ENVIRONMENTAL HEALTH & ENGINEERING

Emissions of Hazardous Air Pollutants from Coal-fired Power Plants

EMISSIONS OF HAZARDOUS AIR POLLUTANTS FROM COAL-FIRED POWER PLANTS

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About the Report

Scientists from Environmental Health and Engineering, Inc. (EH&E) were commissioned by the American Lung Association to prepare a report on public health and environmental impacts of hazardous air pollutant emissions from coal-fired power plants that would be a useful resource for the general public. This report represents the integrated effort of numerous talented individuals within our organization whose contributions were made under the direction of David L. MacIntosh, Sc.D., C.I.H., and John D. Spengler, Ph.D.

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John D. Spengler, Ph.D. is the Akira Yamaguchi Professor of Human Health and Habitation, Harvard School of Public Health and Director of the Sustainability and Environmental Management program at the Extension School. Dr. Spengler has conducted research in the areas of personal monitoring, air pollution health effects, indoor air pollution, and a variety of environmental sustainability issues. He is the author of numerous articles on air quality and other environmental issues, and co-author or co-editor of *Health Effects of Fossil Fuel Burning: Assessment and Mitigation*; *Indoor Air Pollution: A Health Perspective*; *Particles in Our Air: Concentrations and Health Effects*; and *Indoor Air Quality Handbook*. In 2003, Dr. Spengler received a Heinz Award for the Environment; in 2007, he received the Air and Waste Management Association Lyman Ripperton Environmental Educator Award; and in 2008 he was honored with the Max von Pettenkofer award for distinguished contributions in indoor air science from the International Society of Indoor Air Quality and Climate's Academy of Fellows.

EH&E is grateful to James E. Staudt, Ph.D., Andover Technology Partners, for preparing the first draft of sections on air pollution control systems for hazardous and criteria air pollutant emissions.

EH&E is also grateful to John Bachmann, Vision Air Consulting, LLC for providing input and advice on the science and policy matters presented in the report.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACI	Activated carbon injection
ACS	American Cancer Society
ATSDR	Agency for Toxic Substances and Disease Registry
BTU	British Thermal Unit
CAA	Clean Air Act
CASAC	U.S. EPA Clean Air Scientific Advisory Committee
CDF	Chlorodibenzofuran
DOE	U.S. Department of Energy
DSI	Dry Sorbent Injection
EH&E	Environmental Health & Engineering, Inc.
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
ESP	Electrostatic Precipitator
FBC	Fluidized bed combustion
FGD	Flue gas desulfurization
HAP	Hazardous air pollutant
HCl	Hydrochloric acid
HCN	Hydrogen cyanide
HF	Hydrogen fluoride
ICR	U.S. EPA Electric Utilities Information Collection Request
ISA	U.S. EPA Integrated Science Assessment
lb	Pound
MACT	Maximum Available Control Technology
MW	Megawatt
NADP	National Atmospheric Deposition Program
NEI	National Emissions Inventory
NESHAP	National Emissions Standard for Hazardous Air Pollutants
NOx	Nitrogen oxides
NRC	National Research Council of the National Academies
PAH	Polycyclic aromatic hydrocarbon
PM	particulate matter
$PM_{2.5}$	particulate matter that is 2.5 micrometers or smaller in size
PM_{10}	particulate matter that is 10 micrometers or smaller in size
SO_2	Sulfur dioxide
2,3,7,8-TCDD	Tetrachlordibenzo-*p*-dioxin
TEQ	Toxicity equivalent
$\mu g/m^3$	microgram per cubic meter
WHO	World Health Organization

EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) will soon propose new limits on hazardous air pollutants released to the atmosphere from coal- and oil-fired power plants. The proposal, known as the "Utility Air Toxics Rule", will set new limits on emissions of hazardous air pollutants, which are defined by Congress as chemical pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive problems or birth defects, and that adversely affect the environment. The new power plant limits are to be based on the emissions performance of the best performing power plants and pollution control systems currently in use. When the rules are in place, this will be the first time that EPA has implemented federal limits on mercury, arsenic, lead, hydrochloric acid, hydrofluoric acids, dioxins, and other toxic substances from coal-fired power plants.

The American Lung Association commissioned Environmental Health & Engineering, Inc. to prepare a report on public health and environmental impacts of hazardous air pollutant emissions from coal-fired power plants that would be a useful resource for the general public. The major findings of the report are summarized here.

Sources and Emissions

- Over 440 power plants greater than 25 megawatts located in 46 states and Puerto Rico, burn coal to generate electric power (USEPA, 2010a); coal combustion accounts for 45% of electricity produced in the United States (USDOE, 2009a).

- The National Emissions Inventory prepared by EPA indicates that emissions to the atmosphere from coal-fired power plants:
  - contain 84 of the 187 hazardous air pollutant identified by EPA as posing a threat to human health and the environment,
  - release 386,000 tons of hazardous air pollutants annually that account for 40% of all hazardous air pollutant emissions from point sources, more than any other point source category, and
  - are the largest point source category of hydrochloric acid, mercury, and arsenic releases to air (USEPA 2007).

- Coal-fired power plants are also a major source of emissions for several criteria air pollutants; including sulfur dioxide, oxides of nitrogen, and particulate matter.

Toxicity and Impacts on Public Health and the Environment

- Hazardous air pollutants emitted to the atmosphere by coal-fired power plants can cause a wide range of adverse health effects including damage to eyes, skin, and breathing passages; negative effects on the kidneys, lungs, and nervous system; the potential to cause cancer; impairment of neurological function and ability to learn; and pulmonary and cardiovascular disease (USEPA, 1998; USEPA, 2011a; USEPA, 2011b).

- Public health risks associated with exposure to mercury in food and metals in airborne fine particulate matter are among the most notable adverse health and environmental impacts associated with emissions of hazardous air pollutants from coal-fired power plants.

- Coal-fired power plants can be significant contributors to deposition of mercury on soil and water.
  - A study in eastern Ohio reported that coal combustion accounted for 70% of the mercury present in rainfall (Keeler et al., 2006).
  - In the same area, 42% of the mercury in samples of rain collected in the summer was attributed to emissions from a coal-fired power plant located less than a mile away (White et al., 2009).
  - Mercury that deposits to the earth's surface from air can make its way into waterways where it is converted by microorganisms into methylmercury, a highly toxic form of mercury (Grandjean 2010).

- EPA has determined that exposure to fine particulate matter is a cause of cardiovascular effects including heart attacks and the associated mortality; is likely a cause of hospital admissions for breathing problems and worsening of existing respiratory illness such as asthma; and is linked to other adverse respiratory, reproductive, developmental, and cancer outcomes (USEPA, 2009a; CASAC 2010).

- Hazardous air pollutants, such as arsenic, beryllium, cadmium, chromium, lead, manganese, nickel, radium, selenium, and other metals, are integral components of fine particulate matter emitted directly from coal-fired power plants.

- The metal content of fine particulate matter has been linked to cardiovascular public health impacts in epidemiological and other studies (e.g. Zanobetti et al., 2009).

- In a recent population-based health impact assessment, particulate matter emitted directly from coal-fired power plants was estimated to account for an average of $3.7 billion[1] of public health damages each year (NRC, 2010).

- Environmental impacts of power plant hazardous air pollutant emissions include acidification of the environment, bioaccumulation of toxic metals, contamination of rivers, lakes, and oceans, reduced visibility due to haze, and degradation of buildings and culturally important monuments.

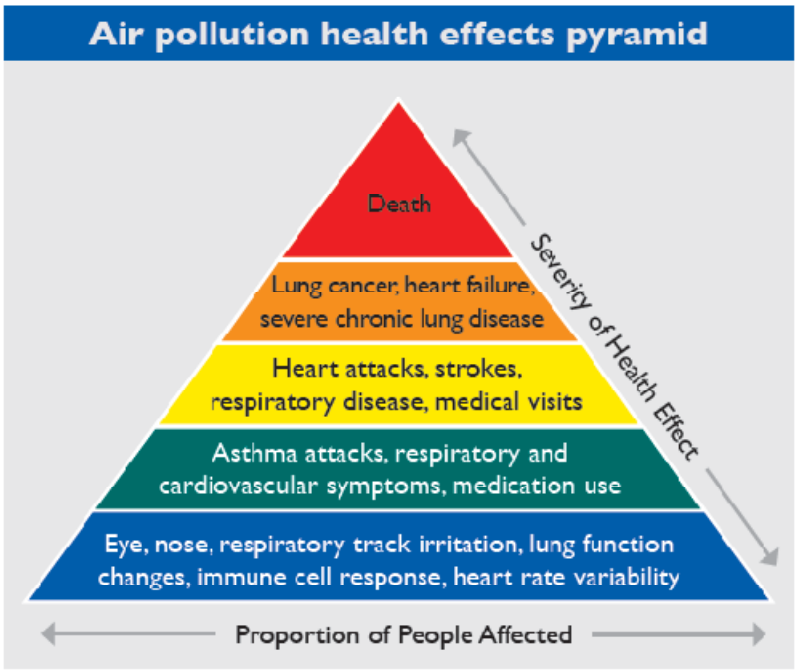


Figure 1. Air Pollution Health Effects Pyramid. Health effects of air pollution are portrayed as a pyramid, with the mildest and most common effects at the bottom of the pyramid, and the more severe but less frequent effects at the top of the pyramid. The pyramid shows that as severity decreases the number of people affected increases. Exposure to air pollution can affect both the respiratory and the cardiac systems. Adapted from USEPA, 2010b.

