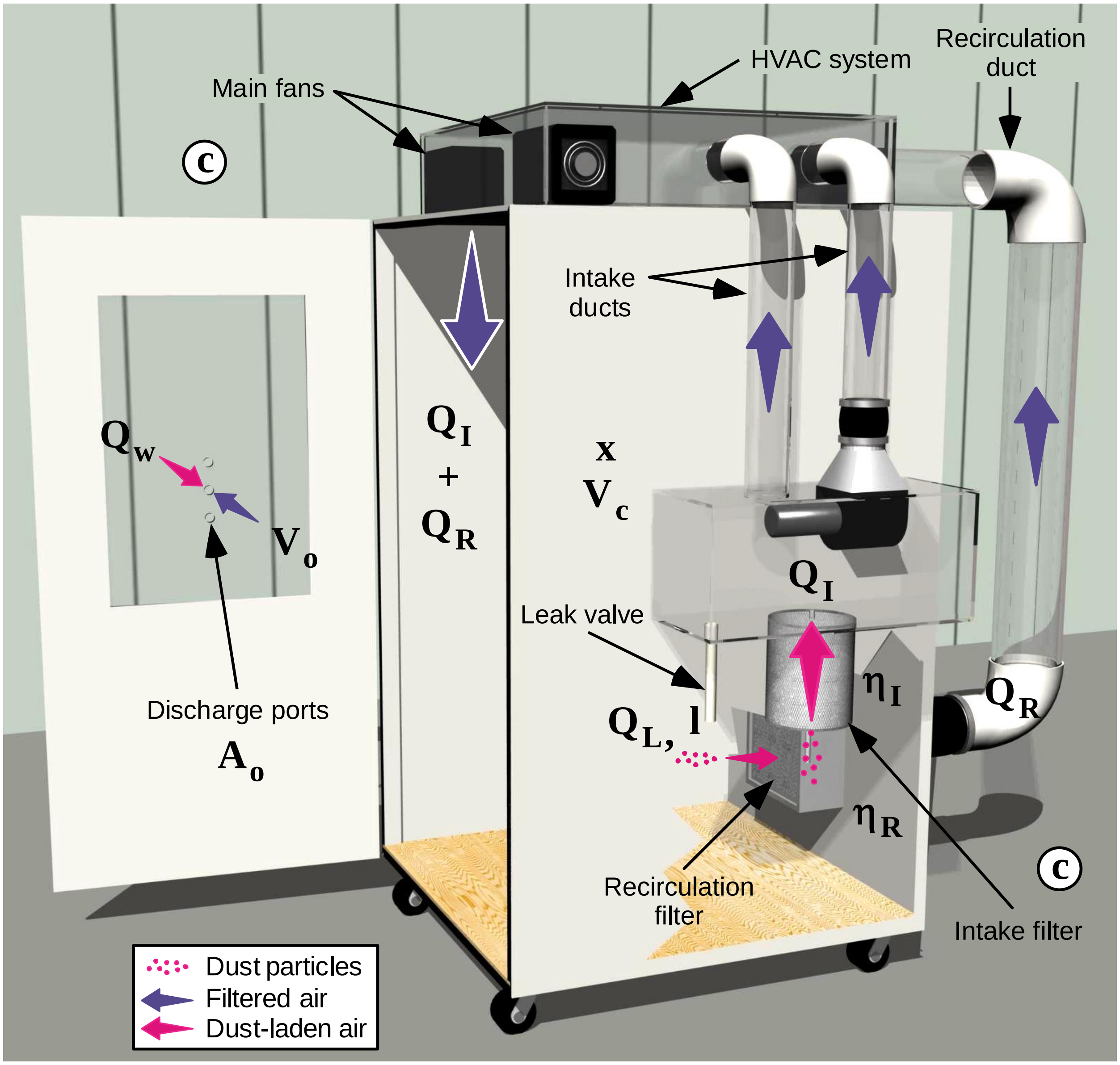


Figure 10.1. Illustration of a simulated enclosed cab tested in the laboratory showing the various test components and parameters for a filtration and pressurization system.

Figure 10.2 shows the node analysis diagram developed for a one-intake filter design. This diagram is valid with or without the use of a recirculation filter. This model formulation was based on the mass balance of incoming and outgoing contaminants (dust, particles, etc.) at the interior cab node. Equations 10.2 and 10.3 were developed for the one- and two-filter systems, respectively. These models are dimensionless and show that the enclosure PF is related to the intake filter efficiency, intake airflow, intake air leakage, recirculation filter efficiency, recirculation airflow, and wind quantity infiltration. If adequate positive pressurization is achieved to resist wind infiltration into the enclosure, the wind airflow quantity (Q_w) would be 0 in the model.

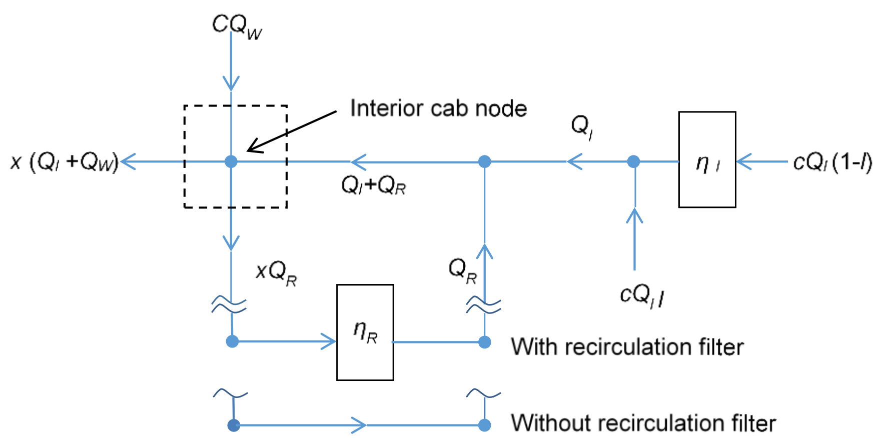


Figure 10.2. Two- and one-filter cab systems with and without a recirculation filter. Q's denote air quantities, x's & c's denote contaminant concentrations, and η's denote filter efficiencies.

A mathematical model was also formulated for a three-filter system design studied on several underground equipment cabs. This model was developed to examine the cab system's operational parameters with respect to field study performance measurements [Organiscak et al. 2014]. Figure 10.3 shows the intake, recirculation, and final filter locations within the HVAC system designed by an OEM and field tested by the National Institute for Occupational Safety and Health (NIOSH) [Cecala et al. 2016]. Figure 10.4 shows the node layout of this system, and Equation 10.4 represents the model formulated for this system [Organiscak et al. 2014]. Note that if a 0 value is used for the final filter efficiency in Equation 10.4, it reduces to Equation 10.3, which is the two-filter system. Similarly, putting in 0 for the recirculation filter efficiency of Equation 10.3 reduces it to Equation 10.2, which is the single-filter system.

$$PF = \frac{c}{x} = \frac{Q_I + Q_W}{Q_I(1 - \eta_I + l\eta_I) + Q_W} = \frac{1}{Pen} \tag{10.2}$$

$$PF = \frac{c}{x} = \frac{Q_I + Q_R\eta_R + Q_W}{Q_I(1 - \eta_I + l\eta_I) + Q_W} = \frac{1}{Pen} \tag{10.3}$$

$$PF = \frac{c}{x} = \frac{Q_I + Q_R(\eta_R + \eta_F - \eta_R\eta_F) + Q_W}{Q_I(1 - \eta_I + l\eta_I)\left(1 - \eta_f\right) + Q_W} = \frac{1}{Pen} \tag{10.4}$$

where: c = outside contaminant concentration penetrating the filtration system;
x = inside cab contaminant concentration (interior cab node);
η = filter reduction efficiency, fractional;
1-η = filter penetration, fractional;
Q = airflow quantity;
l = intake air leakage, fractional;

with the following filter efficiency and air quantity subscripts:
I = intake;
F = final;
R = recirculation; and
W = wind.

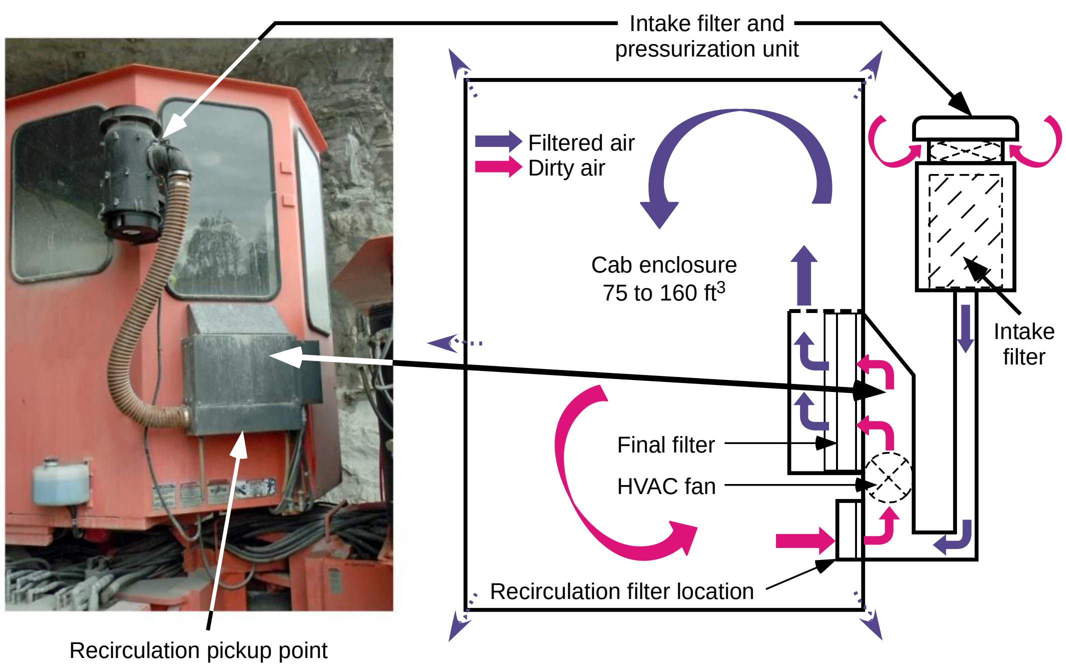


Photo by NIOSH

Figure 10.3. Intake, recirculation, and final filter locations within an HVAC system designed by an original equipment manufacturer and field tested by NIOSH.

Mathematical models can also be used to examine cab filtration system protection factors that can be achieved for various filter configurations, airflow conditions, and outside air leakage around filtration systems. The calculated PFs are the expected performance that can be achieved under optimum conditions with the enclosure doors and windows remaining closed for extended periods of time, usually greater than 30 minutes. Frequent opening and closing of the doors and windows reduces the cab's PF performance from the modeled optimum because the outside air bypasses the filtration system [Organiscak et al. 2014].

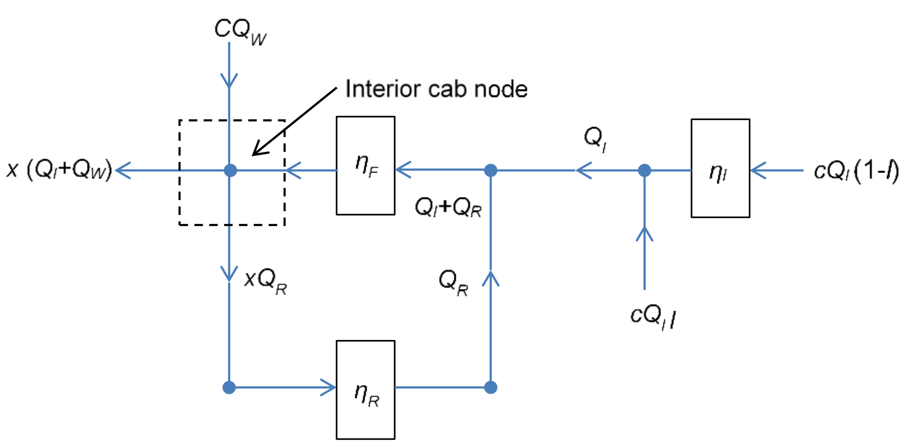


Figure 10.4. Three-filter cab system with the final filter downstream of the intake and recirculation filters. Q's denote air quantities, *x*'s & *c*'s denote contaminant concentrations, and η's denote filter efficiencies.

A sample calculation is shown below for a three-filter system using a 95 percent efficient intake filter, a 75 percent efficient recirculation filter, and a 95 percent efficient final filter (on respirable dust) for the system shown in Figure 10.4 and modeled in Equation 10.4. This calculation also includes what the cab filtration PF would be with a hypothetical 5 percent outside intake air leakage around the intake filter and with no direct outside wind infiltration into the cab enclosure (0 ft^3/min).

$$PF = \frac{50 + 200 \times \left(0.75 + 0.95 - (0.75 \times 0.95)\right) + 0}{50 \times \left(1 - 0.95 + (0.05 \times 0.95)\right) \times (1 - 0.95) + 0} = 1{,}015$$

As previously mentioned, wind infiltration into the cab is minimized with adequate cab pressurization [NIOSH 2008a; Heitbrink et al. 2000]. Additionally, using a cab intake airflow of 50 ft^3/min and a recirculation airflow of 200 ft^3/min yields a modeled cab PF calculation of 1,015. This protection factor is shown below in Table 10.3 for the particular cab filtration configuration at these airflow and leakage conditions. The above models (Equations 10.2, 10.3, and 10.4) could also be used to compare one-, two-, and three-filter systems at various operating parameters to examine their impact on a cab's PF.

Table 10.3 shows these filtration systems and how they are affected by recirculation airflow and outside air leakage around the intake filter. As seen, the number of filters and their location make a significant difference on the cab PFs. Using only an intake filter is very constraining on the cab's PF because it only filters the intake portion of the cab airflow and thus does not address any of the in-cab dust sources. However, adding a recirculation filter more than doubles the cab's PF considering both recirculation quantities, which indicates the importance of the recirculation component because it addresses the in-cab dust sources and the impact of a user-controlled HVAC fan. Adding a recirculation filter also reduces the time it takes to reach the optimum cab PF [NIOSH 2008a]. Placing a final filter downstream of both filters drastically improves the cab PF because it refilters all the previously filtered air before it is discharged into the cab enclosure, indicating the importance of this final filter and cleaning to the air quality. Removing the recirculation filter upstream of the final filter has the least impact on the cab's PF because the final filter still cleans all the HVAC airflow as well as refilters the intake airflow. Finally, increased intake air leakage into the filtration system can severely diminish the cab's PF regardless of filter configuration. Reduced recirculation airflow with the two- and three-filter systems notably reduces cab PF because the rate of all airflow filtration is reduced. Long-term field studies of cab PFs, airflow quantities, pressures, and tested filter configurations showed good relative agreement with modeled cab variables [Cecala et al. 2016; Organiscak et al. 2014].

Table 10.3. Summary results of modeling one- , two- , and three-filter cab systems

Intake filter efficiency, %	Recirculation filter efficiency, %	Final filter efficiency, %	Intake Air Quantity (ft^3/min)	Recirculation Air Quantity (ft^3/min)	Model PF with 0% Intake Air Leakage	Model PF with 5% Intake Air Leakage	Model PF with 10% Intake Air Leakage
95	No filter	No filter	50	200	20	10	7
95	No filter	No filter	50	100	20	10	7
95	75	No filter	50	200	80	41	27
95	75	No filter	50	100	50	25	17
95	75	95	50	200	1,980	1,015	683
95	75	95	50	100	1,190	610	410
95	No filter	95	50	200	1,920	985	662
95	No filter	95	50	100	1,160	595	400

Figure 10.5 shows the results from a field study comparing cab performance levels when testing a matrix of filter combinations, as well as new and used filters. This field testing was performed at a mining site on a roof bolter machine with the OEM-installed filtration and pressurization system. The filters in this field study had minimum efficiency reporting value (MERV)-16 rated efficiencies for both the intake and final filters, whereas the recirculation filter was determined in a lab test to be of approximately 70 percent filter efficiency on respirable-sized particles, making it comparable to a MERV-13 filter. This figure also shows the intake and recirculation airflow measured during each test configuration. These results provide an array of useful information and similarly reflect the modeling results computed in Table 10.3. First, the results indicate the substantial improvement in PF with the implementation of a final filter in the system. With only a used intake and recirculation filter, the PF was 3, while with the addition of the final filter the PF increased dramatically to 76. Because the recirculation filter in this system was undersized (which restricted the airflow very quickly), when the recirculation filter was removed, the airflow went from 50 up to 180 cubic feet per minute (cfm). This threefold increase in the airflow significantly impacted the air flowing through the final filter and the ultimate cleaning of this air. In addition, for this system, there was noticeable leakage around both the recirculation and intake filters, and the effects of this leakage were mitigated with the implementation of the final filter. The PF increased from 76 up to 465, which indicates a major increase in the air

quality inside the enclosed cab from the increased airflow and the additional air being cleaned by multiple passes through the filter. Given the cab's lower PFs measured in the field, comparing this field data to similar PF case models in Table 10.3 indicates that this filtration system had greater than 10 percent air leakage around the filtration system.