Transport and Range of Impacts

- Hazardous air pollutants released from coal-fired power plants influence environmental quality and health on local, regional, and global scales.

[1] Based on average damages of $9 million per coal-fired power plant determined in an analysis of 406 plants.

- Impacts of certain hazardous air pollutants, including most acid gases and some forms of mercury, appear to impact most heavily on the immediate vicinity of the facility.

- Impacts of non-mercury metals and other persistent hazardous air pollutants released from coal-fired power plants are greatest near the source, but can also influence the environment and health far from the source.
  - Analyses of coal-fired power plants have found that public health damages per person were two to five times greater for communities near the facilities than those for populations living at a greater distance from the plants (Levy and Spengler 2002).
  - Analyses conducted by EPA, the National Research Council, and other scientists show that emissions from coal-fired power plants cross state lines and impart public health damages on a regional scale.

Emission Controls for Hazardous Air Pollutants

- Emission rates of hazardous air pollutants vary widely among coal-fired power plants in the United States, in part because of variation in the use of technologies that can remove pollutants from exhaust gases.

- Hazardous air pollutant emissions from a sample of coal-fired power plants that use multiple modern control technologies were 2 to 5 times lower on average than for a random sample of plants selected by EPA.

- Controls on acid gas and non-mercury metal emissions are likely to reduce emissions of sulfur dioxide and primary particulate matter. As a result, controlling hazardous air pollutant emissions is expected to generate substantial public health and environmental benefits.

- Use of more effective control technologies by more coal-fired power plants as a result of the Utility Air Toxics Rule is expected to reduce the public health and environmental impacts of electricity generated by combustion of coal.

Table 1. Toxicological and Environmental Properties of Hazardous Air Pollutants (HAPs) Emitted from Electric Generating Stations Fueled by Coal.			
Class of HAP	**Notable HAPs**	**Human Health Hazards**	**Environmental Hazards**
Acid Gases	Hydrogen chloride, Hydrogen fluoride	Irritation to skin, eye, nose, throat, breathing passages.	Acid precipitation, damage to crops and forests.
Dioxins and Furans	2,3,7,8-tetrachlorodioxin (TCDD)	Probable carcinogen: soft-tissue sarcomas, lymphomas, and stomach carcinomas. May cause reproductive and developmental problems, damage to the immune system, and interference with hormones.	Deposits into rivers, lakes and oceans and is taken up by fish and wildlife. Accumulates in the food chain.
Mercury	Methylmercury	Damage to brain, nervous system, kidneys and liver. Causes neurological and developmental birth defects.	Taken up by fish and wildlife. Accumulates in the food chain.
Non-Mercury Metals and Metalloids (excluding radioisotopes)	Arsenic, beryllium, cadmium, chromium nickel, selenium, manganese	Carcinogens: lung, bladder, kidney, skin. May adversely affect nervous, cardiovascular, dermal, respiratory and immune systems.	Accumulates in soil and sediments. Soluble forms may contaminate water systems.
	Lead	Damages the developing nervous system, may adversely affect learning, memory, and behavior. May cause cardiovascular and kidney effects, anemia, and weakness of ankles, wrists and fingers.	Harms plants and wildlife; accumulates in soils and sediments. May adversely affect land and water ecosystems.
Polynuclear Aromatic Hydrocarbons (PAH)	Naphthlalene, benzo-a-anthracene, benzo-a-pyrene, benzo-b-fluoranthene, chrysene, dibenzo-a-anthracene	Probable carcinogens. May attach to small particulate matter and deposit in the lungs. May have adverse effects to the liver, kidney, and testes. May damage sperm cells and cause impairment of reproduction.	Exists in the vapor or particulate phase. Accumulates in soil and sediments.
Radioisotopes	Radium	Carcinogen: lung and bone. Bronchopneumonia, anemia, brain abscess.	Deposits into rivers, lakes and oceans and is taken up by fish and wildlife. Accumulates in soils, sediments, and in the food chain.
	Uranium	Carcinogen: lung and lymphatic system. Kidney disease.	
Volatile Organic Compounds	Aromatic hydrocarbons including benzene, toluene, ethylbenzene, xylene	May cause irritation of the skin, eyes, nose, and throat; difficulty in breathing; impaired function of the lungs; delayed response to a visual stimulus; impaired memory; stomach discomfort; and effects to the liver and kidneys. May also cause adverse effects to the nervous system. Benzene is a known carcinogen.	Degrade through chemical reactions in the atmosphere and contribute to carbon-based radicals that contribute to formation of ground-level ozone and its human health effects.
	Aldehydes including formaldehyde	Probable carcinogen: lung and nasopharyngeal cancer. Eye, nose, and throat irritation, respiratory symptoms.	
Hazard information compiled from toxicological profiles and concise chemical assessment documents for specific pollutants published by the Agency for Toxic Substances and Disease Registry and World Health Organization and available on-line (ATSDR, 2011; WHO, 2011).			

1.0 INTRODUCTION

In accordance with the Clean Air Act, the U.S. Environmental Protection Agency (EPA) will propose new limits on emissions of hazardous air pollutants released to the atmosphere from large power plants that burn coal and oil to generate electricity for sale. EPA will issue the proposed rule by March 16, 2011 as required by a court settlement (US District Court Consent Decree, 2010). The proposal will establish, for the first time, federal limits on emissions of hazardous air pollutants from coal- and oil-fired power plants. Commonly abbreviated as HAPs, hazardous air pollutants are chemical pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive problems or birth defects, and that adversely affect the environment. At this time, EPA has identified 187 chemical pollutants as HAPs (USEPA, 2010c).

Known formally as the National Emission Standards for Hazardous Air Pollutants for Utility Boilers, this rule will apply to all coal- and oil-fired combustion units that generate more than 25 megawatts of electricity. The new limits are to be based on the emissions performance of the maximum available control technology (MACT). According to the Clean Air Act, the MACT standards for existing sources are to be at least as stringent as the average emissions achieved by the best performing 12 percent of existing sources. For new sources, MACT standards are to be at least as stringent as the control level achieved by the best controlled similar source. The set of regulations and impending limits for electric generating stations is known as the "Utility Air Toxics Rule". Unlike most industry sectors, coal-fired power plants are currently not subject to federal limits on mercury and other HAP emissions.

The American Lung Association commissioned Environmental Health & Engineering, Inc. to prepare this report on HAPs and power plants that generate electricity by burning coal. The report is intended to be a resource for the non-scientific community that summarizes:

- Releases of HAPs to the atmosphere from combustion of coal (i.e., emissions),
- How these substances are transported and where they end up in the environment (i.e., transport and fate),
- Hazards posed by these HAPS and their impacts on human health and the environment (i.e., toxicity and impact), and
- Controls on releases of HAPs and the likely implications of more widespread use on coal-fired power plants (i.e., air pollution control technologies and their benefits).

2.0 HAZARDOUS SUBSTANCES IN COAL

Coal is a carbon-rich mineral that has been used to generate electricity in this country since the 1800s (NRC 2010). The United States is home to more than a quarter of the world's recoverable coal reserves. In 2008, more than 1 billion tons (2 trillion pounds) of coal was extracted from the earth at more than 1,600 mining operations throughout the country, approximately half of which was used for electricity generation. The electric energy generated from coal accounts for 45% of all electricity produced in the United States (USDOE, 2009a).

Coal is formed from fossilized plant life that is subjected to pressure and heat over millions of years. As coal is formed, it incorporates substances (impurities) from the surrounding soil and sediment, including sulfur and heavy metals. Some of these impurities consist of hazardous materials such as mercury, arsenic, lead, and nickel. The nature and extent of impurities in any given seam of coal depends on the conditions over the long period during which the coal is formed.