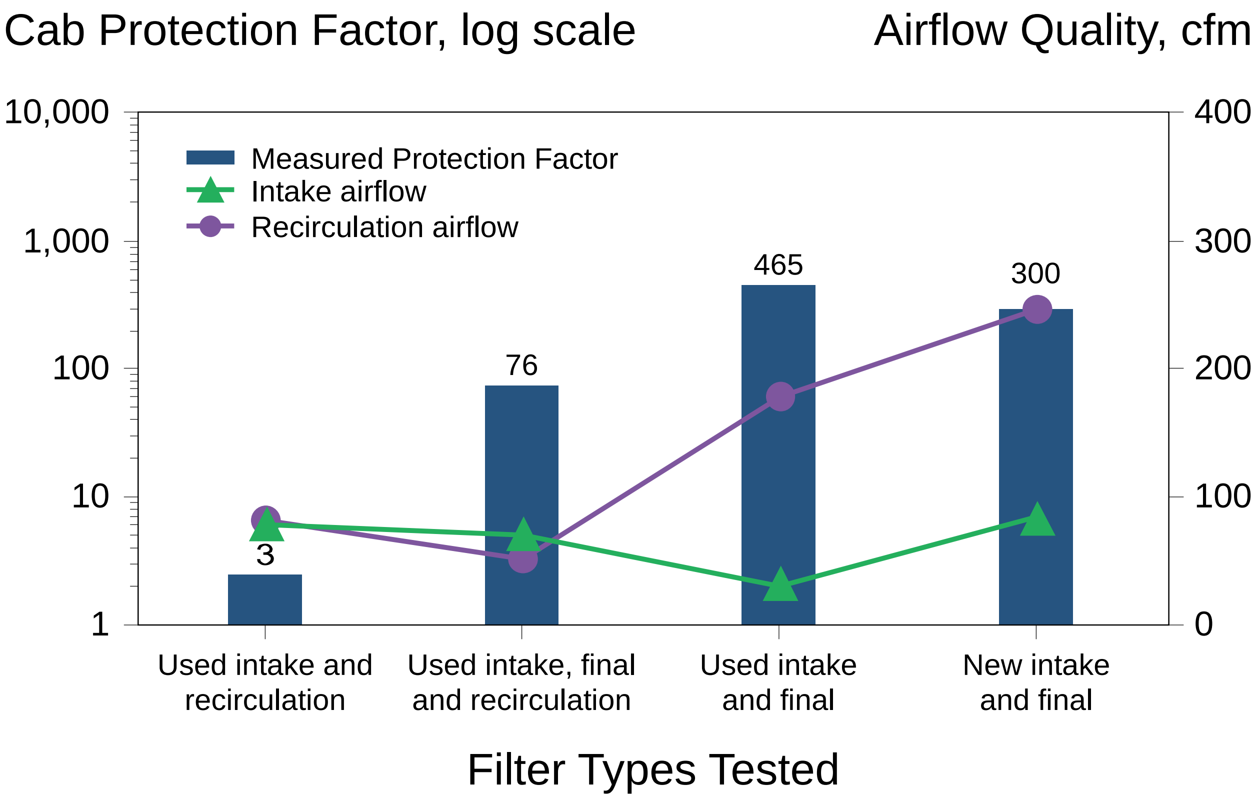


Figure 10.5. Bar chart comparison of cab performance variations with respect to different filters used in a filtration and pressurization system in a field study.

KEY COMPONENTS FOR EFFECTIVE ENCLOSURE OF FILTRATION AND PRESSURIZATION SYSTEMS

The advancement of engineering and scientific knowledge gained from the research efforts described above has led to the understanding and development of key critical components and design features for effective filtration and pressurization systems. To improve the air quality inside enclosures and lower respirable dust and other contaminants, the two most necessary components are as follows:

1. A competent filtration system comprised of a pressurized intake and a recirculation component. This system cleans both outside and inside recirculation air that is brought into the enclosure.
2. An enclosed area with structural integrity to minimize air leakage around the filtration system and to achieve positive pressurization.

Further, the most effective filtration and pressurization systems are usually those that are integrated into the HVAC units.

As an overview, Figure 10.6 shows a general design of a filtration and pressurization system for two typical applications—one showing an enclosed cab and the other showing a control room or operator booth application. The types of filtration system applications are not limited to these specific examples but would be interchangeable between both applications. In the remainder of this chapter, the two key components—a competent filtration system and an enclosed area with structural integrity—are addressed, along with numerous secondary design considerations that should be considered to reduce contaminants and improve the air quality in enclosures when using filtration and pressurization systems.

Ensuring Enclosure Integrity by Achieving Positive Pressurization against Wind Penetration

Enclosure integrity is necessary in order to achieve pressurization, which is critical for an effective system. Testing has shown that installing new door gaskets and plugging and sealing cracks and holes in the shell of the enclosure have a major impact on increasing the enclosure pressurization. To prevent dust-laden air from infiltrating into the enclosure, the enclosure's static pressure must be higher than the wind's velocity pressure [Heitbrink et al. 2000]. Equation 10.5 is used to determine the wind velocity equivalent for an enclosure (the wind velocity at which the cab is protected from outside infiltration as determined by the static pressure):

$$Wind\ velocity\ equivalent = \left(4000\sqrt{\Delta p_{cab}}\right) fpm \times 0.011364\ mph/fpm \quad @\ standard\ air\ temperature\ and\ pressure \tag{10.5}$$

where Δp = cab static pressure in inches wg.

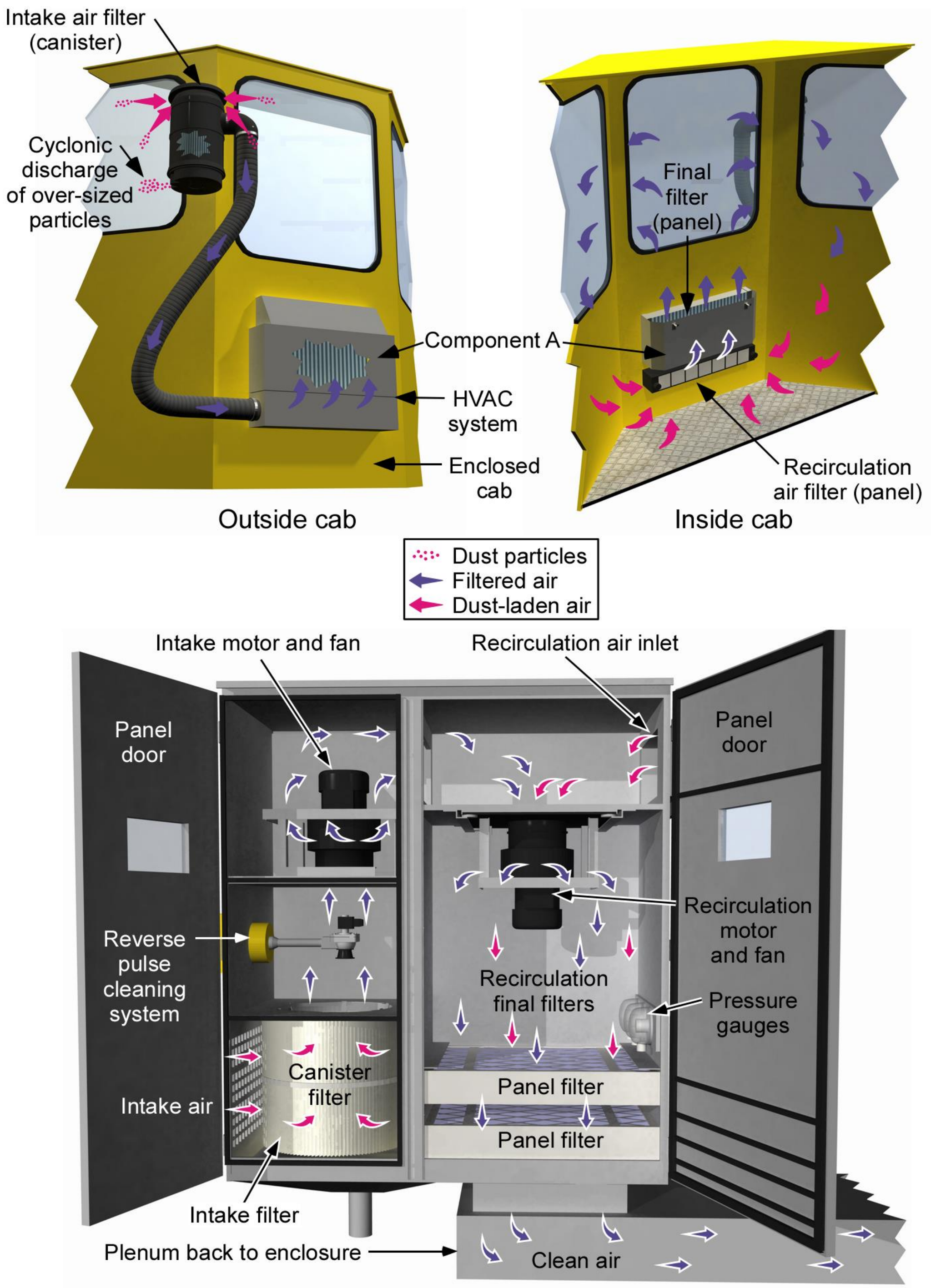


Figure 10.6. Examples of effective filtration and pressurization system designs. The top illustration shows a system for an enclosed cab using a cyclonic precleaning canister intake air filter with a panel recirculation and final filter. The bottom illustration shows a system design for control rooms and operator compartments with a reverse pulse cleaning canister intake filter and two panel filters in series used for recirculation cleaning and final filter design.

Figure 10.7 provides a graphical display of this wind velocity equivalent. This shows that enclosure pressures of 0.05, 0.1, 0.25, 0.5, and 1.0 inches wg would be able to withstand wind velocities of 10.2, 14.4, 22.7, 32.1, and 45.5 mph, respectively, from penetrating dust into the enclosure. Although minimum pressurization has been shown to have positive results from field studies, a good rule of thumb is to have at least 0.05 inches wg of positive pressure in enclosures. A reasonable range of enclosure pressure is between 0.05 to 0.25 inches wg.

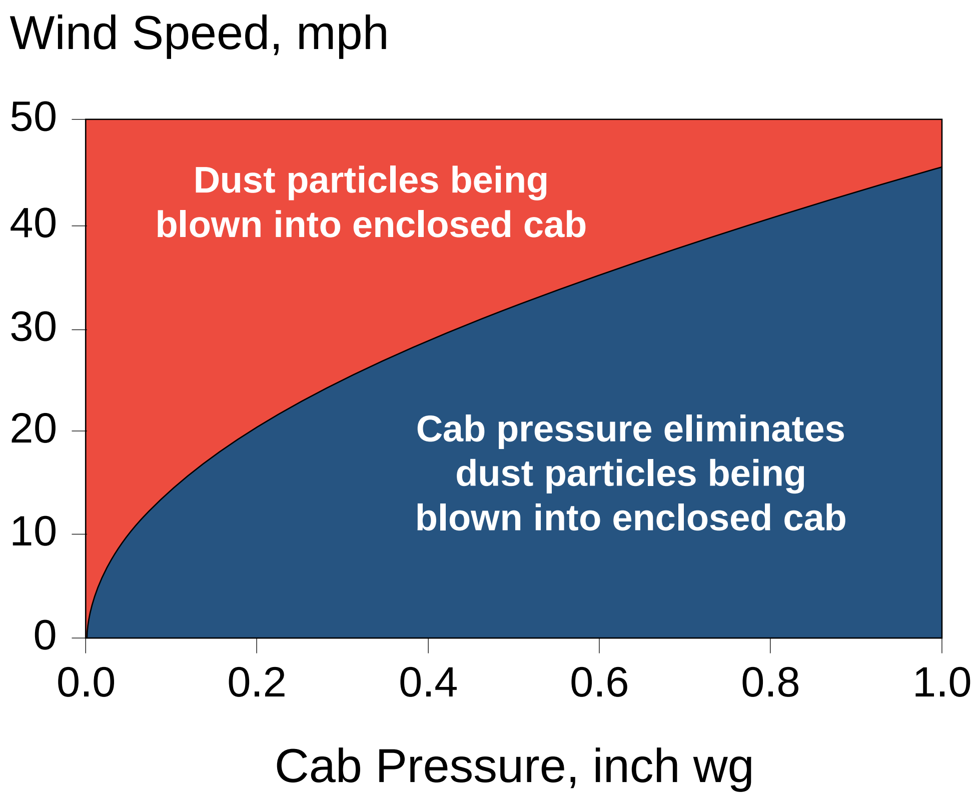


Figure 10.7. Graph showing how positive cab pressure is necessary to prevent dust-laden air from infiltrating an enclosed cab at various wind velocities.

Effective Pressurized Intake Air

An effective pressurized intake air component provides numerous important functions in an optimized system. First, it provides the required amount of outside air to ensure the equipment operator does not become asphyxiated from being in an enclosed area. A minimum quantity of at least 25 cfm of intake/outside air per person is necessary to dilute the CO_2 quantity exhaled by each worker [ASABE 2013; ASHRAE 2007]. Considering that enclosed cabs on mobile equipment are almost always designed for a single operator, a recommended lower limit for pressurized intake air would be somewhere around 40 cfm in order to achieve minimal cab pressurization while also ensuring a level of safety in regard to the CO_2 issue. A good rule of thumb for an acceptable pressurized intake air range is between 40 and 140 cfm. For crusher operator booths and controls rooms, it is recommended to increase this minimum value of 40 cfm by 25 cfm for each additional worker that could be in the enclosure for any time period. For example, for a control room where there can be three workers, the minimum intake air should at least be 90 cfm (40 cfm + (25 cfm × 2 operators)).

The second important aspect in relation to an intake air component is to create enough positive pressurization to prevent the wind from blowing dust and contaminants into the enclosure (discussed above). The amount of intake air delivered to create this pressurization must be carefully controlled and optimized. Optimal intake air quantity is relative to the size of the enclosure, the number of occupants, the capacity of the enclosure to hold pressure, and the efficiency of the intake and recirculation filtration. Maintaining the correct balance between these factors over extended periods is the goal of an optimized system. Increasing the air volume beyond this point degrades the system by increasing particle penetration and decreasing filter efficiency by allowing more contaminants to flow through the filter media. As the intake air volume increases, it creates higher demands on the HVAC system to either heat or cool the air for operator comfort, which is another reason to optimize the intake air volume.

High-efficiency intake filters are also a necessity for an effective design. For the majority of enclosures in mining and construction applications, a MERV-16 intake filter using mechanical filter media would be the optimal design. A MERV-16 filter media with a greater than or equal to 95 percent filtering efficiency on particles in all respirable-sized ranges (i.e., 0.3–10-micron particles) would be optimal (see Table 2.3 in Chapter 2—Fundamentals of Dust Collection Systems). This filter should also be fabricated mainly from mechanical filter media, which becomes more efficient as it loads with dust and develops a filter cake, thus becoming even more efficient at removing particles from the intake airflow over time and use. Both the MERV-16 and the mechanical filter media recommendation will be discussed in greater detail in the "Secondary Design Considerations" section to follow.

The last critical aspect is that the intake be a powered unit versus a static (non-powered) system. Figure 10.8 shows two types of recommended powered intake systems as compared to the static design. On a powered unit, the intake air has its own fan, so the air is delivered into the cab regardless of the fan airflow setting on the HVAC unit. In this case, a more consistent range of intake air is always being blown into the enclosed cab. As the intake filter loads with dust, the intake air quantity will decrease, but there is a more consistent air quantity range from a clean to a fully loaded filter. In addition, there are two proven techniques that can be used to minimize dust loading on the intake filter: the use of a self-cleaning filter technique (Figure 10.8A) or the use of a centrifugal design that spins out the oversized dust particles (> 5.0 microns) before the intake filter (Figure 10.8B).

A common self-cleaning method is a reverse pulse or backflushing technique, which uses a compressed air system to blow the dust cake off the filter. This reverse pulse can be set up on a regular time interval or based upon a differential pressure across the filter. With the centrifugal design, the system spins the oversized particles out of the system back into the atmosphere to minimize the number of particles being deposited on the intake filter. This system has an approximately 90 percent efficiency with particles greater than 5 microns. Both of these techniques have been tested and were shown to be very effective at providing a more consistent quantity of intake air to the enclosed cab while minimizing dust loading on the intake filter [Cecala et al. 2004; Cecala et al. 2012]. In a static design (Figure 10.8C), the actual intake air quantity is more dependent on the loading rate of all the filters used in the system; thus, it is difficult to determine or control the intake to recirculation air ratio. It also becomes much more difficult to ensure that the minimal air quantity of 40 cfm is being maintained.