Figure 2. Coal, in Natural Form

Ultimately however, coal is classified into one of four types based on its heating value, ash content, and moisture, which in part reflect the extent of impurities present. As shown in Table 2, two types of coal – bituminous and sub-bituminous – account for over 90% of coal use in the country. Pyrite, a mineral rich in iron and sulfur, is a common impurity in bituminous coal, and is a primary host for arsenic and mercury. Sub-bituminous coal contains substantially less sulfur than bituminous coal and is therefore often favored by power plants that desire relatively low emission rates of sulfur dioxide, an important precursor to acid rain and fine particle pollution. Coal is sometimes washed with water and special chemicals to reduce some of the impurities. When burned, the impurities in coal are released and can be emitted to the atmosphere if not captured by air pollution control equipment operated at the power plant.

The average concentrations of hazardous substances present in various types of coal as reported by EPA are also shown in Table 2. Comparing the two types of coal used predominantly in the U.S.; sub-bituminous coal contains two to three times lower concentrations than bituminous coal of many substances that become HAPs when emitted from the exhaust stack of a power plant. However, sub-bituminous coal has a lower heating value than bituminous coal. As a result, more

sub-bituminous coal than bituminous coal must be burned to produce the same amount of electricity. This means that emissions of mercury and non-mercury HAPs from the two major types of coal can be comparable for a given amount of electricity output even though concentrations of HAPs within the coal types are different.

Table 2. Characteristics of Major Coal Types Used to Generate Electricity in the United States

Characteristic	Anthracite	Bituminous	Sub-bituminous	Lignite
Principal Characteristics[1]				
Percentage of U.S. Production	Less than 0.1%	46.9%	46.3%	6.9%
Heating Value (BTU/lb)	15	11 - 15	8 - 13	4 – 8
Sulfur (%)	Less than 1%	3 – 10%	Less than 1%	Less than 1%
Hazardous Air Pollutants in Coal[2]				
Arsenic	NR	0.5	0.1	0.3
Beryllium	NR	0.11	0.03	0.2
Cadmium	NR	0.03	0.01	0.06
Chlorine	NR	35	2.7	24
Chromium	NR	1.1	0.4	2.2
Lead	NR	0.6	0.2	1.0
Manganese	NR	1.8	1.3	20
Mercury	NR	0.007	0.006	0.03
Nickel	NR	0.9	0.4	1.2

BTU/lb—British Thermal Units per pound of coal; a measure of energy density of coal

NR—Not reported

1—NRC, 2010, Table 2-3.

2—Geometric mean concentration of selected elements in coal; units are pounds per billion BTU (USEPA, 2010a).

3.0 HAZARDOUS AIR POLLUTANT EMISSIONS

3.1 Emissions

Over 440 power plants in the United States generate electricity for sale by burning coal (USEPA, 2010a). As shown in Figure 3, coal is burned to produce electricity in power plants located throughout the country; with Idaho, Maine, Rhode Island, and Vermont being the only states not to host a coal-fired power plant. Coal consumption is concentrated in states of the Midwest and Southeast, although 3 of the top 10 coal consuming plants are located in Texas, near its border with Louisiana and Arkansas. As described in more detail in Section 4.0, HAPs and other pollutants released to the air by coal-fired power plants impact local air quality, but are also carried across state borders and throughout the country by prevailing winds that generally flow from west to east.

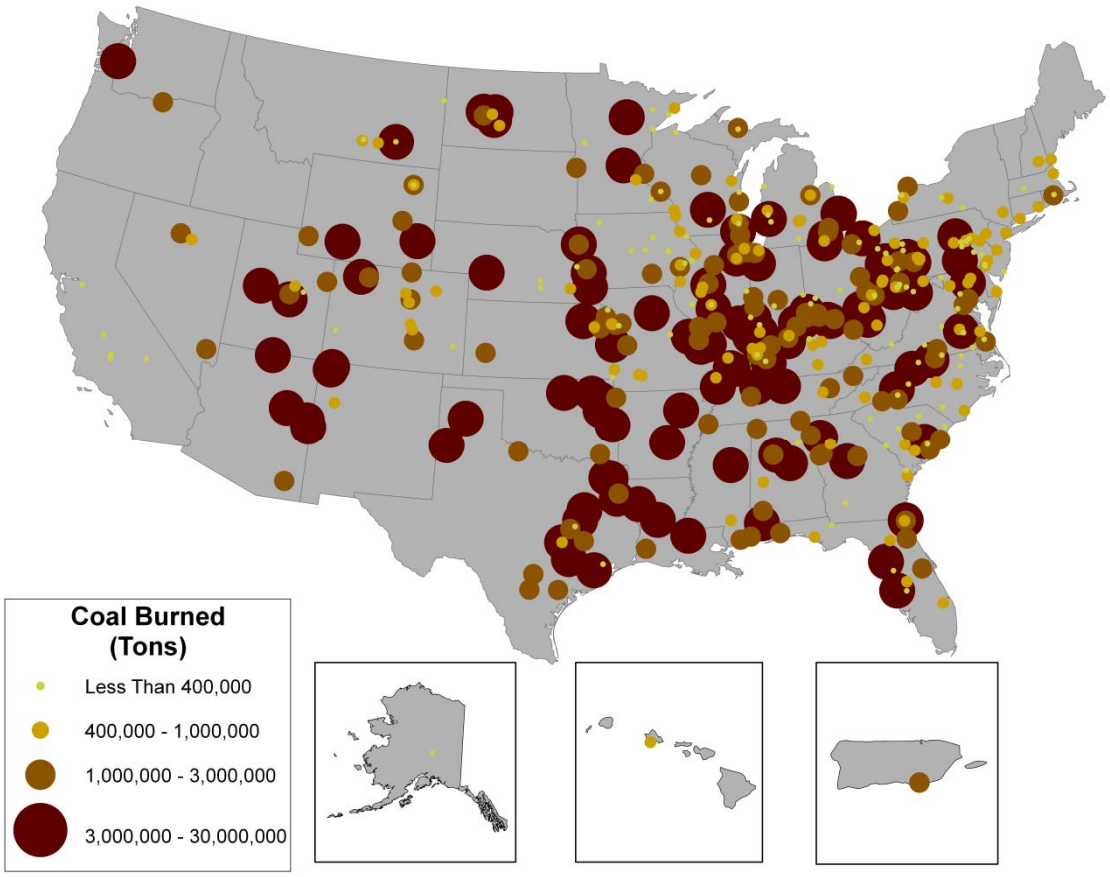


Figure 3. Annual Coal Consumption (tons per year) for Generation of Electricity for Sale by Coal-Fired Power Plants in the United States (USEPA 2010a; USDOE, 2009b). Additional information about the coal consumption of individual power plants is available at www.lungusa.org/ToxicAirReport from the Table of Electric Generating Utility Coal-fired Plants in the U.S.

Coal-fired power plants emit 84 of the 187 HAPs identified by EPA as posing a threat to human health and the environment (USEPA, 2007). With total emissions of 386,000 tons of HAPs annually, coal-fired power plants account for 40% of all HAP releases from point sources[2] to the atmosphere, more than any other point source category (Figure 4). These emissions include both 'fuel-based pollutants' – e.g., metals,[3] hydrogen chloride, hydrogen fluoride, and mercury – that are a direct result of contaminants in the coal that is combusted; as well as 'combustion-based pollutants' – e.g., dioxins and formaldehyde – which are formed during burning of the coal (USEPA, 2011a).

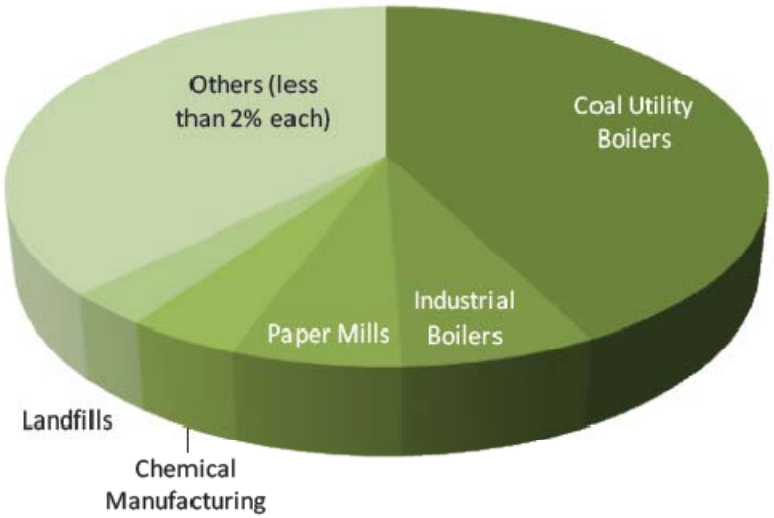


Figure 4 Proportion of Total Hazardous Air Pollutant Emissions From Coal-Fired Power Plants and Other Stationary Sources According to Data in the National Emissions Inventory from the U.S. Environmental Protection Agency (USEPA, 2007).

HAPs emitted from coal-fired power plants include neurotoxins such as mercury and lead, corrosive substances such as hydrochloric acid, carcinogens such as arsenic and benzene, radioactive elements such as radium, and potent organic carbon-based toxins such as dioxins and formaldehyde (USEPA, 2007; USEPA, 2010a). In addition to being the single largest class of total point source HAP emissions, coal-fired power plants are also a major source of emissions for many of these individual HAPs. As shown in Table 3, combustion of coal to generate electricity is the predominant source of hydrochloric acid emissions to the atmosphere (as well as sulfur dioxide and oxides of nitrogen, which are the most

[2] The term 'point source' refers to emissions released from a source that is stationary (does not move). Point sources are distinct from sources that can cover a large area, such as a wildfire, and mobile sources such as cars, trucks, and off-road machinery including bulldozers and other earth-moving equipment. Values reported here are based on the latest EPA National Emissions Inventory. EPA is anticipated to publish updated estimates of hazardous air pollutants from coal-fired power plants as part of the Utility Air Toxic Rule.

[3] As in some EPA materials, the class of pollutants referred to for simplicity here as 'metals' includes some elements (e.g. arsenic and selenium) that are not, strictly speaking, fully metallic.

important sources of atmospheric acidity). Likewise, electricity generating stations powered by coal account for 46% of mercury, and 60% of arsenic released to the atmosphere from point sources.

Table 3. Contributions of Coal-Fired Power Plants to Selected Hazardous Air Pollutant Emissions

Hazardous Air Pollutant	Percentage of Point Source Emissions
Acid Gases (hydrochloric acid and hydrofluoric acid)	76%
Arsenic	60%
Beryllium	28%
Cadmium	30%
Chromium	20%
Cobalt	34%
Lead	15%
Manganese	11%
Mercury	46%
All Non-Mercury Metal HAPs Emitted by Coal-Fired Power Plants	25%
Data obtained from USEPA, 2007	

3.2 Toxicological Properties

HAPS released to the atmosphere from coal-burning power plants have a wide range of toxicological properties, a summary of which is provided in Table 4. Some of these hazardous air pollutants are released in the form of acid gases, which can cause irritation of and tissue damage to eyes, skin, and breathing passages at high levels of exposure. Long-term exposure to metals has the potential to affect the kidneys, lungs, and nervous system. Beryllium can cause sensitization reactions that can remain latent for many years then develop into a serious condition called "Chronic Beryllium Disease." Exposure to several of the trace elements, dioxins and furans, polynuclear aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs) in coal-fired power plant emissions increases the risk of cancer. Finally, mercury is a potent neurotoxin, and high accumulation in humans is a cause of brain damage, while lower body burdens are associated with impairment of people's ability to learn and fine motor control, and may be a factor in heart disease. HAPs emitted from coal-fired power plants that have long-term impacts on the environment, such as accumulation in soil, water, and fish, and which can ultimately affect human health are also shown in Table 4.

Table 4. Toxicological and Environmental Properties of Hazardous Air Pollutants (HAPs) Emitted from Electric Generating Stations Fueled by Coal.			
Class of HAP	**Notable HAPs**	**Human Health Hazards**	**Environmental Hazards**
Acid Gases	Hydrogen chloride, Hydrogen fluoride	Irritation to skin, eye, nose, throat, breathing passages.	Acid precipitation, damage to crops and forests.
Dioxins and Furans	2,3,7,8-tetrachlorodioxin (TCDD)	Probable carcinogen: soft-tissue sarcomas, lymphomas, and stomach carcinomas. May cause reproductive and developmental problems, damage to the immune system, and interference with hormones.	Deposits into rivers, lakes and oceans and is taken up by fish and wildlife. Accumulates in the food chain.
Mercury	Methylmercury	Damage to brain, nervous system, kidneys and liver. Causes neurological and developmental birth defects.	Taken up by fish and wildlife. Accumulates in the food chain.
Non-Mercury Metals and Metalloids (excluding radioisotopes)	Arsenic, beryllium, cadmium, chromium nickel, selenium, manganese	Carcinogens: lung, bladder, kidney, skin. May adversely affect nervous, cardiovascular, dermal, respiratory and immune systems.	Accumulates in soil and sediments. Soluble forms may contaminate water systems.
	Lead	Damages the developing nervous system, may adversely affect learning, memory, and behavior. May cause cardiovascular and kidney effects, anemia, and weakness of ankles, wrists and fingers.	Harms plants and wildlife; accumulates in soils and sediments. May adversely affect land and water ecosystems.
Polynuclear Aromatic Hydrocarbons (PAH)	Naphthlalene, benzo-a-anthracene, benzo-a-pyrene, benzo-b-fluoranthene, chrysene, dibenzo-a-anthracene	Probable carcinogens. May attach to small particulate matter and deposit in the lungs. May have adverse effects to the liver, kidney, and testes. May damage sperm cells and cause impairment of reproduction.	Exists in the vapor or particulate phase. Accumulates in soil and sediments.
Radioisotopes	Radium	Carcinogen: lung and bone. Bronchopneumonia, anemia, brain abscess.	Deposits into rivers, lakes and oceans and is taken up by fish and wildlife. Accumulates in soils, sediments, and in the food chain.
	Uranium	Carcinogen: lung and lymphatic system. Kidney disease.	
Volatile Organic Compounds	Aromatic hydrocarbons including benzene, toluene, ethylbenzene, xylene	May cause irritation of the skin, eyes, nose, and throat; difficulty in breathing; impaired function of the lungs; delayed response to a visual stimulus; impaired memory; stomach discomfort; and effects to the liver and kidneys. May also cause adverse effects to the nervous system. Benzene is a known carcinogen.	Degrade through chemical reactions in the atmosphere and contribute to carbon-based radicals that contribute to formation of ground-level ozone and its human health effects.
	Aldehydes including formaldehyde	Probable carcinogen: lung and nasopharyngeal cancer. Eye, nose, and throat irritation, respiratory symptoms.	
Hazard information compiled from toxicological profiles and concise chemical assessment documents for specific pollutants published by the Agency for Toxic Substances and Disease Registry and World Health Organization and available on-line (ATSDR, 2011; WHO, 2011).			

3.3 Health and Environmental Impacts

Acid Gases

Hydrogen chloride and hydrogen fluoride are strongly corrosive acids, and coal-burning power plants are reported to be the largest anthropogenic source of hydrogen chloride and hydrogen fluoride emissions to air (USEPA, 2007). The amounts of hydrogen chloride and hydrogen fluoride produced by a particular power plant depend in large part on the concentrations of chloride and fluoride in the coal that is burned, and whether any emission control systems are in use.

Hydrogen fluoride is emitted as a gas or particle and can be adsorbed onto other particles (USEPA, 1998). Hydrogen fluoride particles tend to remain suspended in the atmosphere and can travel 500 kilometers or more as fine particles (USEPA, 1998). The majority of hydrogen chloride is believed to deposit rapidly to soil and water by wet and dry deposition or attach to particles in the atmosphere (Sanhueza, 2001).

Because of their high solubility in water, acid gas vapors can readily deposit in the upper airways. Likewise, water bound to microscopic particles can act as a "delivery system" for acids to the alveolar regions of the lung (USEPA, 1998). Controlled exposures of people with asthma have shown irritation and restriction of the airways from exposure to hydrogen chloride (Fine et al., 1987). Other studies have shown both acids to irritate and damage tissue of the eyes, nasal passages and lungs (USEPA, 2011b). The Agency for Toxic Substances and Disease Registry (ATSDR) characterizes hydrochloric acid as "corrosive and can cause irritation and burns" at high concentrations (ATSDR, 2011). Similarly, for high exposures to hydrogen flouride the Agency states that "hydrogen fluoride is irritating to the skin, eyes, and mucous membranes, and inhalation may cause respiratory irritation or hemorrhage".

When combined with water, hydrogen chloride produces "strong acid". Strong acidity in the atmosphere also results from emissions of nitrogen-based and sulfur-based gases released from coal-fired power plants. Other "strong acids" in the atmosphere can result from emissions of nitrogen-based and sulfur-based gases released from coal-fired power plants (producing nitric acid and sulfuric acid, respectively). Strong acids or their precursors that are present in inhaled particles and gases have been linked with respiratory effects in large-scale epidemiological studies. A study of 13,000 children in 24 U.S. and Canadian cities found that strong acidity in particles was associated with increased episodes of bronchitis and reduced lung function and acid gases were associated with asthma and related symptoms in children (Raizenne et al., 1996; Dockery et al., 1996). A more recent major children's

study found also acid gases and particle pollution were associated with reduced lung function (Gauderman et al., 2004). The focus of these landmark studies on children is significant; as children are likely more vulnerable than healthy adults to air pollution, including acidic gases and particles. Children have narrower airways, a faster breathing rate and tend to spend more time outdoors than adults, resulting in greater overall exposures (Bateson and Schwartz, 2008).