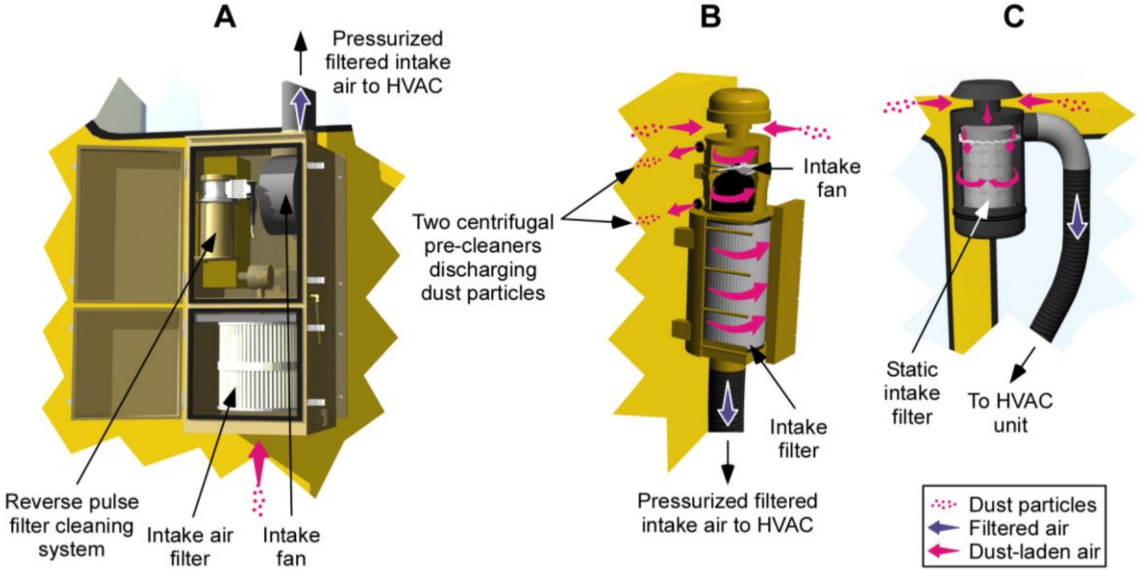


Figure 10.8. Illustration of two types of recommended powered intake systems. A and B show a powered unit design (recommended) while C shows a static, non-powered system (not recommended).

Effective Recirculation Filtration

The use of the recirculation system is a very important component for any filtration and pressurization system design, and a range of operating parameters can be used to achieve an effective system. The first area to consider is the filtration efficiency of the recirculation filter, and the recommended range should be between a MERV-14 and a MERV-16 filter (see Table 2.3 in Chapter 2—Fundamentals of Dust Collection Systems). A MERV-14 filter media has a 75 percent to 84.9 percent capture efficiency on 0.3- to 1.0- μm particles and > 90 percent capture efficiency on respirable particles > 1.0 μm. The actual operating conditions where the environmental enclosure is located should dictate the filter efficiency rating chosen, and this rating should be based upon such factors as the dust type, the silica content, the dust levels and dust sources inside the enclosure, the frequency with which workers enter or exit the enclosure, or even how often a worker opens a door to perform a task or communicate with coworkers. It must be remembered that the ultimate effectiveness of the recirculation system is determined by the reductions that can be achieved by way of multiple cycles of the interior enclosure air through the recirculation filter [Organiscak and Cecala 2009].

The other consideration with the recirculation component is the volume of air recirculated and its proportion to the amount of intake air. Optimally, the amount of recirculation air should be in the range of three to four times greater than the quantity of intake air—thus normally being in the range of 200 to 300 cfm for a typical enclosure. When the recirculated air is in this range, it can quickly remove dust from enclosure contaminants or from workers entering or exiting the area. Even a 1:1 ratio of intake to recirculation air could be used, but this is not as effective because it requires more tempering of the air for heating or air-conditioning needs. Laboratory experiments have shown that the protection factor increased from 3.4 to 10.5 times more than with the intake filter alone when using an at least > 70 percent efficient filter on submicron particles (0.3–1.0

μm). Laboratory testing also showed that the time for the interior to stabilize after the door was closed (decay time) was reduced by more than 50 percent when using the recirculation filter. The average decay times were between 16 and 29 minutes without the recirculation filter and between 6 and 11 minutes with the recirculation filter. Thus, the use of a recirculation filter greatly improved the air quality and reduced the exposure time after the cab door was closed [NIOSH 2007; NIOSH 2008a; Organiscak and Cecala 2008]. One additional benefit of using a recirculation filter is that it allows cleaner air to be circulated through the HVAC system, thus providing better thermal efficiency and resulting in less maintenance.

Use of a Three-filter System (Final Filter)

Filtering and pressurizing environmental enclosures with cleaned outside air is foundational to achieving any meaningful reductions in contaminants. Regarding the number of filters used in a filtration and pressurization system, a one-filter system that only filters the intake air can be effective and is superior to not providing any filtering. Also, adding a recirculation component only further enhances the air cleaning capabilities of the system to achieve lower airborne contaminant levels inside the environmental enclosure. Further substantial and cost-effective improvements in contaminant reductions can be achieved by adding a high-efficiency final air filter to the system. Importantly, this type of ultimate filtration system needs to be designed up front so the HVAC fans can be selected to accommodate the additional restriction and pressure drop of a high-efficiency final filter.

With the above guidelines in mind, a three-filter system with a final filter arrangement should be used whenever possible because it greatly improves the performance of filtration and pressurization systems in environmental enclosures and has been verified through both theoretical and field tests. From a theoretical standpoint, Figure 10.5 and Table 10.3 demonstrate the model design layout and the calculated system performance when a final filter is used in a filtration and pressurization system. This performance is also confirmed in a field study in Figure 10.9, which shows the actual PF along with the measured intake and recirculation airflow based upon a matrix of various filter arrangements. This figure shows the comparison of the measured cab PFs and the modeled cab PFs, with reasonable agreement along a unity line for both the face drill and the roof bolter machines. The spread in the data is presumed to be primarily a result of the actual unknown field leakage deviations from the assumed modeled leakages. This figure shows that the lowest PFs were measured and modeled when no final filter was used. Additionally, the opening points in the figure show there was no observable cab PF benefit from adding the recirculation filter into the system when using the final filter. Adding the recirculation filter into the system significantly reduced the recirculation airflow and cab PF [Cecala et al. 2016].

A negative aspect of not having the recirculation filter in the system is that dirt and dust from inside the cab would get drawn into and deposited in the HVAC system, thereby increasing maintenance issues. An alternative solution to improving this cab filtration system would be to increase the size of the recirculation filter to increase its airflow capabilities. Finally, multiple leakages in the HVAC/filtration system can have a significant impact on cab PFs, as seen when comparing the measured and modeled PFs of the two vehicle cabs. Therefore, the cab HVAC/filtration system needs to be well sealed to extract the benefits of using high-efficiency dust filters.

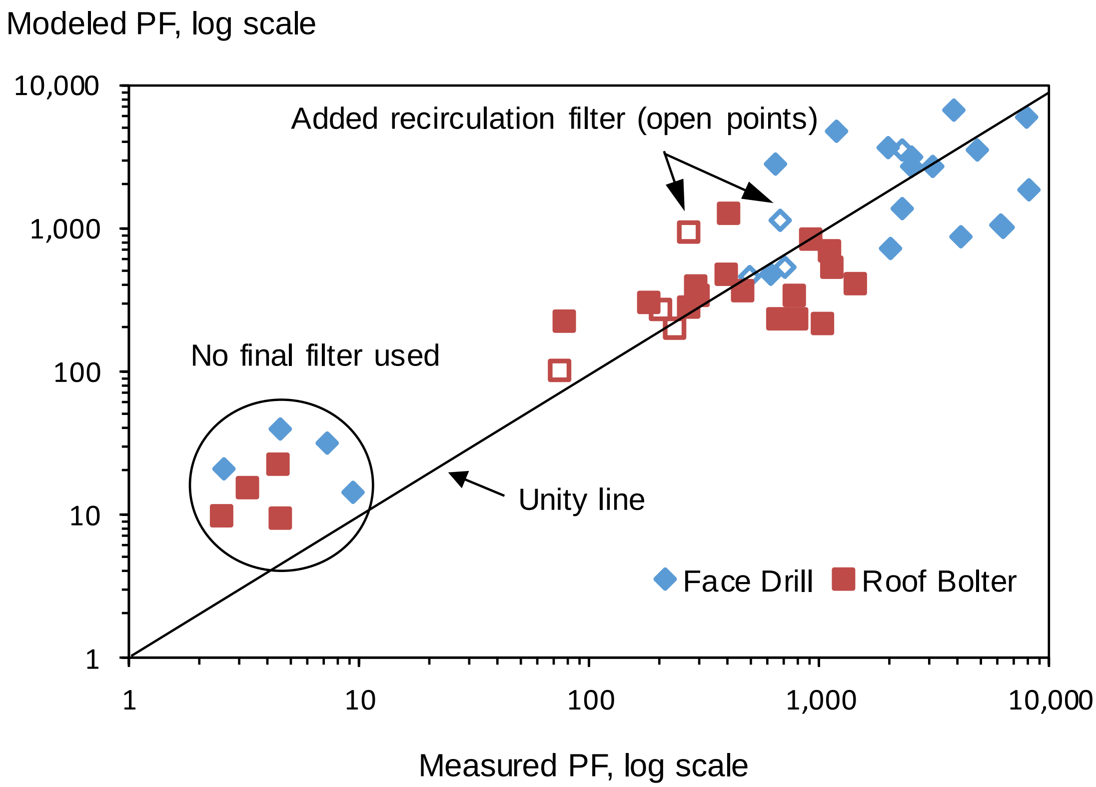
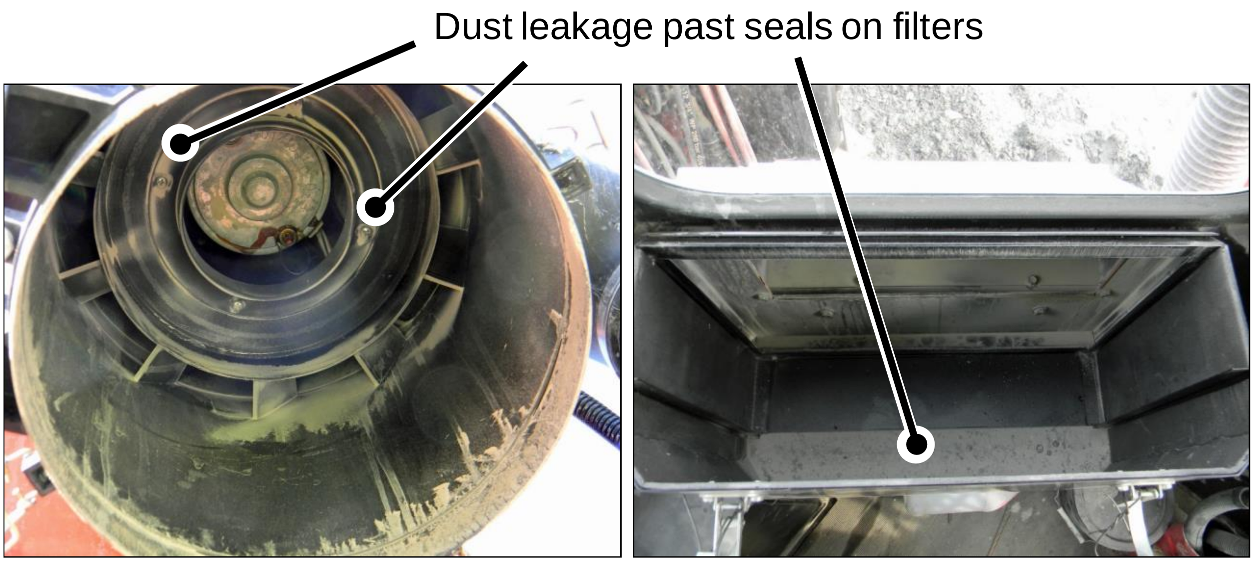


Figure 10.9. Graph showing the measured and modeled protection factors of a face drill and a roof bolter during field testing with different filter combinations.

Cab Integrity

The second key component for an enclosed cab system—structural integrity—is necessary in order to achieve pressurization, which is critical to system effectiveness. Testing has shown that the installation of new door gaskets and seals, as well as plugging and sealing cracks and holes in the shell of the enclosure, has a major impact on increasing the enclosure pressurization. To prevent dust-laden air from infiltrating the enclosure, the enclosure's static pressure must be higher than the wind's velocity pressure, as discussed above.

In addition to maintaining the integrity of the structure on enclosed cabs as outlined above, integrity is also important in regard to the filtration and pressurization system. Gaskets and seals within the filtration and pressurization system also need to be monitored and changed when signs of age (cracking or wear) or damage occur. Such aging can cause dust-laden air to be drawn into the unit, bypass the filtration component, and be blown directly into the cab. In addition, it is also beneficial during inspection of the system to determine the cleanliness of the unit's ductwork. Dust seen inside the ductwork on the clean air side of the system is a good indication of a system failure (Figure 10.10).



Photos by NIOSH

Figure 10.10. Dust leakage path past seals on a canister filter (left) and a panel filter (right).

Secondary Design Considerations

The following are secondary design considerations for an effective filtration and pressurization system for environmental enclosures.

Intake Air Inlet Location

The intake air inlet pickup location needs to be considered in the system design. Locating the air inlet near major dust sources causes unnecessary high dust loading on the air filtration system. This high dust loading burdens the filtration system and reduces its effectiveness by increasing the pressure drop across the loaded filter and decreasing the quantity of air and cab pressurization. In addition, the increased pressure drop across the loaded filter also increases the potential for dust leakage around the filter cartridge. This requires that the filter cartridge be cleaned or changed more frequently, which also increases the filter cost. Finally, air filtration is based on relative dust capture efficiency, so filtering higher outside dust levels creates higher inside cab dust concentrations.

In an effort to minimize these effects, it is recommended to place the enclosure's air inlet location strategically away from dust sources to reduce dust loading of the filter cartridge [NIOSH 2001a]. This can usually be accomplished by locating the outside air intake inlet at higher levels, away from the ground, and on the opposite side from dust sources. This location also enables the cab to shield some of the dust from the inlet.

Keeping Doors and Windows Closed

In order to achieve and maintain enclosed cab pressurization, doors and windows must be closed at all times except while the operator is entering or exiting the cab. This problem was noted during a field study on a surface drill when the operator repeatedly opened the cab door to manually guide the drill steel into place each time an additional section was needed [Cecala et al.

2007; NIOSH 2008b]. The cab door was usually open somewhere between 20 and 45 seconds each time this process took place before being closed again. Because no drilling was occurring and no dust cloud was visible as the cab door was opened, the impact to the drill operator's respirable dust exposure was initially thought to be insignificant. However, when dust data from inside the enclosed cab were analyzed, a substantial increase in respirable dust concentrations was noted during the periods when the door was open. This significant increase was unexpected when one considers that drilling had ceased approximately two minutes before the door was opened. Figure 10.11 shows average concentrations for each of the three days of testing for the time period when the cab door was closed and open. The average concentration for all three days was 0.09 mg/m^3 with the cab door closed and 0.81 mg/m^3 with the door open. Despite no visible dust cloud during the time when the cab door was open, respirable dust concentrations inside the cab were nine times higher than when the door was closed and drilling was being performed.

The results of this testing clearly stress the importance of keeping doors and windows closed at all times in an effort to keep the compartment pressurized and working properly. Again, the only exception to keeping the door closed should be when the equipment operator enters or exits the cab. It also needs to be stressed that even when dust clouds are not visible outside, respirable dust levels can be significantly higher than filtered levels inside cabs.

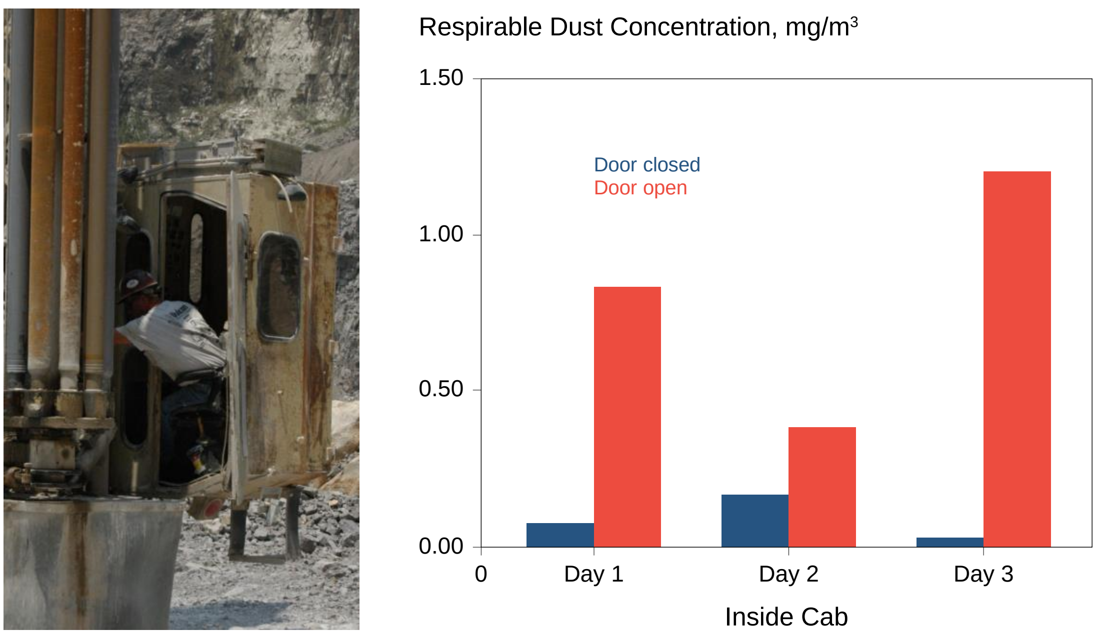


Photo by NIOSH

Figure 10.11. Bar chart showing respirable dust concentrations inside an enclosed cab for three days of testing with the cab door closed and open. The photo shows the operator opening the cab door and significantly increasing his exposure, even though drilling had ceased two minutes earlier.