Chloride released from hydrogen chloride is associated with cloud acidity (USEPA, 1998) which can contribute to acid deposition over a regional scale. While much of the strong acidity has generally been thought to be related to sulfur dioxide and nitrogen oxide emissions, hydrogen chloride in particular likely plays a significant role in acid deposition in the vicinity of coal-burning power plants (USEPA, 1998).

Dioxins

The term dioxins refer to the family of structurally and chemically related polychlorinated dibenzo dioxins and polychlorinated dibenzo furans; another group of HAPs released to the atmosphere by coal-fired power plants. Dioxins are mainly formed as a by-product of combusting fossil fuels (WHO, 2010). Dioxins and furans are similar in chemical structure and consist of two six-sided rings composed of carbon and oxygen to which are attached either hydrogen or chlorine atoms. The number and position of chlorine atoms on these molecules determines the identity of each specific type of dioxin and furan, and also strongly influences their toxicity.

Dioxins have been measured in the atmosphere in both gas and particle forms. The low-chlorinated compounds have been found to be most prevalent in the gaseous form and the highly-chlorinated compounds dominant in particle form (Oh et al., 2001). The compounds undergo photochemical reactions in the lower levels of the atmosphere (troposphere). The lower-chlorinated compounds are removed from the atmosphere primarily by this photochemical process in as little as one day. The higher-chlorinated compounds are often associated with small particles and may reside in the atmosphere for more than 10 days (Atkinson, 1991) during which time people can be exposed through inhalation.

Most of the higher chlorinated dioxins eventually deposit onto soil or water bodies. Deposition of airborne particle-bound dioxins is likely the most important direct source of dioxin input to water and soil ecosystems (Lohmann and Jones, 1998; Zhang et al., 2009), where they tend to accumulate in

sediments and persist in the environment for many years. Dioxins have a high affinity for fatty molecules, which allows them to accumulate in aquatic and terrestrial food webs. As a result, humans can be exposed to these compounds by consumption of fish and meat. A study conducted by the Food Safety and Inspection Service of the U.S. Department of Agriculture in 2002-2003 found dioxin-like compounds in four classes of U.S. meat and poultry (Hoffman et al., 2006). Once ingested, it can take from 7-12 years for half of the most toxic dioxin; 2,3,7,8-TCDD; to leave the body (ATSDR, 2011). Dioxins have also been measured in the breast milk of nursing mothers (Lorber and Phillips, 2002).

Most of the information on health effects in humans comes from studies of people who were exposed to dioxins through contaminated food or from occupational activities (Kogevinas, 2001). Short-term, intense exposures to dioxins can cause liver damage and skin lesions called chloracne. Long-term exposures have been shown to harm the immune system, the developing nervous system, the reproductive system and can disrupt hormone function. Human exposure to 2,3,7,8-TCDD and to some mixtures of other dioxins have been linked to an excess risk of cancer for many types of cancer. Studies have also shown a slight increased risk of developing diabetes (WHO, 2010).

Current research is focusing on the ability of dioxins to mimic natural hormones in the body and alter their normal function; i.e., a class of contaminants known as endocrine-disrupting compounds (Casals-Casas and Desvergne, 2011). A study of 1 to 9 year-old boys accidentally exposed to 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) in 1976 reported that there were irreversible effects to reproductive hormone levels and reduced semen concentration and quality in those same individuals as adults 22 years later (Mocarelli et al. 2008). According to the World Health Organization (2010), "The developing fetus is most sensitive to dioxin exposure. The newborn, with rapidly developing organ systems, may also be more vulnerable to certain effects."

Radioisotopes

The scientific term radioisotope refers to forms of certain elements that are radioactive. Materials that are radioactive emit ionizing radiation that can damage cells and contribute to various forms of cancer and other illness. While coal does not contain large amounts of radioactive material, the large volumes of coal burned in power plants lead to substantial releases of radium and uranium to the atmosphere in particle form. Combustion of coal is the leading source of radium releases to the atmosphere (ATSDR, 2011). One study estimated that 100 times more radioactivity is released from a coal-fired plant as compared to a nuclear power plant of a similar size (McBride et al., 1978).

Mercury

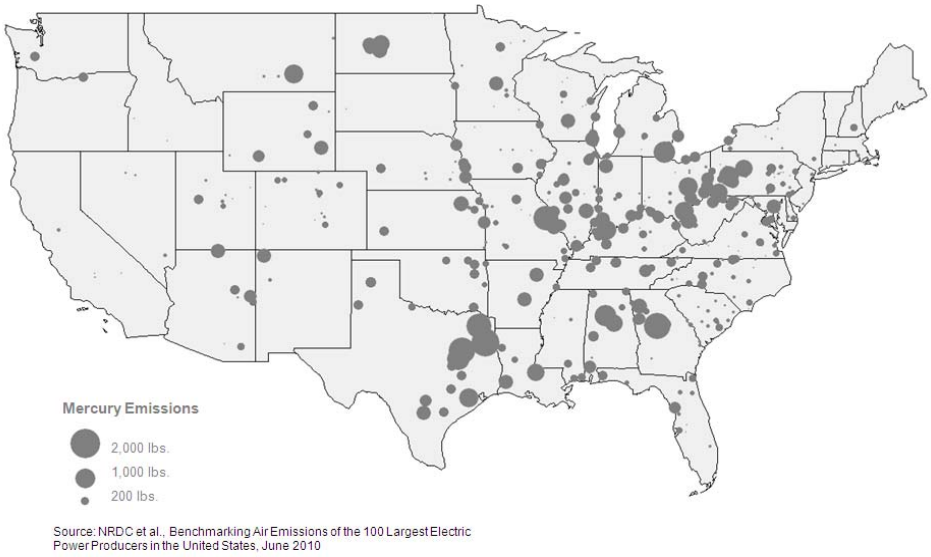
EPA identifies mercury as one of the most toxic HAPs released by coal-fired power plants, primarily because of its ability to impair functioning of the central nervous system. Coal-fired power plants are responsible for about one-third of all mercury emissions from human activity (USEPA, 1997). After being released to the atmosphere, mercury can return to the earth in rain or snow.

The local impacts of that mercury can be seen in studies of eastern Ohio. Coal combustion was estimated to account for 70% of mercury in rainfall of Steubenville, Ohio (Keeler et al., 2006), reflecting the fact that coal-fired power plants are a major source of mercury emissions to the environment. Comparing mercury emissions from coal-fired power plants and areas of local mercury deposition between the western and eastern U.S. provides qualitative support for that conclusion as well (Figure 5).[4] In another study in eastern Ohio, 42% of the mercury in samples of rain collected in the summer was attributed to emissions from a coal-fired power plant located less than a mile away (White et al, 2009). This finding demonstrates that coal-fired power plants can be significant contributors to deposition of mercury on a local scale.

Mercury that deposits to the earth's surface from air can make its way into waterways where it is converted by microorganisms into methylmercury, a highly toxic form of mercury (Grandjean 2010). As these microorganisms are eaten by larger organisms, methylmercury concentrations increase with each successive level of the food chain, in a process called bioaccumulation. The large and long-lived predators of marine and freshwater ecosystems, including many fish favored by consumers in the U.S., end up with the highest methylmercury concentrations. As a result, consumption of fish and other aquatic organisms is the predominant pathway of exposure to mercury. The amount of mercury in people correlates with typical fish intake (MacIntosh et al., 1997; Carta et al., 2003; Mozaffarian and Rimm, 2009).

[4] Note that mercury deposition shown in the map reflects contributions from all sources as well as the effects of local and regional meteorology, including wind patterns and rainfall. Consider Florida example, a state where there are few coal-fired power plants, yet mercury deposition is high in comparison to some other areas of the country. Burning of everyday garbage (i.e., incineration of municipal solid waste) is known to be an important local source of mercury deposition in Florida (Marsik et al., 2009)

Panel A: Location and Size of US Power Plants by Mercury Emissions



Panel B: Annual Amounts of Mercury Deposition in Rainfall

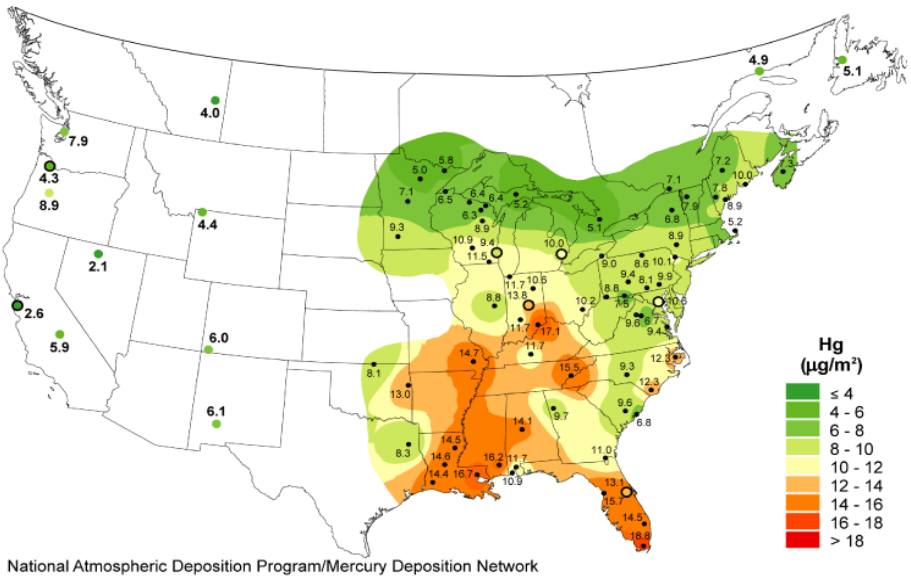


Figure 5 **Panel A**—Location and Size of Annual Mercury Emissions to Air (MJ Bradley, 2010)
Panel B—Annual Amounts of Mercury Deposition in Rainfall (NADP, 2007)

In consideration of this evidence, the major public health concern for the general population is potential health effects of long term, low-level exposure to methylmercury that could result from regular consumption of contaminated fish. Because of concern about the effect of methylmercury on the developing brain in infants, numerous government agencies have issued recommendations on fish

consumption to minimize dietary intake of mercury for women who are or may become pregnant, nursing mothers, and young children. Children are especially at risk because mercury exposure can interfere with nerve development, particularly in the brain (Bose-O'Reilly et al., 2010). Each year more than 300,000 children are born in the US with high enough levels of mercury in their blood to cause impaired performance on brain development tests and to cause permanent effects to intelligence (Trasande et al., 2005; Axelrad et al., 2007). As part of this public health information campaign, at least 39 states have issued advisories warning against fish consumption from local waters due to mercury contamination (USEPA, 2011c).

More recently, interest about public health of the general population and mercury in fish has begun to focus on risks of cardiovascular disease and outcomes (Domingo, 2007). Current evidence indicates that methylmercury in fish may lessen the cardiovascular benefits of regular fish consumption. As stated by Mozaffarian (2009), this is "a finding that has major implications for regulatory decisions regarding control of mercury emissions, because greater public health benefit may be derived from fish consumption if mercury levels were decreased."

Non-Mercury Metals

Many metals present in coal are released to the atmosphere and become part of the mix of microscopic particles produced by coal-fired power plants. The majority of the mass of the microscopic particles emitted from coal-fired power plants consists of sulfur compounds which are not HAPs, but are hazardous nonetheless and addressed by a different section of the Clean Air Act. The remainder of particles includes arsenic, beryllium, cadmium, chromium, lead, manganese, mercury, nickel, radium, and other HAP and non-HAP elements.

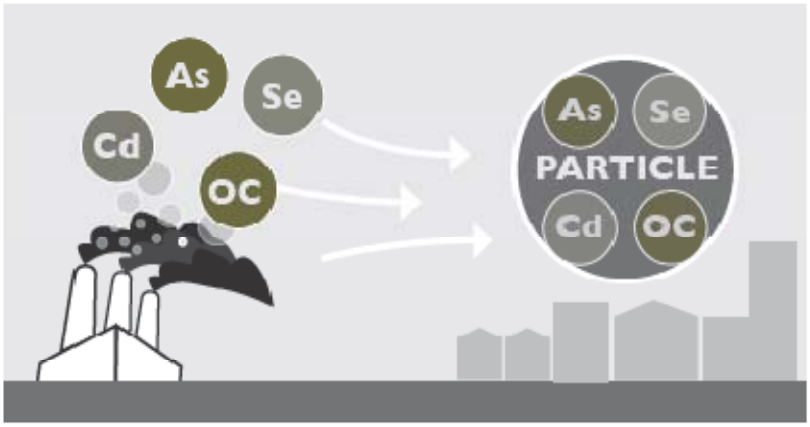


Figure 6. Hazardous Air Pollutants as a Component of Particulate Matter

Emissions of these metals[5] from coal-fired power plants are frequently referred to as primary particulate matter (PM). They are distinct in origin from PM that is formed by chemical reactions in the atmosphere, so called secondary PM.[6]

> Because of the integral relationship between HAPs and particles in exhaust from coal-fired power plants, EPA established particulate matter as a surrogate for emissions of non-mercury metals from industrial boilers required to demonstrate attainment with the *NESHAP for Industrial, Commercial, and Institutional Boilers and Process Heaters at Major Source Facilities* (USEPA, 2011a).

The vast majority of primary PM emissions from coal-fired power plants are part of a class of air pollutants known as fine PM. Fine PM is defined as aerosols that are smaller than 2.5 micrometers ($PM_{2.5}$) and are smaller than the width of a human hair. Thus in addition to posing a hazard to human health and the environmental individually, many of the metal HAPs emitted from coal-fired power plants become part of the burden of fine particulate matter pollution in the United States (USEPA, 2009a).

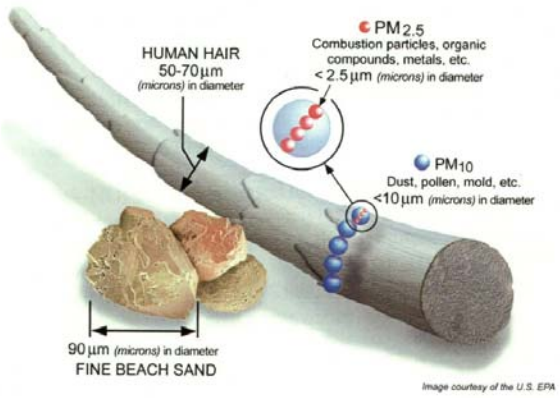


Figure 7. Fine PM: Aerosols Smaller than 2.5 microns Across ($PM_{2.5}$), Compared with a Human Hair and a Grain of Sand. (EPA Office of Research and Development, http://www.epa.gov/ord/ca/quick-finder/particulate-matter.htm)

[5] As in some EPA materials, the class of pollutants referred to for simplicity here as 'metals' includes some elements (e.g. arsenic and selenium) that are not, strictly speaking, fully metallic.

[6] Emissions of sulfur dioxide and oxides of nitrogen from coal-fired power plants are a major source of secondary PM in the United States. Secondary PM can also include large organic carbon-based molecules, such as dioxins, furans, and PAHs; that attach to aerosols as they are carried through the air. Secondary PM will be discussed further in Section 5.

The fact that non-mercury metals emitted from exhaust stacks of coal-fired power plants comprise part of PM is important. When inhaled by people, some particles deposit along the respiratory tract, while others penetrate deeply into the lung where they can enter the bloodstream. These particles aggravate the severity of chronic lung diseases causing loss of airway function, cause inflammation of lung tissue which results in the release of chemicals that impact heart function, and leads to changes in blood chemistry that results in clots that can cause heart attacks (USEPA, 2010b). Inhalation of $PM_{2.5}$ over both short and long periods of time is recognized to cause cardiovascular effects, including heart attacks and the associated mortality. Exposure to $PM_{2.5}$ is also a likely cause of hospital admissions for breathing problems and worsening of existing respiratory illness such as asthma. $PM_{2.5}$ exposure has been linked to other adverse respiratory, reproductive and developmental, and carcinogenic outcomes as well (USEPA 2009a; CASAC, 2010).

Some of the largest studies of health effects related to fine particles were conducted with participation from healthy adults living in areas across the United States. In one of the first and most important of these community-based studies, a research group from the Harvard School of Public Health followed over 8,000 healthy adults living in six U.S. cities for more than 14 years (the Six Cities Study). They concluded that death rates were higher in cities with higher fine particle pollution levels; in other words, people in those cities didn't live as long as people in cities with cleaner air (Dockery et al., 1993). The association between fine particles and early death was repeated in two much larger studies using an American Cancer Society (ACS) database of over 500,000 adults located in 151 cities across the country (Pope et al. 1995; Pope, et al. 2002). In 2000, a reanalysis of both the 1993 Six Cities study and data from the 1995 ACS cohort provided confirmation that fine particles could shorten life (Krewski et al., 2000). A follow-up analysis from the Six Cities Study found increased mortality associated with the fraction of $PM_{2.5}$ attributed to coal combustion (Laden et al., 2006).