Floor Heaters

Any type of floor heater or fan located low in the enclosed cab that can stir up dust should be eliminated for an effective design. During a field study, it was found that a floor heater fan used during the winter months to provide heat to an operator of a surface drill greatly increased the respirable dust concentrations inside the enclosed cab (Figure 10.12) [Cecala et al. 2001; NIOSH 2001b]. The floor heater can be a serious problem because the floor is the dirtiest part of the cab from the operator bringing dirt in on his or her work boots. Then, as the operator moves his or her feet around, dust is created, which is then blown throughout the cab by the fan on the floor heater. This fan also tends to stir up dust that may be on the drill operator's clothes.

Because of the significant increase in dust levels with floor heaters, it is recommended that they not be used. If removal is not an option, they should be repositioned to a higher area in the enclosure where they are less prone to pick up dust from the floor and operator's clothing. Also, no type of fan should be used low in the cab because of the potential to stir up in-cab dust sources. Ideally, the heater unit should be tied into the filtration and pressurization unit to deliver the heated air at the roof of the cab.

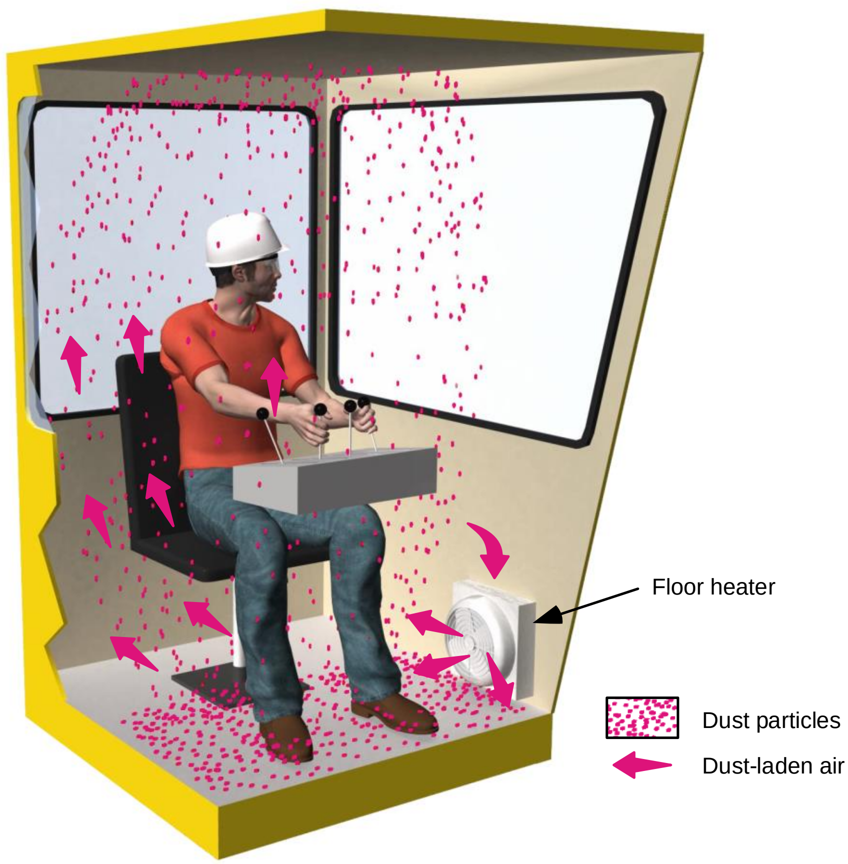
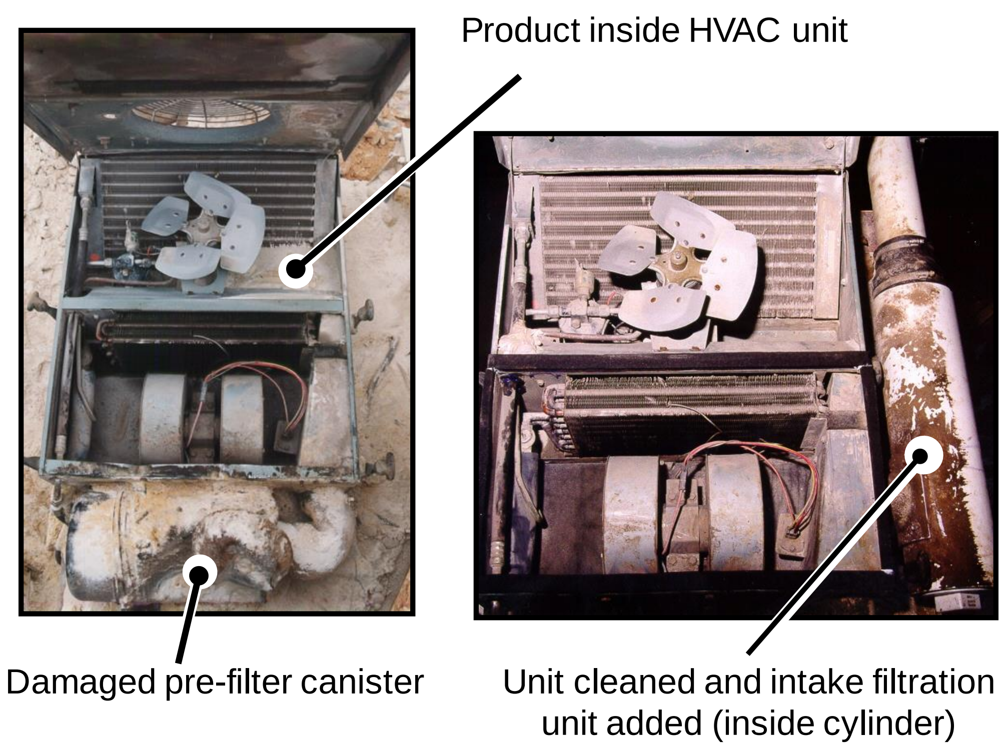


Figure 10.12. Illustration of the problem created by a heater stirring up dust from the floor and blowing dust off of the worker's clothing.

Cab Upkeep, Maintenance, and Cleanliness

To maintain pressurization and filtration systems, good housekeeping practices are essential in that systems need to be cleaned periodically and filters need to be changed when necessary. In addition, the enclosed cab must also be inspected for integrity and signs of wear. This ensures that pressurization is maintained by replacing worn gaskets and seals and by plugging and sealing holes and cracks in the wall, ceiling, and cab floor. A system that is not properly maintained will deteriorate over time to a point where it no longer provides an acceptable level of protection, thus causing workers to be exposed to respirable dust.

During NIOSH field studies, a number of filtration units were found in all forms of disarray and had deteriorated to a condition where they were no longer providing acceptable levels of protection to the worker (Figure 10.13, left). In some cases, it appeared that the air quality or the protection provided to the worker was not a priority as long as the operator remained comfortable in regard to temperature controls. Although many cabs used standard heaters and air conditioners to control temperatures, in some instances, workers resorted to simply opening windows in an effort to be comfortable, thus bypassing the protection provided by the enclosed cab. With a little time, effort, and financial investment, effective maintenance can be performed on filtration and pressurization systems to transition them from being poor systems to ones that will again provide clean and acceptable air quality to workers (Figure 10.13, right).



Photos by NIOSH

Figure 10.13. Damaged filtration units, representing poor housekeeping. The left photo shows a filtration unit with an obvious lack of maintenance and care, and the right photo shows the unit after cleaning and with the addition of a new intake air filtration unit.

Enclosure floors are commonly soiled from workers tracking dirt and product inside the enclosure upon entering from the mine site. In almost all cases, a substantial amount of dust and product gets tracked into the cab, and therefore, housekeeping should be performed on a daily or shift basis. It is critical that the inside of an enclosed cab be maintained in a manner that minimizes the worker's respirable dust exposure, understanding that some types of interior materials or cleaning materials can reduce dust from being generated. In limited testing, the use of a sweep compound when applied to rubber/vinyl floor matting used along with vinyl seat material was shown to be effective in reducing dust levels as compared to carpeted floors and fabric seats [NIOSH 2001c].

Ease of Filter Change

When designing filtration and pressurization systems, one key component is the ease with which filters can be replaced when necessary. It defeats the purpose of a good system if a filter to be changed is so difficult to access that the operator or maintenance worker does not want to take the time to perform the task. Another consideration is dust contamination during the filter change. It also should be noted that in many cases, this dust-laden filter will have some percentage of silica mixed in with the other types of dust—therefore, extreme care should be taken to minimize the exposure to the worker changing the filter. The easier a filter is to change, the less contamination that should occur to the worker performing the task and to the work area. When changing a canister filter, a common and effective technique is to remove the new filter from the cardboard box and then insert the old dust-laden filter into the box, tape it closed, and dispose of it.

Mechanical Filter Media

It is highly recommended that both the outside air and recirculation filters be a mechanical filter media as compared to an electrostatic media. Mechanical filters become more effective as they load with product. This occurs because as the filter loads with dust, a dust cake forms on the filter media and captures additional dust particles, which further improves the filter efficiency. As the size of this filter cake continues to increase, the efficiency continues to increase. This causes the pressure differential across the filter to increase, which in turn causes the airflow to decrease. As the pressure increases further, it will become so restrictive that the filter will need to be cleaned or replaced.

Filtering Efficiency—MERV-16 versus HEPA Intake Filtration

Three recent studies verified the benefits of the MERV-16 intake filter by comparison to a high-efficiency particulate air (HEPA) filter. In the first study, the contaminant tested was DPM. In a laboratory test, a MERV-8, MERV-16, and two HEPA filters were tested, and the results indicated that the filter capture efficiencies were approximately 50 percent, 96–98 percent, and over 99 percent, respectively, for DPM [Noll et al. 2010]. This study highlighted that the MERV-16 filter was less expensive and less restrictive to cab airflow than the HEPA filters and most likely the optimal choice.

A second study compared an F95 filter (efficiency on > 0.3-µm particles—MERV-16 filter) to an F99 filter (efficiency on > 0.3-µm particles—HEPA filter) in a single-filter system in a crusher operator booth at an underground mine. This testing was performed over a 15-month period, examining the differences of two filter types as they loaded with dust and contaminants. The results of this study showed that the F95 filter was five times more effective than the F99 filter [Patts et al. 2017]. In a simple bench test on these filters using particle count instruments at NIOSH's laboratory in Pittsburgh, the results showed that the F99 filter had at least 2 percent higher efficiency at removing submicron particles. However, this filter was also more restrictive, which exacerbates any leakage paths as well as reduces the airflow because of the additional resistance. In comparison, the F95 filter allowed 1.7 times more airflow, while the field results showed a 1.8-times improvement. This vast improvement in airflow more than made up for any difference in filter efficiencies.

To further demonstrate the difference in the filter media, as well as account for the differences that may have occurred throughout the study (seal degradation, additional holes being drilled in booth, etc.), four unique filters (F95 used, F95 new, F99 used, F99 new) were tested in the booth during a single shift. When the protection factor was calculated in an identical manner as was done for the monthly samples, these tests resulted in the F95 filters outperforming the F99 filters by a factor of 3.87, for an average PF of 60.9 vs. 15.7. Even an end-of-life loaded F95 filter performed 2.5 times better than a brand new F99 filter.

The third study was performed at an underground mining site comparing MERV-16 to HEPA filters on two pieces of mobile equipment (roof bolter and face drill) over a two-year period [Cecala et al. 2016]. In this study, whenever the intake airflow on either piece of equipment reached or dropped below the 25-cfm level, a new intake filter was installed. When this occurred, after taking the particle count and airflow measurements with the old filter as a comparison, a new intake filter was installed and the particle count and airflow measurements were repeated. For the face drill testing using MERV-16 filters, there were no intake filter changes necessary (Figure 10.14). By comparison, for the HEPA testing, new intake filters were necessary on three occasions. Comparing the decline in the intake airflow shows how quickly the HEPA filters loaded with dust and diesel particles and needed to be replaced. This graph shows the starting point for intake airflow and cab pressure for both filter types and then how these values declined as the both the intake and final filters loaded with dust. This graph also highlights how the operating life cycle for the MERV-16 filter was superior to that of the HEPA filter with higher cab pressure throughout the life cycle. Recirculation airflows for both cabs were between 144 and 247 cfm for the MERV-16 final filter and between 135 and 207 cfm for the HEPA final filter, with the HVAC on the highest fan setting during the study.

In the majority of mining and construction applications, it is believed that MERV-16 filters—having a greater or equal to 95 percent filtering efficiency on particles in all respirable-sized ranges—i.e., 0.3–10-micron particles—would be the optimal choice over HEPA filters. In order for HEPA filters to meet a 99.97 percent filtering efficiency on respirable-sized particles, the filtering media is much more demanding and restrictive than in MERV-16 filters. This restrictiveness decreases the amount of airflow passing through the filter, which decreases the filtering efficiency of the overall system. In addition, this restrictiveness also equates to an increased pressure across the filter, thus creating a greater likelihood for airflow leakage paths around the filter media, which also lowers the system's effectiveness. Over time and use, as the HEPA filter builds a dust cake, this only further exacerbates both issues. Since HEPA filters are more expensive than MERV-16 filters and would have to be changed much more frequently, they are less attractive on a cost comparative basis.

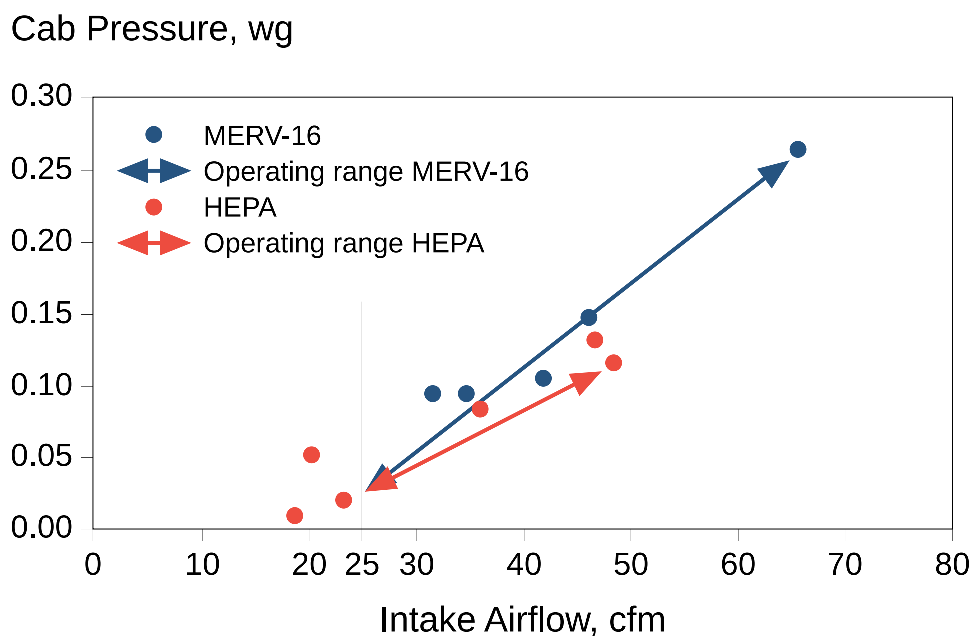


Figure 10.14. Graphical comparison of the intake airflows and positive cab pressures for a face drill test at a mine site comparing MERV-16 and HEPA filters.

Determining Cab System Performance Using a Pressure Monitor

An effective method to monitor a cab filtration and pressurization system's performance is the use of a pressure differential indicator, which notifies the operator of pressure changes between the interior of the environmental enclosure and the outside ambient environment. A pressure monitor provides a real-time indication of an environmental enclosure's performance and can also provide instantaneous notification of a major system failure or flaw.

NIOSH has evaluated three types of commercially available environmental enclosure pressure monitors to compare their ability to accurately measure and output enclosure pressure (Figure 10.15). The following three monitors were tested in both a laboratory and field study:

- Dwyer Instruments Incorporated, DM-2000-LCD Pressure Transmitter, Michigan City, IN.
- Hummingbird Electronics, Cab Pressure Monitor, HMPS1000BKIT, Taylors Beach, Australia.
- Sy-Klone International, Electronic Pressure Monitor System, KT-CABPRES-EL1-ENG, Jacksonville, FL.

In the laboratory testing, a matrix of these three instruments was arranged so that their inlets were on a single plane within the enclosure and their order was evenly distributed (3 x 3) to minimize bias on both the horizontal and vertical direction. Booth pressure was varied from 0 to 0.5 inches wg and was held for three minutes at each pressure point. Booth pressure was also randomized to remove the possible bias of instrument drift. This comparison was done in a level configuration and also at an angled one to mimic the usage conditions found on mobile equipment.

Photo by NIOSH

Figure 10.15. Comparison of three different types of pressure gauges in an experimental filtration laboratory test booth.

During the course of mining operations, mobile equipment necessarily traverses varied terrain, including hills, both in the horizontal and lateral planes, which causes pitch (ascending or descending hills) as well as roll (maneuvering sideways across a slope).

Of the three sensors tested, the Dwyer showed the largest response to pitch angle, underreading by as much as -0.11 inches wg with negative pitch and overreading by 0.07 inches wg with positive pitch. The Hummingbird showed an average error of -0.025 inches wg, while the Sy-Klone ranged from 0.05 to -0.05 inches wg. The Dwyer gauge is intended only to be mounted in a level orientation, and because of this, it should not be considered for use in mobile mining equipment unless the manufacturer eliminates this bias.

The three different pressure monitors were also tested in a crusher booth at an underground mine and compared to a certified pressure reference instrument (Figure 10.16) for a period of four months. The instruments' pressure ports were all plumbed together into one manifold so they had the same inside and outside reference booth pressure. Similar to the lab test results, all instruments underread: -0.018, -0.012, and -0.013 inches wg for the Dwyer, Hummingbird, and Sy-Klone instruments, respectively. The instruments' readings of cab pressure are plotted for a period of more than four months against a known standard in Figure 10.17.

Photo by NIOSH

Figure 10.16. Comparison test of three pressure monitors at a crusher booth at an underground mine compared to a certified pressure reference instrument. The Dwyer gauge is on the far left.

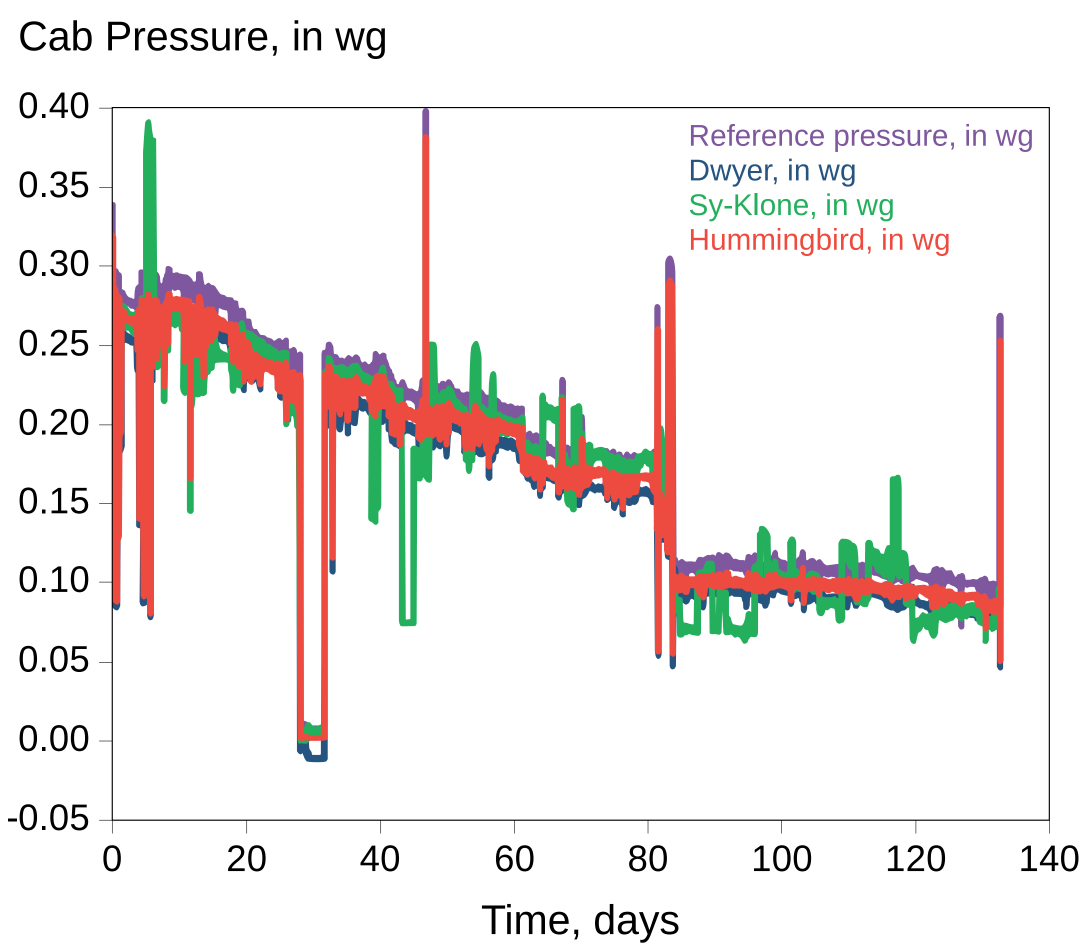


Figure 10.17. Graphical comparison of pressure readings from three units under a field test and one reference gauge during an in-mine test.

An adequate filtration system must be designed, installed, and maintained to ensure workers' protection against respirable particulates over the course of their shift. Since filter loading rates are different in all cases based on contaminant levels, using a filter cleaning or changing schedule based on time is not the preferred method because, as previously mentioned, a mechanical filter becomes more efficient as it loads. Pressure monitors offer an inexpensive and effective way to continuously track the performance of an enclosure's filtration system over time. By referencing the pressure immediately after a new filter installation, as well as that which allows air intake levels to drop below minimum airflow requirements, operators can estimate the filter's remaining life and better plan maintenance tasks. The monitor informs the operator or maintenance worker of the ideal filter changing time when the enclosure pressure has decreased to such a level that it is detrimental to the overall system performance and the system's ability to protect workers is compromised.

In addition to providing filter changing schedules, pressure measurements are also useful for determining overall system problems. For example, a sudden decrease in enclosure pressure may indicate that a door is stuck open, a seal is damaged, or something is clogging the intake ductwork. On the other hand, a sudden increase in pressure could include such things as a hole or tear in the filter media; a clog in the recirculation system such as a plastic bag or a rag covering the recirculation inlet; or even a maintenance worker removing a used filter and then forgetting to replace it with a new one.

Another attractive feature of pressure monitors it that the pressure can be logged and adjustable alerts can be set to inform the operator or mine staff of pressure levels that can be used to facilitate maintenance and filter changes. Models are available that can provide feedback directly to the operator in the form of a light or alarm as well as some that include an output that can be logged and monitored by mine staff.

Pressure monitors are available in various form factors and transducer types depending on the application. Transducers include both mechanical styles (flexible diaphragms) and electronic styles (piezoelectric strain gauges). All three pressure monitors tested and mentioned above are applicable for installations in stationary applications, such as operator compartments and control rooms. With regard to mobile equipment, of the units tested, only the Sy-Klone and Hummingbird pressure monitors are recommended. Currently, the Dwyer unit is negatively affected by horizontal and lateral changes in the orientation of the unit, which would occur in mobile equipment.

Enclosure pressure monitors provide valuable information to inform operators and mine staff when maintenance or filters changes are necessary on filtration and pressurization systems for environmental enclosures. As discussed, when using mechanical filter media, the filters become more efficient with loading and the creation of a dust or filter cake, and they should not be changed until they become detrimental to the overall system performance and the system's ability to have a sufficient intake airflow and maintain positive pressure. On the other hand, based on field experience, it is believed that the filters should be changed after a certain number of hours of use or at least once a year for integrity issues (mold, etc.)—even if the system is maintaining acceptable intake airflow and positive pressure.

Unidirectional Design

The use of a unidirectional airflow pattern, as shown in Figure 10.18, should be considered whenever possible to maximize the air quality at the breathing zone of the operator inside the enclosure. In most systems, both the intake and discharge for the recirculation air are located in the roof. Unfortunately, this location causes the dust-laden air within the enclosure to be pulled directly over the worker as it is drawn into the ventilation system. Further, in many designs, the contaminated return air and clean filtered air are ducted within inches of each other at the ceiling. This poor design allows for recirculated air to be short-circuited and allows dust-laden return air to be pulled directly back into the ventilation system and over the operator's breathing zone. A more effective design is to draw the recirculated air from the bottom of the enclosure and away from the worker's breathing zone [Cecala et al. 2009].

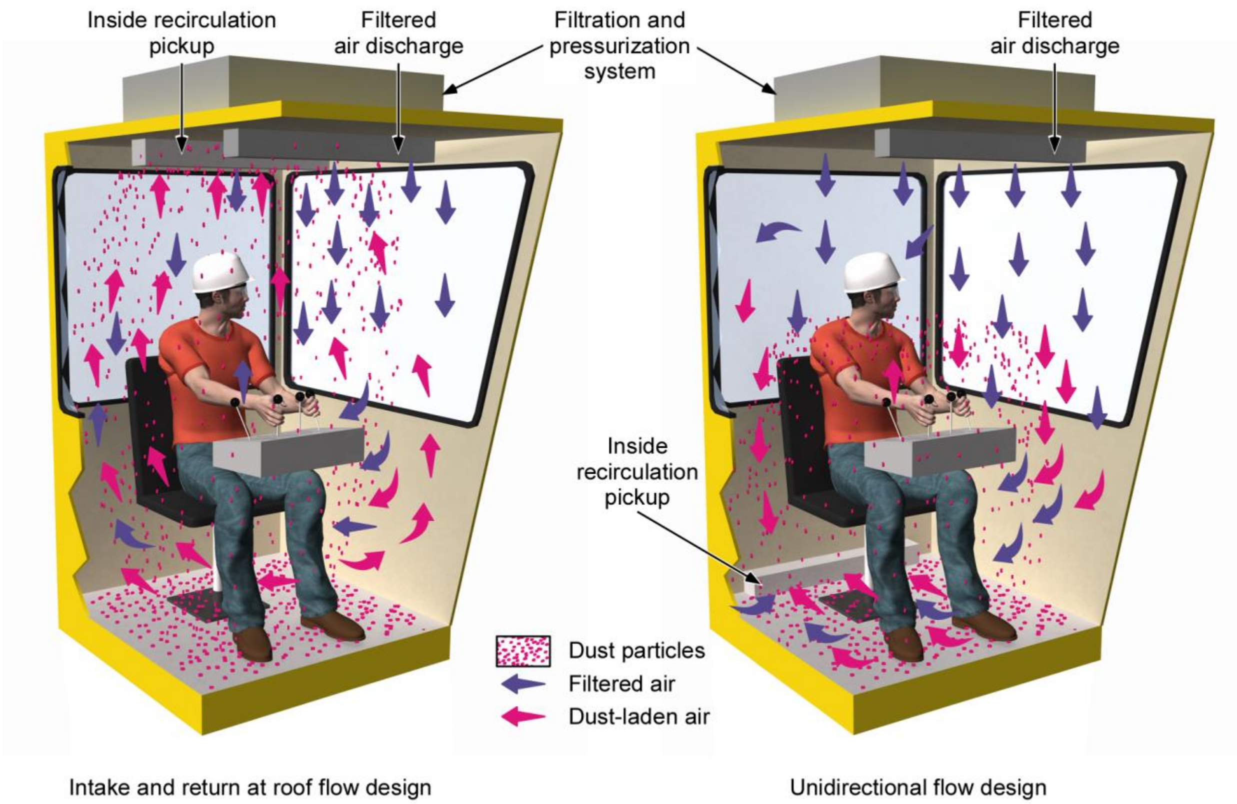


Figure 10.18. Illustration of the airflow pattern for intake and return at the roof of a cab and a unidirectional airflow design.

Ineffective Secondary Design Consideration—Small In-Unit HEPA Filters

In some operator booths and control rooms, stand-alone air purifier units containing a HEPA filter have been installed. These stand-alone systems are small and portable units that are available at a fraction of the cost of permanent systems. However, these systems can only be effective if they are sized to handle the volumetric capacity of the booth or control room and if the filters are replaced when necessary [Logson 1998/1999]. A shortcoming with these systems is they do not provide any pressurization to keep dust from leaking into the booth or room. A few studies have shown that in many instances, they do not provide sufficient protection, and companies would be better served to invest their money and time into improving their existing roof-mounted units [Cecala and Zimmer 2004a, 2004b]. Therefore, stand-alone air purifier units containing a HEPA filter are not recommended in most cases and should be replaced with more comprehensive and properly sized recirculation systems.

EVALUATION TECHNIQUES FOR FILTRATION AND PRESSURIZATION SYSTEMS

Sampling of airborne contaminants inside and outside of environmental enclosures is essential in determining the exposure of the occupants to various respiratory hazards and the relative effectiveness of the filtration and pressurization system at controlling airborne contaminants and protecting workers. In industrial mineral processing operations, respirable dust is normally the main contaminant being evaluated. Currently, there are three evaluation techniques that can be used for determining filtration and pressurization system effectiveness. In all three cases, one sampling unit is located outside and the other inside for a comparative evaluation and protection factor calculation. These are (1) gravimetric dust sampling, (2) light-scattering (nephelometer) sampling, and (3) particle counting sampling. Figure 10.19 illustrates the three different types of sampling instruments used for these evaluations.

Photos by NIOSH

Figure 10.19. Three types of sampling instruments used for determining filtration and pressurization system effectiveness. The left photo shows a personal gravimetric sampler, the center photo shows a nephelometer light-scattering instrument, and the right photo shows a handheld optical particle counter.

Gravimetric respirable dust sampling is performed using a size-selective cyclone, a constant-flow personal sampling pump, and a dust filter (Figure 10.19, left). From the mass-gain on the dust filter, along with the sampling time and flowrate, the average respirable dust concentration can be determined for the sampling period or working shift. By then comparing the outside and inside respirable dust concentrations, the protection factor can be calculated to provide a relative measure of the enclosure's overall dust reduction during the sampling period or shift. Gravimetric analysis is time-consuming and only provides an average concentration for the sampling period, but the dust mass can be analyzed for its silica content [NIOSH 2010]. Table 10.2 shows the data collected with this type of dust sampler.

The second dust evaluation method makes use of light-scattering instruments known as nephelometers. A nephelometer is an electronic light-scattering instrument that detects real-time respirable concentrations (Figure 10.19, center). Its real-time respirable dust concentrations can be calibrated to a gravimetric concentration by multiplying its dust levels by the ratio of the gravimetric to average nephelometer concentrations concurrently collected together [Listak et al. 2007; NIOSH 2010]. This real-time dust data can be analyzed for shorter time periods of a shift and was used to examine the dust concentrations measured inside a drill cab with the door opened and closed, as previously described and shown in Figure 10.11. Such real-time dust information allows for analysis of operational variables or work practices related to high respirable dust concentrations.

The third evaluation method—particle counting—is used to quantify filtration system performance with respect to the number and size of airborne particles removed. This measurement method is used by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to classify air filter efficiency ratings [ASHRAE 1999]. The American Society of Agricultural Engineers (ASAE) also previously devised a consensus standard for field testing a cab's protection factor performance with particle counters, specifying a minimum 50:1 cab PF performance criteria on 3-μm-diameter particles for pesticide applications [ASAE 1997]. NIOSH recommended using smaller submicron particles as test media for cab filtration system performance, given the larger number of submicron particles present in the air [Heitbrink et al. 1998].

The advantage of particle counting as compared to gravimetric sampling for measuring an enclosure's filtration system performance is that a large number of smaller particles in the submicron size range (< 1 micron) are available at lower respirable dust mass concentrations, providing a better test medium for comparative performance testing of environmental enclosures [Organiscak et al. 2004; NIOSH 2008a; Organiscak et al. 2013; Organiscak et al. 2016]. Figure 10.19, right, shows an example of a six-channel particle counting instrument that can detect six particle size ranges of 0.3–0.5 microns, 0.5–0.7 microns, 0.7–1.0 microns, 1.0–3.0 microns, 3.0–5.0 microns, and > 5.0 microns.

Particle counting performance testing of enclosures can use either a two- or one-instrument sampling methodology. Ideally, this type of testing should be performed at or near steady state concentration conditions, thereby measuring the optimum protection factor performance achieved by the enclosure's filtration system. Steady state enclosure conditions are achieved when the interior contaminant concentrations decrease to their lowest stable levels provided by the filtration system being challenged by uniform outside concentrations. To best achieve particle count testing near (resembling) steady state conditions, it is recommended that the environmental enclosure be stationary (particularly for mobile vehicle cabs) and unoccupied, with the filtration system operating in the ambient air during nonproductive periods or idle maintenance shifts. This stops ingress and egress into the environmental enclosure and moderates outside concentration variations during testing.