The findings of community-based research are supported by results of detailed studies on individuals exposed to $PM_{2.5}$ in both everyday and laboratory settings. Those studies demonstrate that $PM_{2.5}$ exposure elicits markers of cardiovascular damage, including irregular heartbeat as well as pulmonary and systemic inflammation (USEPA 2010b). These findings provide consistent and compelling evidence of fine particle pollution health impacts. In consideration of the weight of evidence, USEPA (2009a), leading scientists (CASAC 2010; Pope and Dockery, 2006), and the American Heart Association (Brook et al., 2004) all agree that exposure to fine particles increases the risk of asthma attack, stroke, heart attack, and other serious illness as well as a variety of less serious, but important, effects including

irritation of the eyes, nose, and throat, chronic bronchitis, restriction of activities, and temporary changes in lung function.

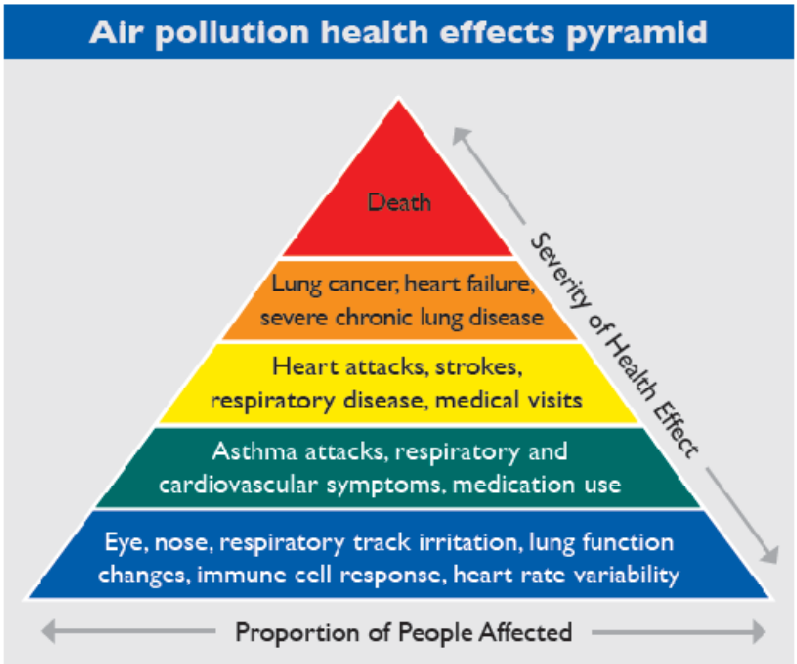


Figure 8. Air Pollution Health Effects Pyramid.

Health effects of air pollution are portrayed as a pyramid, with the mildest and most common effects at the bottom of the pyramid, and the more severe but less frequent effects at the top of the pyramid. The pyramid shows that as severity decreases the number of people affected increases. Exposure to air pollution can affect both the respiratory and the cardiac systems. Adapted from USEPA, 2010b.

The presence of metals or other pollutants in or on particles may be important in determining the toxicity of fine particles (Bell et al., 2007). Researchers have found that metals interact with particles to generate 'reactive oxygen species' which limit the body's ability to repair damage to its cells and contribute to inflammation of tissue (Carter et al., 1997; Gurgueita et al., 2002; Wilson et al., 2002; Valko, 2008). Exposure to particles enriched in sulfate, selenium, iron, nitrate, and organic carbon have been associated with immune cell response and heart variability in human volunteers (Huang et al., 2003; Chuang et al., 2007). A recent community-based study that used Medicare records from 26 communities found greater effects on hospital admissions for cardiovascular disease when the levels of certain metals, including chromium and nickel, were elevated in the $PM_{2.5}$ (Zanobetti et al., 2009). Similarly heart attack admissions were elevated for $PM_{2.5}$ enriched in arsenic, chromium, manganese, nickel and organic carbon. In the same study, diabetes-related hospital admissions were associated with

PM high in arsenic, organic carbon and sulfate, potential indicators of coal combustion. Another important and recent study examined more than one million deaths across the US and found more deaths when the fraction of aluminum, sulfate and nickel in the fine particles was highest (Franklin et al., 2008). This study also found the number of deaths to be even higher for the combination of aluminum with sulfate, compared to aluminum or sulfate alone, indicating they may be more toxic when combined.

Assessments of population-based health impacts as a result of exposure to primary PM released from coal-fired power plants also indicate the importance of non-metal HAP emissions on public health. As described above, the scientific evidence for adverse cardiovascular and respiratory effects of fine particulate matter is very strong and in fact sufficient to support quantitative assessments of public health damages. The health impacts and cost to society of primary PM emissions from coal-fired power plants have been determined in a number of analyses. For example, emissions from a single 1,230 MW facility in Wisconsin were estimated to account for 7 premature deaths, 100 emergency room visits, and 520 asthma attacks each year, with an annual cost of $42 million (MacIntosh et al., 2003). Estimated impacts are significantly larger when coal-fired power plants throughout the U.S. are considered. The National Research Council (NRC) estimated $9 million of costs as a result of direct emissions of $PM_{2.5}$ from the average U.S. coal-fired power plant (NRC, 2010). The NRC analysis considered 406 coal-fired power plants across the country, which yields cumulative annual damages of $3.6 billion as a result of primary $PM_{2.5}$ emissions from those facilities.

4.0 TRANSPORT OF COAL-FIRED POWER PLANT HAZARDOUS AIR POLLUTANTS

Hazardous air pollutants released from coal-fired power plants influence environmental quality and health on local, regional, and global scales. The extent to which a given pollutant or facility impacts each of the scales depends on a number of factors, but principally (i) how long a given pollutant remains in the air, (ii) physical attributes of the power plant, (iii) weather and (iv) the proximity of human populations. These characteristics determine whether human and environmental impacts of a power plant-related HAP are generally local or can extend to a regional or global scale.

A key factor that affects the distribution of pollution from power plant emissions is the average length of time that HAPs stay airborne, in other words their *atmospheric residence time*. Atmospheric residence time varies greatly for different classes of coal-fired power plant HAPs. This variation in persistence directly influences how far HAPs are carried by wind and accompanying weather systems. Assuming a typical ground-level wind speed, HAPs can travel approximately 5 to 10 miles from their source in an hour unless they first deposit to the earth, are transformed through a chemical reaction, or are lost from the atmosphere by any number of other means. Consequently, impacts of HAPs with atmospheric residence times of a few hours are limited to within 15 to 30 miles of their source. Longer-lived HAPs can travel hundreds to thousands of miles before being removed from the atmosphere. Representative atmospheric residence times are shown in Table 5 for several major classes of coal-fired power plant HAPs.

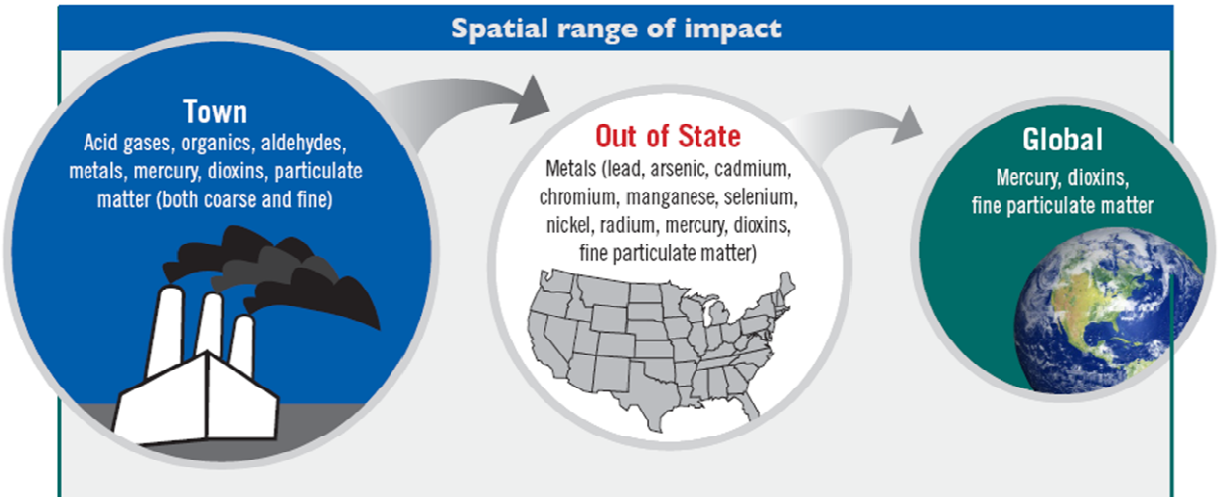


Figure 9. Schematic of the likely range that hazardous air pollutants are transported.