A two-instrument sampling methodology simultaneously measures the outside and inside particle count concentrations of the environmental enclosure. Since this sampling method introduces individual instrumental error biases into the particle counting measurements, it is recommended that the instruments be rotated between the sampling locations an equal number of times during testing to average out these biases. The two-instrument methodology was initially specified for mobile testing of a cab by ASAE and was primarily used by NIOSH in laboratory and field studies [ASAE 1997; Heitbrink et al. 1998; Hall et al. 2002; Heitbrink et al. 2003; NIOSH 2008a; Organiscak and Cecala 2008; Cecala et al. 2012; Organiscak et al. 2013; Cecala et al. 2016; Organiscak et al. 2016].

When performing this type of enclosure testing, particle concentrations should be continuously measured to detect when they reach their lowest and most stable interior levels for comparison with the outside concentrations for the same time period. In NIOSH laboratory and field testing, researchers typically conducted enclosure testing for 45 minutes when using only an intake filter and for 30 minutes when using both an intake filter and a recirculation filter [NIOSH 2008a; Organiscak and Cecala 2008; Cecala et al. 2012; Organiscak et al. 2013; Cecala et al. 2016; Organiscak et al. 2016]. The most stable data and the last 15 minutes of data for these test periods were averaged and were used for the protection factor calculations of each test discussed above.

A single-instrument sampling methodology removes instrument bias from the testing but does not continuously measure both sampling locations during enclosure testing. To perform this type of sampling, equal lengths of sample tubing are routed to the inside of the cab and outside of the cab near the intake airflow inlet. The particle counter should be initially used to monitor the inside of the cab until it reaches the lowest steady state conditions and then be alternated for several minutes between the inside and outside sampling locations. When alternating the instrument between sampling locations, the sample lines should be purged for at least the first minute, and the data collected after the line is purged should be used for determining the average inside and outside particle count concentrations. Sampling inside and outside the enclosure should be replicated at least twice and may require additional replications if the outside concentrations are highly variable during testing. This procedure was used to quantify cab submicron particle (0.3–0.5 microns) protection factors of at least 50:1 for a pesticide spraying company after refurbishing and performing maintenance on 13 tractor cabs [Moyer et al. 2005].

All three of the evaluation techniques discussed above are proven methods for sampling airborne contaminants inside and outside of environmental enclosures as a means to determine the reduction in contaminants and the ultimate protection afforded to workers from environmental enclosures. In choosing among the three techniques, mining and industrial mineral processing operations should consider such factors as the length of the sampling period or shift, the ability of the technique to analyze for silica content, the steady state enclosure conditions, and the need for real-time exposure information.

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Chapter 11: Haul Roads, Stockpiles, and Exposed Areas

CHAPTER 11: HAUL ROADS, STOCKPILES, AND EXPOSED AREAS

This chapter examines haul road dust emissions and control, a significant issue at surface mine sites (Figure 11.1), as well as dust generated at stockpiles and wind erosion of exposed areas. Generally classified as a fugitive dust, the source material for these emissions is typically mineral particles and soil disturbed during transport or stockpiling processes.

Past research has shown that haul trucks generate the majority of dust emissions at these surface sites, with their contribution being 78–97 percent of total dust emissions for particulate matter less than 10 micrometers (µm) [Cole and Zapert 1995; Amponsah-Dacosta and Annegarn 1998; Reed et al. 2001]. The high contribution of airborne respirable dust emissions from haul trucks has the potential to overexpose mine personnel, which is of heightened concern if this dust contains respirable crystalline silica.

Photos by NIOSH

Figure 11.1. Examples of haul road dust from mine haul trucks. The photo on the right, with the red box outlining a light fleet vehicle, shows the level of dust obstruction that can result from dusty haul roads.

As the right photo in Figure 11.1 illustrates, fugitive dust generated from haul roads can also result in reduced visibility, which creates safety concerns. Although there is no defined correlation between dusty conditions and vehicle accidents at mine sites, observations of extreme dusty conditions make it obvious that these conditions increase the potential for collisions.

HAUL ROADS

Mobile equipment travels haul roads and access roads to move material and personnel in and out of the mining areas. The road network at a surface mine site can be quite extensive, and the potential for dust generation depends upon the traffic patterns, quality of road construction, dust controls used, and weather conditions at the site. Overexposures to respirable dust can occur to both equipment operators and workers in the vicinity of the road.

Low-cost Alternatives

Although a properly constructed haul road is the most effective control, there are additional low-cost administrative aids that are effective in controlling dust emitted from haul road use. Such administrative controls include speed and traffic considerations.

Speed Control

A majority of the fugitive dust is generated through the forces of the wheels on the road surface and by the turbulence created by the vehicles [Moosmüller et al. 2005]. As the speed of haul trucks increases, the amount of turbulence and dust liberation also increases, as shown in Figure 11.2 [Thompson and Visser 2001]. In one study, reducing vehicle speed from 25 to 10 miles per hour (mph) reduced the generation of dust particles < 10 µm by approximately 58 percent, and by 42 percent when speeds were reduced from 25 to 15 mph [Watson et al. 1996]. In another study, limiting speeds on unpaved roads to 25 mph reduced dust levels by 44 percent [Countess Environmental 2006]. Although reducing the speed of vehicles traveling on haul roads can be an effective method for dust control, these actions may impact the production rate of the mine.

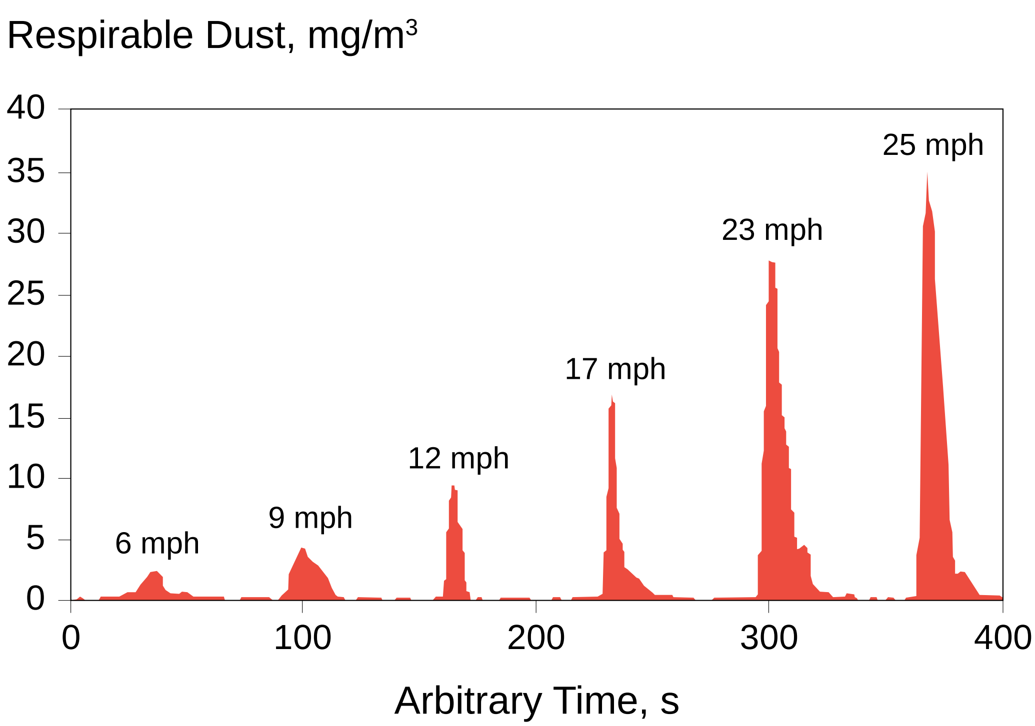

Figure 11.2. Graph showing a dust profile measured at roadside for a haul truck traveling at various speeds (mph) [adapted from Thompson and Visser 2001].

Traffic Control

If haul trucks travel in close proximity to one another on unpaved roads, the dust plume created by the leading truck can engulf the trailing truck and expose this driver to elevated dust levels. One study showed that maintaining a 20-second following distance between haul trucks resulted in up to a 52 percent reduction of respirable dust exposure to the trailing truck driver [Reed and

Organiscak 2005]. Also, this 20-second time interval allows for the dust cloud generated from the lead truck, which can impair the visibility of the trailing driver, to dissipate.

Additionally, the proper use and maintenance of enclosed cabs are important for controlling the dust exposure of the workers operating the haul trucks. Issues related to filtration/pressurization systems of mobile equipment are discussed in Chapter 10—Filtration and Pressurization Systems for Environmental Enclosures.

Basics of Road Construction

A properly constructed road has higher initial costs but requires less road maintenance; reduces equipment maintenance costs, including increased tire life; and aids in effective dust control. Specifically, dust control is improved through a reduction of fine material generated and an increase in the longevity of dust suppressants.

When a vehicle travels over a haul road, the wheels exert forces on the road surface. On a properly designed road, the compression and tension cycle occur within the elastic limits of the road structure. However, permanent deformation of the road can occur if it is not properly designed. Roads constructed of weak materials readily degrade, producing fine material that can be liberated and entrained by mobile equipment traveling the road. Additionally, road failure can cause any applied dust suppressant to exceed its bonding strength, reducing the effectiveness of the suppressant. Alternatively, roads constructed of the proper materials degrade less rapidly, lessening the dust emission potential of the road over the same period of use.

Materials selected for road construction must possess certain physical properties: resistance to wear, soundness, maximum size, particle shape, and gradation [Midwest Research Institute 1981].

- A high *resistance to wear* is desired for the road material so that it will not easily disintegrate under traffic load. The resistance to wear can be measured by conducting abrasion tests such as the Los Angeles abrasion test [AASHTO T 96-02 2015]. Generally, the most desirable materials include granite or limestone. Soft and unsound materials such as shale, coal, mica, or vermiculite should be avoided because they lower the road's strength and durability.
- *Soundness* of material is desirable because it represents the ability of the material to withstand climatic conditions. Materials that are weak, extremely absorptive, and easily cleavable, as well as those that swell when saturated or are susceptible to breakdown through natural weathering processes, are not recommended for road construction.
- *Maximum size* is the largest particle size allowable in the road material. Generally it is undesirable to use aggregate sizes larger than 1 inch for the surface course in order to maintain ease of maintenance with a road grader.
- *Particle shape* of the road material affects the stability, density, and durability of the road surface. Shapes that contain angular and rough-surfaced material result in good interlocking and produce a desirable road surface.
- *Gradation* is the distribution of particle sizes throughout the road material. A well-graded aggregate material contains a good representation of particle size fractions from large to small sizes of material.

Mine haul roads have unique construction requirements due to the support needed for wheel loads from large-capacity (up to 400 tons) off-road mine haul trucks. In addition to possessing the appropriate material properties, a properly constructed road consists of three components: *subgrade*, *subbase*, and *wearing surface* (Figure 11.3). Sufficient thicknesses of these three layers are important to enable the road to support the necessary loads, improve the life of the road, and minimize dust generation. The American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO) have standards that define the minimum properties required for a haul road.

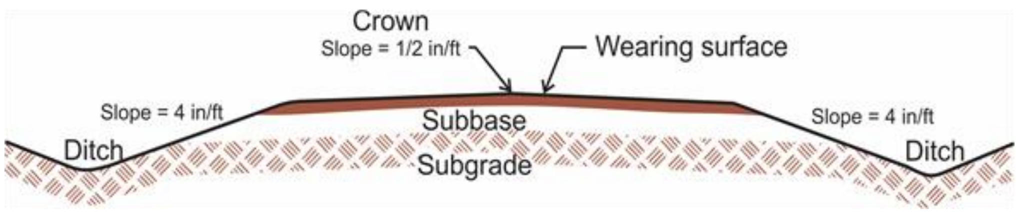

Figure 11.3. Illustration showing a cross section of a haul road.[30]

The *subgrade* is the underlying soil or rock that serves as the foundation of the road, supporting the entire load of the vehicles. There are two techniques for maximizing and maintaining subgrade strength: compaction at optimum moisture [AASHTO T 99 and T180 2015] and adequate drainage. To achieve maximum strength, the subgrade area should be scarified prior to adding water to the location. Then, compaction is generally accomplished using a vibratory compactor with a smooth drum roller [National Stone Association 1991]. Additionally, the subgrade should be designed with a crown in the center to promote proper water drainage away from the road. Any areas of the subgrade consisting of poor-quality material should be upgraded or repaired prior to adding additional bases to avoid frequent maintenance.

The *subbase* is the layer between the subgrade and the wearing surface. The material for the subbase layer is a compacted angular aggregate, is well-graded, and consists of material that has a broad particle size range (3 to 1.5 inches) depending on traffic density [Midwest Research Institute 1981]. The thickness of the subbase ensures that the surface load will be properly distributed over the subgrade area. To determine the proper thickness for the subbase of a mine haul road, the California Bearing Ratio (CBR) [AASHTO T 193-99 2003; ASTM D 1883 2005], developed by the U.S. Bureau of Mines, can be used [USBM 1977].

Thickness of the base and wearing surface are important considerations in road designs. Sufficient thickness of these layers enables the road to support the load for which it was designed. A road that is not able to support the vehicle loading will deteriorate rapidly, which can in turn result in higher dust production.

To determine the proper thickness for the subbase of a mine haul road, Figure 11.4, developed by the U.S. Bureau of Mines, should be consulted [USBM 1977]. This method uses the CBR[31] test

[30] Berms are not present on the drawing in order to focus on the design of the three layers. However, berms should and would be present at the cross section of a mine haul road.
[31] The California Bearing Ratio test provides results as a ratio from the comparison of the bearing capacity of a material to the bearing capacity of a well-graded crushed stone. It is used for evaluating the strength of cohesive materials having maximum particle sizes of 0.75 inches. The test involves applying a load to a small-diameter

values of the host road material to determine the thickness of the subbase. Figure 11.4 also uses soil types to determine subbase thickness; however, the soil type ranges are approximations of typical ranges of CBRs for that particular soil type, and should be used only as a rough preliminary design guideline for determining subbase thickness. The CBR is a more accurate method in relation to subbase construction.

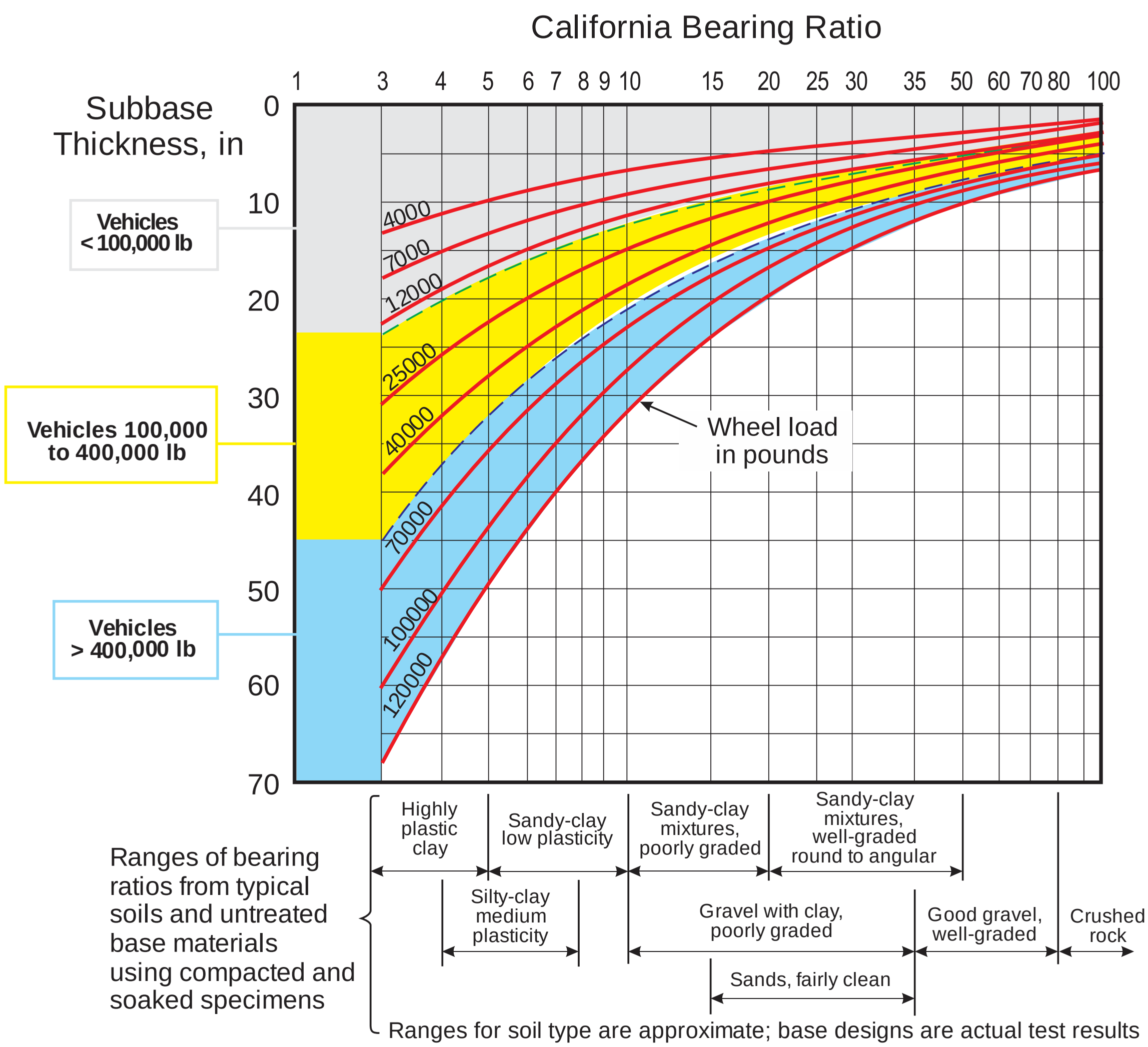

Figure 11.4. Subbase thickness from California Bearing Ratio tests on road material [from USBM 1977].

penetration piston, which is applied to the sample material at a rate of 0.05 inches per minute, recording total load at penetration distances ranging from 0.025 inches up to 0.300 inches. Specifications for the test can be found in AASHTO T193, "The California Bearing Ratio," or ASTM D 1883, "Bearing Ratio of Laboratory Compacted Soils."

To effectively use Figure 11.4, the wheel load of the largest truck using the road must be determined. The wheel load can be determined from haul truck specifications provided by the manufacturer. For example, the wheel load for a 200-ton truck [Caterpillar 2018] is calculated by dividing the axle load by the number of tires per axle. For this example truck, the wheel load is approximately 120,000 lbs (479,050 ÷ 4).

Using the wheel load along with the CBR, the thickness of the subbase, the wearing surface, and any intermediate layer is determined and used as the design criteria for the haul road layers. To demonstrate the use of the graph in Figure 11.4, an example taken verbatim from the 1977 USBM publication is provided below.

> A haulage road is to be constructed over a silty clay of medium plasticity with a CBR of 5. The maximum wheel load for any vehicle using the road is 40,000 pounds. Fairly clean sand is available with a CBR of 15 to serve as subbase material. Road surface is to be constructed of good gravel which has a CBR of 80.
>
> - Step A. The 40,000-pound wheel-load curve intersects the vertical line for a CBR of 5 at 28 inches. This means that the final road surface must be at least this distance above the subgrade.
> - Step B. A clean sand CBR of 15 intersects the 40,000-pound curve at 14 inches, indicating that the top of this material must be kept 14 inches below road surface.
> - Step C. An intersection of the 80 CBR for gravel and the 40,000-pound wheel load occurs at 6 inches. Since this will constitute the final surface material, it should be placed for the remaining 6 inches.

Figure 11.5 illustrates the construction of a road as determined by this example.

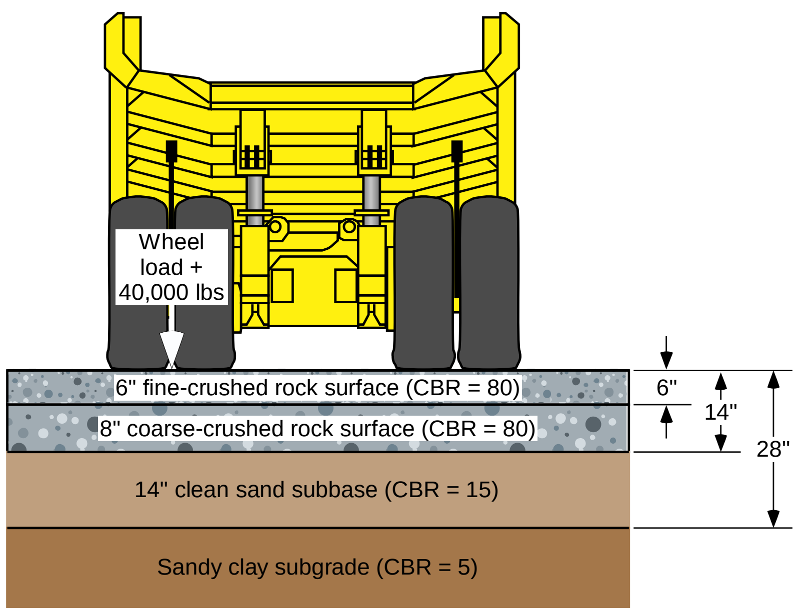

Figure 11.5. Composition and thickness of haul road layers using the California Bearing Ratio [adapted from USBM 1977].

It is best to spread the material for the base using a spreader box attached to a bulldozer (Figure 11.6) or other mobile equipment. After the material is layered to a uniform loose depth (8 to 10 inches), it is compacted. To minimize the segregation of the fine and coarse mat, a grader should be used to blade the material to a uniform surface. A vibratory roller can then be used to compact the road material.

When constructing the last component, the *wearing surface,* it is important for the crown to be maintained throughout the construction process to direct water away from the road surface. Additionally, the surface should meet the following criteria:

- be compacted at optimum moisture to achieve maximum strength;
- be constructed of material that is resistant to abrasion, weathering, and large particle displacement from the road; and
- contain sufficient fines to fill the voids between the larger particles and to minimize large particle loss.

Photos by DoMor Equipment

Figure 11.6. Photos of a spreader box used to spread the material for the base of a haul road. The left photo shows an aggregate spreader mounted onto a bulldozer blade and the right photo shows base material being spread onto a roadway.

Access roads are similar in nature to haul roads, except that vehicle traffic is less frequent and vehicles are typically lower in weight. It is generally accepted to overdesign access roads, and because of the dynamic nature of mining, an access road may be upgraded to a haul road. Additional information for the proper design of the smaller access roads can be found in *Gravel Roads: Maintenance and Design Manual* [Skorseth and Selim 2000].

Haul Road Dust Control Measures

Even the best constructed haul roads provide material for dust entrainment. The most common method of dust control on haul roads is periodic application of water. Although water is the most common, other suppressants include salts, petroleum emulsions, polymers, and adhesives, with selection dependent on mine site conditions. Performance of each dust control agent is evaluated through the use of control efficiency. Control efficiency, defined in Equation 11.1, compares the dust concentration of a treated road surface to that of an untreated or uncontrolled road surface:

$$CE = 1 - \left(\frac{T}{U}\right) \times 100 \qquad (11.1)$$

where CE = control efficiency, percent;
U = untreated or uncontrolled road dust concentration, mg/m^3; and
T = treated or controlled road dust concentration, mg/m^3.

Generally, the higher the control efficiency for a dust control agent, the better its performance, which results in less dust emissions from the road surface. The control efficiencies presented are for total suspended particulates (TSP).

Road Preparation

Haul roads should be properly prepared before applying a chosen dust suppressant. The equipment used for the application of the dust suppressants includes a dozer with a spreader box mounted to the front (refer to Figure 11.6), a compactor, and a water truck for distribution of the suppressant. The road should be fully prepared before and during application to allow the dust suppressant to work at its maximum efficiency, as described below.

- Any blade work required to eliminate road corrugations and potholes should be completed before dust suppression is initiated.
- Any large material that would not make for a good road surface should be bladed off the road.
- The road should have a good crown to eliminate the potential for any standing water because it can have a detrimental effect on the road surface, creating potholes.
- The dust suppressant is applied as the final step.

Guidelines for each specific dust suppressant application should be obtained from the dust suppressant manufacturer chosen for use on the road. Generally, however, there are two options for applying dust suppressants after the road surface is scarified, as described below.

- The first variation, generally used with salt suppressants, is to ensure that a 1- to 2-inch loose layer is spread evenly across the road surface. Next, the dust suppressant is applied to the loose layer at the recommended rate. Finally, the surface is compacted, preferably with a pneumatic roller, although other types can be used. Traffic should be kept off the road until the dust suppressant cures (generally 24 hours) [Skorseth and Selim 2000].
- The second variation is to blade most of the loose material into windrows on both sides of the road to ensure that the dust suppressant does not run off the road surface. One-third of the dust suppressant is applied to the road surface at the recommended rate between the windrows. Next, the windrows are bladed to the center and spread evenly across the road surface. Then, another one-third of the dust suppressant is applied to the road surface. The road is regraded to mix the dust suppressant and the aggregate. The final one-third of the dust suppressant is applied to the road surface as a topcoat after regrading is complete, avoiding excess runoff of the dust suppressant. Finally, the road surface is compacted before the dust suppressant dries, and the road should be allowed to cure (generally 24 hours) [Midwest Research Institute 1981].

Water Application

Watering roads with a dedicated water truck is the most common and simplest method for haul road dust control. Water trucks consist of a tank capable of holding up to 90,000 gallons, a water pump, and plumbing designed to deliver water to spray nozzles mounted at the rear of the truck. The nozzle spray pattern and layout are typically designed to wet at least one lane of a haul road in one pass, as shown in Figure 11.7. Although watering requires no road preparation prior to application, it must be reapplied on a consistent basis. Additionally, the dust control efficiency for water can be highly variable because it depends on road material type, traffic, and weather conditions.

Photos by Mega Corporation

Figure 11.7. Water trucks wetting down haul roads. The left photo shows a water truck with rear-mounted water sprays and the right photo shows a haul truck with a water distribution manifold.

The spray nozzles for road watering are generally fan sprays and are mounted on the truck at a stationary position. These nozzles can be various types of fan spray nozzles fabricated by a manufacturer (Figure 11.8), or they can be simple water distribution manifolds. These simple manifolds are constructed by drilling holes along the bottom of a water pipe at the back of the water truck or by cutting horizontal slots in water stand-pipes (or endcaps) at the corners of the water truck. To achieve optimal spray coverage, it is best to orient the nozzles in a manner to minimize overlap of the water spray from other nozzles [James and Piechota 2008]. It is also important that the water reaches the desired target location and is not blown awry by the ambient wind. As a result, lower water pressures, 15 pounds-force per square inch gauge (psig) or less, that produce larger-sized water droplets are often utilized [Franta 2016].

Three photos on left by Access Truck Parts

Two photos on right by Spraying Systems Co.

Figure 11.8. Various types of manufactured spray nozzles (not to scale) for use on a water truck.

There are no universal guidelines for the amount of water to use for dust control on haul roads nor for determining optimum haul road watering intervals. The quantity of water sprayed onto the road during each application, the composition and layout of the road, the traffic volume on the road, and the prevailing weather conditions are factors that should be used to determine site-specific optimum intervals for watering [Cowherd et al. 1988]. Water application rates ranging from 0.02 to 0.50 gals/yd^2 have been utilized at surface mining operations in various countries [Midwest Research Institute 1981; Tannant and Regensburg 2001; Bulger 2015].

Figure 11.9 illustrates the importance of keeping the road wet at one operation as airborne respirable dust levels increased substantially as the road dried out. Regular light watering may be more effective for dust control than infrequent heavy watering and also reduces the potential hazards resulting from excess water (e.g., slick ramps, degradation of roadway) [Thompson and Visser 2007; Bolander and Yamada 1999]. Utilization of speed-sensitive watering systems can assist with the uniform application of water on haul roads. These systems adjust the quantity of water that is discharged onto the road in relation to the travel speed of the watering truck [Bulger 2015]. Another technique that has been recommended to reduce the potential of tire slippage, particularly critical on ramps, is intermittent or spot watering, which results in alternate wet and dry sections of roadway [Bennink 2007; Thompson 2014].

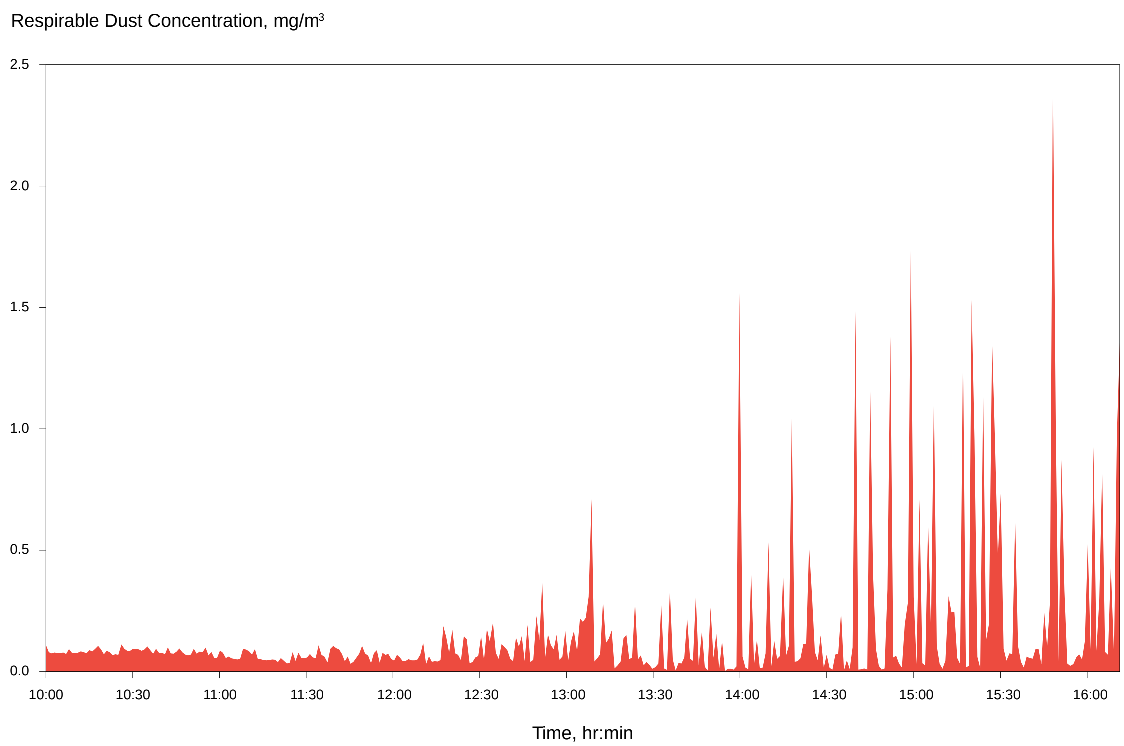

Figure 11.9. Graph showing respirable dust concentrations measured from a haul road after water application occurred at 10:00 at one operation [from Organiscak and Reed 2004].

Salts

Salt solutions are commonly mixed with water to reduce haul road dust. Magnesium chloride is one of the most common salt-based dust control agents. Other agents are calcium chloride, hydrated lime, and sodium silicates, with calcium chloride being the most common. Application procedures for magnesium chloride/calcium chloride are similar to those described for dust suppressants in the “Road Preparation” section.

Advantages of using chlorides for dust control are that they absorb moisture from the atmosphere to maintain the road’s moisture content at a higher level than normal. They can also act to thaw ice and snow on roads in freezing conditions. Also, chlorides generally do not require time to cure after application. Conversely, chlorides may cause corrosion on equipment using the roads sooner than normal. They can also be harmful to vegetation and to personnel if skin or eye contact occurs. Chlorides are also water soluble and may leach from the road surface during precipitation, thereby degrading in performance over time [Midwest Research Institute 1981].

Petroleum Emulsions

Petroleum resins are engineered products or byproducts of lubrication oil manufacturing. They generally consist of stable emulsions of petroleum residuals, solvent extracts, and acid sludge. The practice of using petroleum resins for dust control on access roads has kept these areas dust free for periods up to six months to one year. Haul roads have been reported to be relatively dust free for a period of three to four weeks [Midwest Research Institute 1981].

A primary advantage to using petroleum emulsions is that they are not corrosive. They are also not water soluble, they are relatively nontoxic and nonflammable, and they do not have adverse effects on plant growth (for revegetation needs). Some of the products require the steps of scarifying to a 1-inch depth, applying the resin, and compacting the road surface; others can be applied by direct application of the resin to the road surface without any conditioning. However, most resins require a 24-hour cure time after application and traffic should be limited to wheeled equipment only to prevent breakdown of the treated surface. Also, storage temperatures of the emulsion products prior to application must be controlled as they cannot endure freezing or boiling conditions [Midwest Research Institute 1981].

Polymers

Polymers include acrylics and vinyls, which are chemical additives mixed with water to form a diluted solution and then applied to the road surface topically. Polymers are generally noncorrosive and nontoxic, and they can be utilized for soil stabilization. As a dust control agent, they are also generally long lasting, although it has been shown that precipitation can affect longevity.

Application procedures can vary by product. Simple procedures include initial road preparation and spraying the solution onto the road surface with a water truck, and complex procedures require initial road preparation and additional blading and regrading when the polymer solution is applied.

Adhesives

Adhesives are compounds, solutions, formulas, etc., that are mixed with the soil surface to form a new road surface. One of the most common and well-established dust control adhesives is lignin sulfonate, a waste product from the paper/pulp industry that is created when wood chips are placed in a sulfonate solution. This adhesive is noncorrosive and is easily obtainable due to the large size of the paper/pulp mill industry.

Application of lignin sulfonate involves procedures mentioned previously in the “Road Preparation” section. When properly applied, lignin sulfonate has been observed to keep access roads dust free for periods ranging from 6 months to two years with periodic application of the solution [Midwest Research Institute 1981]. Heavily traveled haul roads have been observed to be kept dust free for periods of three to four weeks. However, lignin sulfonate can interfere with some mineral processing processes, such as flotation, and since it is water soluble it can be washed away from the road surface, requiring reapplication to maintain proper dust control [Midwest Research Institute 1981].

Multiple factors can impact the dust control efficiency of the haul road applications discussed above, including road material, application concentration, attention to application instructions, and weather conditions. As a result, a range of control efficiencies have been reported and are summarized in Table 11.1.

Table 11.1 Summary of control efficiencies for haul road applications

Control Type	Efficiency, %	Application Frequency	Reference
Water	95 74 40 55	0.5 hours 3–4 hours 1 hour 0.5 hours	EPA 1998 EPA 1998 USBM 1983 USBM 1983
Salt-magnesium chloride	95	22 days	USBM 1987
Salt-calcium chloride	82 14	2 weeks 7 weeks	USBM 1983
Petroleum emulsion	70 4–38	21 days 4 weeks	USBM 1987 USBM 1983
Polymer	74–81 3–14 94–100 37–65	< 4 weeks > 5 weeks < 1 week 11 months	USBM 1983 USBM 1983 Gillies et al. 1999 Gillies et al. 1999
Adhesive	50–63	< 4 weeks	USBM 1983

STOCKPILES AND EXPOSED AREAS

Airborne dust can be generated when loading material onto the stockpile (continuous or batch loading), moving material on the stockpile, or unloading material from the stockpile. There are generally two types of stockpiles: active and idle. Active stockpiles consist of product that is being loaded, unloaded, and/or stored for short periods until it is ultimately used for further processing or is shipped to a customer. An idle stockpile undergoes no disturbance to the pile for several months or more. An example would be a topsoil stockpile where topsoil is stored until reclamation of the mine site is performed.

Open areas with exposed product or soil can also be found at surface mine and processing sites, and these areas have the potential to liberate dust particles into the air. Equipment travel over these exposed areas can result in airborne dust release similar to haul roads. However, these areas are not designated for travel, so travel should be infrequent and discouraged.

Another concern is the wind lifting dust particles from the surfaces of stockpiles and exposed areas, which is known as wind erosion [EPA 1992]. The amount of dust entrained is dependent upon several factors including particle size, moisture content, surface characteristics, and wind velocity. One example of the wind velocity required to lift dust from a stockpile was provided in the Environmental Protection Agency (EPA) report cited above, which stated that the threshold wind velocity was 11 mph when measured six inches above the coal stockpile surface. Also, a finite amount of material will be released from any surface, referred to as erosion potential, but each time the material surface is disturbed, the potential to release additional dust is restored.

Once airborne, dust from these sources can expose workers, cause visibility problems, and raise concerns with the public if the dust exits the mine property. As a result, various control strategies, such as wetting, chemical stabilization, physical stabilization, and enclosures, have been developed in an effort to minimize dust liberation from these sources. In addition, administrative controls such as location of stockpiles [Cong et al. 2012], controlling the height and shape of the stockpile [Toraño et al. 2007], and loading or unloading on the downwind side of the stockpile [Midwest Research Institute 1988] have been applied to minimize the impact of prevailing winds. Unfortunately, historic effectiveness of the available control methodologies are often estimated or modeled without field sampling data available to quantify the actual performance. Regardless, reported efficiencies range from 30 percent (vegetative windbreak) to 100 percent (enclosed storage silo) [Cowherd 1981].

Additional detail for the various control methodologies is provided in the following sections.

Wetting

One of the most common methods for controlling dust emissions from stockpiles is wetting the product as it is loaded onto the stockpile and/or periodically after it has been deposited. The goal of wetting the surface material is to agglomerate small dust particles with larger particles or water droplets to prevent the small particles from becoming airborne. In one study on coal, no dust entrainment occurred from deposited material in wind tunnel testing at velocities up to approximately 45 mph when the moisture content of the coal was kept above 6 percent to 8 percent [King 1996]. However, many products and processes cannot tolerate this level of moisture, so more frequent surface wettings are used in an effort to prevent wind erosion.

If continuous loading onto the stockpile is occurring with a conveyor belt, traditional-type sprays can be installed to wet the product prior to and during discharge from the conveyor. Discussion of these types of spray applications is provided in Chapter 3—Wet Spray Systems. In addition, a circular spray manifold that discharges water around the perimeter of the discharged product stream is available. A water curtain is formed around the product to minimize the wind's impact as product drops through the air and also provides wetting as the product hits the stockpile (Figure 11.10). One manufacturer offers these manifolds in multiple sizes that provide water flow rates of 3 to 53 gallons per minute (gpm), producing water droplets of 50 to 200 microns [MINING.com 2013].

Photo by BossTek

Figure 11.10. A dust suppression ring providing wetting of the product as it is discharged from a conveyor.

Part of the challenge involved in wetting stockpiles is often the large size of the area to be wetted. As a result, a number of technologies other than traditional water spray manifolds have been developed to treat these large areas. One of the primary considerations in these systems is water droplet size. If the droplets are too small, they can be impacted by wind drift, evaporation, or both before reaching the intended wetting zone. Optimal droplet size is around 500 µm [EPA 1992], which reduces impact from wind drift while delivering moisture for small particle agglomeration. A water cannon is one technology that provides large coverage areas for water delivery on stockpiles, as illustrated in Figure 11.11 (left).

Photo by Spray Stream

Photo by BossTek

Figure 11.11. Technology to provide large coverage areas for water delivery on stockpiles. The left photo shows a water cannon wetting a stockpile. The right photo shows spray nozzles mounted at the fan discharge point.

This type of water cannon is an axial fan that has water nozzles inserted in a circular manifold that is mounted at the discharge of the fan, as shown in Figure 11.11 (right). These manifolds frequently contain up to 30 spray nozzles. When activated, these nozzles supply water that is entrained into the discharged air stream and carried to the targeted area, such as a stockpile. The discharge angle of the fan can be adjusted to alter the height of the water stream. Also, these fans can be oscillated over 300 degrees to provide wetting over a wide area. Multiple manufacturers produce water cannons that can be designed for a wide range of operating conditions. Water flow rates of less than 10 gpm to nearly 40 gpm and operating water pressures of 150 to 300 psig with throw distances ranging from 130 to over 300 feet can be found across the product lines of various manufacturers.

Another type of specialized nozzle, also known as a water cannon, can be mounted on water trucks (Figure 11.12). This nozzle can be remotely controlled from inside the operator’s cab. The nozzle can be rotated 360 degrees and also adjusted vertically. Water cannons can be equipped with nozzles that deliver solid streams of water traveling up to 200 feet or fogging-type nozzles. These types of water cannons are better suited for spot applications, such as wetting the area of a stockpile from which material will be removed and loaded into haul trucks.

Photos by Mega Corporation

Figure 11.12. Specialized nozzle for wetting large areas. The photo on the left shows a water cannon nozzle mounted on a water truck and the photo on the right shows the nozzle spraying long distances.

An alternative to fan-powered or truck-mounted water cannons is long-throw sprinklers (Figure 11.13). Depending upon the model, these sprinklers can deliver large quantities of water up to 150 gpm with a height of over 50 feet and a throw distance of over 100 feet. A series of these sprinklers can be mounted around a stockpile, and their operation can be automated from a centralized control location. The operation can be further automated with the addition of a weather monitoring station that helps identify when watering is needed. One installation at an iron ore loading terminal reduced the amount of dust samples exceeding the air quality limit by nearly 54 percent [Rain Bird 2009].

Chemical Application

An alternative to the use of plain water is to add chemicals (wetting agents) to the water in an effort to improve moisture distribution, moisture retention, or particle agglomeration. Other chemicals are designed to develop a wind-resistant crust on the surface of the stockpile in order to prevent wind erosion.

Photo by Rain Bird

Figure 11.13. Long-throw sprinklers wetting stored material [from Rain Bird Corporation 2009].

Wetting agents have had more widespread application in coal mining because of the hydrophobic properties of coal particles. Previous research with wetting agents applied to coal have led to mixed results. In testing conducted at two sites, improved dust control was shown at one site while no benefit was realized at the other [King 1996]. In a series of wind tunnel tests, wetting agents did not add to coal dust control performance beyond that of plain water [Smitham and Nicol 1991].

Crust-forming agents are designed to bind and coat materials to form a crust or film on the surface areas of stockpiles, which can prevent wind erosion. Lignosulfonates, polymers, resins, mineral oils, and other materials can be used as the crust-forming agent. In one wind tunnel test on iron ore product, the amount of dust removed by wind velocity was reduced from 200 grams (with no surface treatment) to 10 grams (when treated with water sprays on two-hour intervals) to no dust removed (with a chemically produced surface film) [Planner 2011]. Another study of three different agents also showed prevention of wind erosion when these agents formed crusts approximately 3/16 of an inch thick [King 1996]. However, if the crust or film is broken, wind erosion of the underlying product can then occur [Smitham and Nicol 1991].

If chemicals are to be applied, runoff into groundwater is a concern, and compliance with federal regulations must be achieved and maintained.

Enclosures and Wind Fences

Another method to prevent the escape of fugitive dust from stockpiles is to erect physical structures near, around, or over the stockpile. Wind fences or three-sided bunkers can be erected that shield the stockpile from high wind velocities. Alternately, silos or domes can be erected that completely enclose the stockpile. In addition, telescoping loading spouts can be used to enclose the product stream as it is being loaded onto the stockpile and shield the falling product stream from the wind.

Wind fences are designed to reduce the velocity of the wind that is reaching the stockpile in order to minimize wind erosion across the pile. The reduced wind velocity will also lower dust generation during active stockpile activities, such as loading or removing product. If the fence does not encircle the stockpile, it is important to erect the fence to address the prevailing problematic wind to optimize the protection afforded. Several design parameters are critical to the relative success of the wind fence and include fence height and length, distance between the fence and stockpile, and porosity of the fence. Previous wind tunnel research has indicated that the porosity of the fence should be approximately 50 percent, which resulted in wind speed reductions of 50 to 70 percent when the wind break was three pile heights upwind of the base of the stockpile [Billman and Arya 1988]. In this study, the wind fence was equal in height to the stockpile height and equal in length to the stockpile base. Other reported research has also indicated that a fence with 50 percent porosity is effective by creating a balance between shielding, turbulence, and stagnant areas [Zimmer et al. 1986].

In a field study [Zimmer et al. 1986], screen length had the greatest impact on measured dust concentrations. Because this was a field evaluation, variation in wind direction was encountered over the study and likely contributed to screen length having the greatest impact. This study also indicated that a screen height equal to pile height should be achieved, and that a screen-to-pile distance equal to two pile heights may be the optimum.

More recently, computational fluid dynamics (CFD) modeling has been utilized in designing wind fences. Variables such as location, height, and porosity can be evaluated in the CFD model to determine optimum specifications. Also, CFD modeling can account for the impact of terrain features and buildings that can greatly influence wind patterns and velocities. Figure 11.14 illustrates the reduction in surface wind velocities around two stockpiles resulting from the installation of a wind fence as determined from CFD modeling [Kibbee 2014].

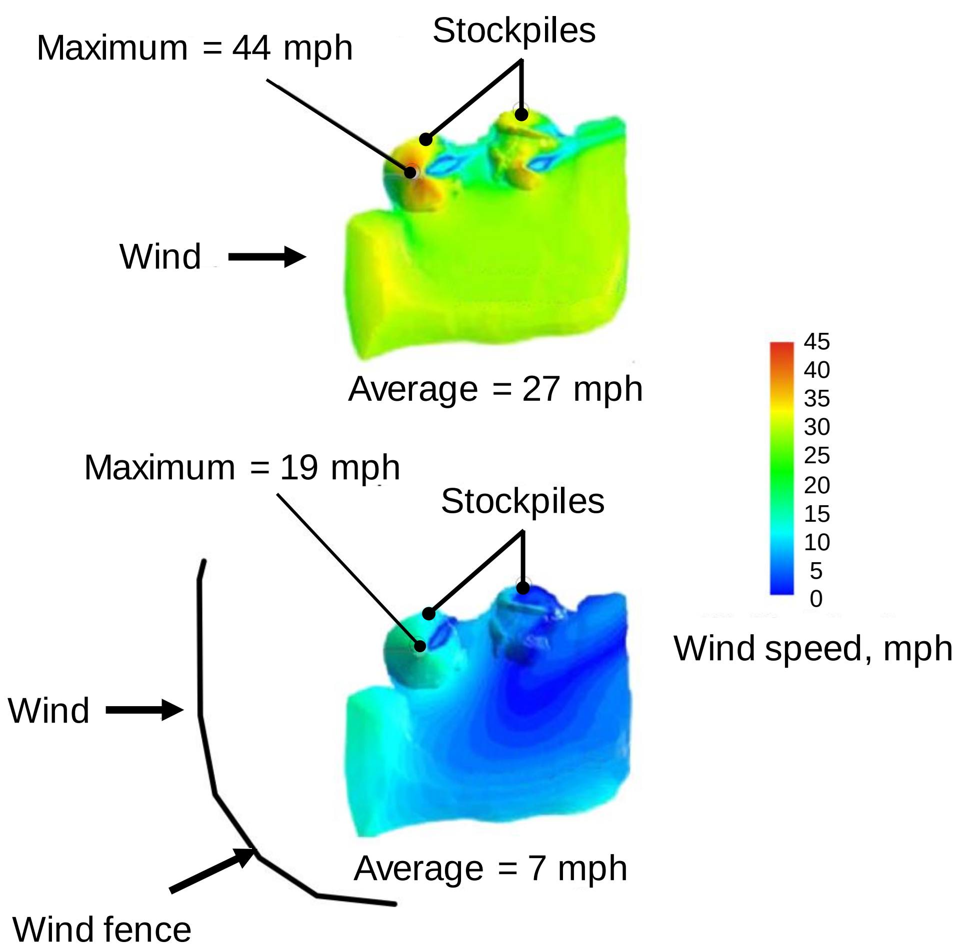

Figure 11.14. Plan view of the area around stockpiles before and after installation of a wind fence as determined from computational fluid dynamics (CFD) modeling. The top model represents the stockpile before wind fence installation and the bottom model represents the stockpile afterwards, with CFD modeling illustrating the changes in wind velocities [adapted from Kibbee 2014].

As noted, the size of the fence has a major impact on the dust reduction effectiveness. Consequently, wind fences can be quite large, as shown in Figure 11.15 (left). This particular fence was constructed to reduce dust emissions from a coal stockpile at a power plant and is 100 feet tall and 1,700 feet long [Larson 2015]. The fence is constructed from polyester fabric, which is resistant to the elements, and can withstand wind velocities in excess of 120 mph. On the other hand, 30- to 50-feet-tall wind fences are more typical, as shown in Figure 11.15 (right).

Photos by Dust Solutions

Figure 11.15. Photos of wind fences. The left photo shows a large wind fence installed at a coal power plant [from Larson 2015]. The right photo shows a more common size of wind fence.

Domes have been built that are able to span up to 1,000 feet without any internal columns [Walker 2016]. These domes have been constructed while the stockpile is still operating and generating dust, as shown in Figure 11.16 (left) [Walker 2016]. The steel tube structure is then covered with corrugated metal sheets to complete the enclosure, as shown in Figure 11.16 (right). Domes have been designed to withstand wind speeds of over 90 mph and ice loads of over 22 lbs/ft^2 [Geometrica 2017].

Photos by Coal Age

Figure 11.16. Photos of domes. The left photo shows dome construction while a stockpile is in operation and the resulting dust generation. The right photo shows the completed dome [from Walker 2016].

Telescoping loading spouts can be used to deposit product onto a stockpile (Figure 11.17). These loading spouts are similar in design and operation to those that are commonly used for loading trucks and railroad cars. For stockpiles, these spouts are typically larger in scale, with the capability of extending up to 100 feet and delivering over 1,000 ft^3 of material per minute. These loading spouts are often enclosed to minimize the dust entrainment impact of wind on the falling product stream. The spouts can also be equipped with dust collection systems and discharge skirting to minimize dust release during loading. Cascade-style loading spouts can be used to slow the velocity of the product as it drops to the stockpile. Chapter 8—Bulk Loading—has additional information related to telescoping loading spouts.

Photo by DCL

Photo by Hennlich Engineering

Figure 11.17. Photos of loading spouts. The left photo shows a retracted spout and the right photo shows a spout delivering product to a stockpile.

Physical Stabilization

Physical stabilization of stockpiles and exposed areas involves coating the surface with less erodible material (such as gravel), altering the surface characteristic (roughness or compaction), or planting vegetation to prevent wind and water erosion. However, these types of applications are typically limited to idle storage piles such as topsoil piles,[32]; are not often applied to product stockpiles; and are more readily applied to large open areas when no immediate plans to use these areas are present. In these areas, applying gravel or planting vegetation are desirable options for long-term dust control.

[32] Additional information on methods for treating soil areas is available in the first edition of this handbook, which can be found on the NIOSH mining website at https://www.cdc.gov/niosh/mining/works/coversheet1765.html.

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DHHS (NIOSH) Publication No. 2019–124
DOI: https://doi.org/10.26616/NIOSHPUB2019124