Table 5. Residence Time of Hazardous Air Pollutants in the Atmosphere			
HAP Group	**Indicator Pollutant(s)**	**Residence Time***	**Likely Range of Transport**
Mercury	Methylmercury	7–10 days	Local, regional, global
Metals	Arsenic	7-9 days (lifetime)	Local, regional, global
	Beryllium	10 days (lifetime)	Local, regional, global
	Cadmium	1-10 days (lifetime)	Local, regional, global
	Chromium	Up to 7-10 days	Local, regional, global
	Nickel	Up to 30 days (half-life)	Local, regional, global
	Manganese	Several days (half-life)	Local, regional
	Selenium	1-10 days	Local, regional, global
	Lead	Up to 10 days	Local, some regional
Radioisotopes	Uranium, Radium	Not reported	Local, regional, global**
Dioxins/Furans	Chlorinated dibenzo-p-dioxins	0.5 - 9.6 days (lifetime)	Local, regional, global
	Dibenzofurans	4 days (half-life)	Local, regional
	Chlorodibenzofuran (CDFs)	More than 10 days (half-life)	Local, regional, global
Aldehydes	Formaldehyde	<20 hours (half-life)	Local
Volatile Organic Compounds	Benzene	4–6 hour (half-life in presence of NOx and SO_2)	Local
	Xylene	8–14 hours (half-life)	Local
	Toluene	13 hours (half-life)	Local
	Ethylbenzene	2 days (half-life)	Local
Acid Gases	HCl/HF	1-5 days (half-life)	Local, regional, global
	HCN	530 days (half-life)	Local, regional, global
Polycyclic Aromatic Hydrocarbons (PAHs)	Benzo-a-anthracene, Benzo-a-pyrene, Fluoranthene, Chrysene, Dibenzo-a-Anthracene	Up to several days (lifetime)	Local, regional, global

*Atmospheric residence time based upon lifetime or half-life as reported in chemical specific profiles published by the Agency for Toxic Substances and Disease Registry and the World Health Organization; available on-line (ATSDR, 2011; WHO, 2011).
**Assumed to be a component of fine particles

HAPs that interact readily with water typically have atmospheric residence times of only hours as they quickly enter the water cycle in the form of clouds or water vapor, rivers or lakes. Hydrogen chloride, hydrogen fluoride, and some forms of mercury are among the notable coal-fired HAPs that can be relatively short-lived in the atmosphere. As a result, environmental and health impacts of these HAPs are likely to be concentrated in the vicinity of the power plants from which they are released. These

observations are consistent with the measurements of local mercury deposition that were described in Section 3.3.

Local impacts of coal-fired power plant HAP emissions are not limited to HAPs with short atmospheric residence times, however. Longer-lived HAPs are also present in the immediate vicinity of the source before being transported to other areas. These include metals such as lead, arsenic, cadmium and chromium. Potential exposures to these HAPS can therefore be elevated in areas surrounding a coal-fired power plant. For instance, a study of coal-fired power plants in New England found that public health damages per person are two to five times greater for communities near the facilities than for populations living at a greater distance from the plants (Levy and Spengler, 2002).

In addition to properties of a given pollutant and weather, the location and magnitude of local impacts from emissions of coal-fired power plant HAP are influenced by the height of the emission point above ground level. In general, lower stacks result in higher impacts near the source than taller stacks. The relationship between stack height and location of ground-level impacts is illustrated in Figure 10.

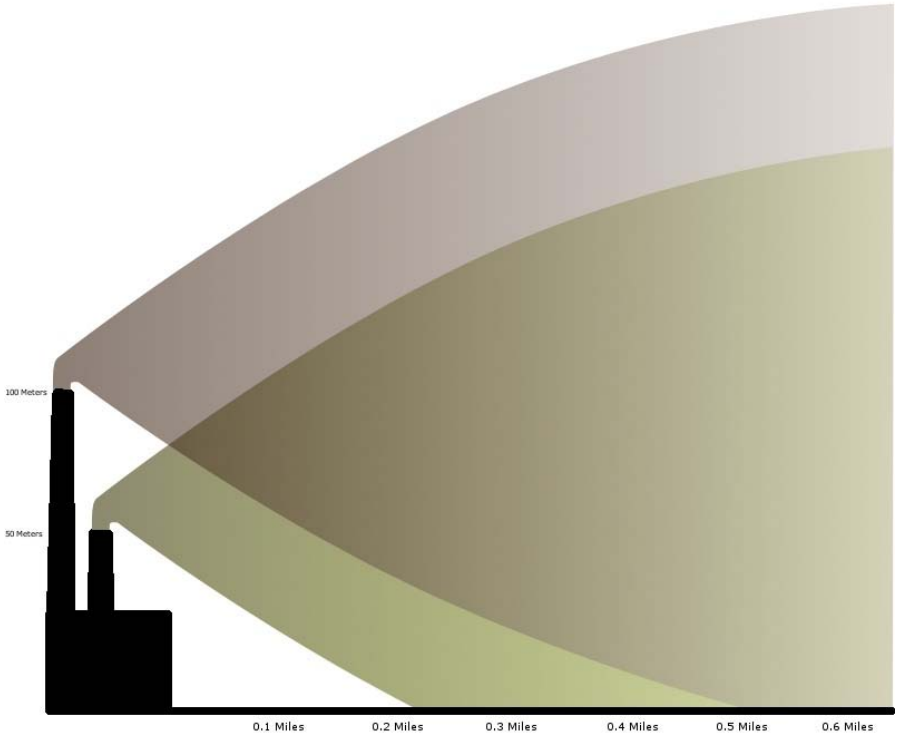


Figure 10 Schematic of location of initial ground-level impacts in relation to height of hazardous air pollutant release.

Stack heights for coal-fired power plants in the U.S. are 440 (134 meters) feet on average and range from 15 feet (about 4 meters) to 1,040 feet (about 316 meters) above ground level (USEPA 2010a). Corresponding maximum ground-level impacts range from 500 feet (about one-tenth of a mile) to 4,000 feet (about three-quarters of a mile). Consequently, the greatest ground-level impacts of HAPs emissions from any given coal-fired power plant are typically within a mile of the facility.

Tall exhaust stacks can mitigate local air quality impacts in general, although higher discharge points also release pollutants at an altitude where they are more readily transported on a regional and even global scale. Taller stack heights therefore enhance instate transport of HAPs and other pollutants. Markers of primary and secondary coal combustion have been reported in many analyses of the composition of regional fine particulate matter pollution (e.g.; Lee et al., 2002; Lee et al., 2003; Lee et al., 2006; Rutter et al., 2009). Regional transport of coal-fired power plant emissions translates to regional impacts on public health as well. One analysis of emissions from a coal-fired power plant in Wisconsin found that 80% of total public health impacts occurred beyond the state border (MacIntosh et al., 2003).

Some research has indicated that the burden of air quality impacts resulting from emissions by local sources may be borne disproportionately by disadvantaged communities. These impacts can occur in terms of both exposure and effect. With regard to exposure, lower-income and ethnic-minority residents have been found to be disproportionately exposed to air pollution because of their proximity to industrial facilities. With regard to plants that burn coal and oil for industrial processes, USEPA (2010d) recently reported that:

> *"demographic analysis showed that major source boilers are located in areas where minorities' share of the population living within a 3-mile buffer is higher than the national average. For these same areas, the percent of the population below the poverty line is also higher than the national average."*

In addition to elevated exposure to coal-fired power plant emissions, other research has suggested that socially disadvantaged populations are at greater risk of adverse health effects of air pollution. In one study, nearly 50% of the risks for premature mortality of power plant-related exposures were borne by the 25% of the population with less than high school education (Levy et al. 2002). This result reflected both higher background rates of mortality and higher relative risks for air pollution related mortality for individuals with lower education. Socially disadvantaged populations also are more likely to lack access to health care and to live in conditions associated with asthma exacerbations (Babey et al 2007). These studies indicate that social-class and ethnic-based environmental injustices appear to exist in the distribution of air pollution exposure and effects.

Another example of regional impacts of coal-fired power plant emissions is provided in Figure 11. In this case, emissions of primary PM, sulfur dioxide, and oxides of nitrogen were modeled for 11 coal-fired power plants in Michigan and used to predict annual average concentrations of $PM_{2.5}$ for counties across the continental United States. As shown on the map, the highest $PM_{2.5}$ impacts from the plants were predicted to occur throughout the Great Lakes region and parts of New York and New England.

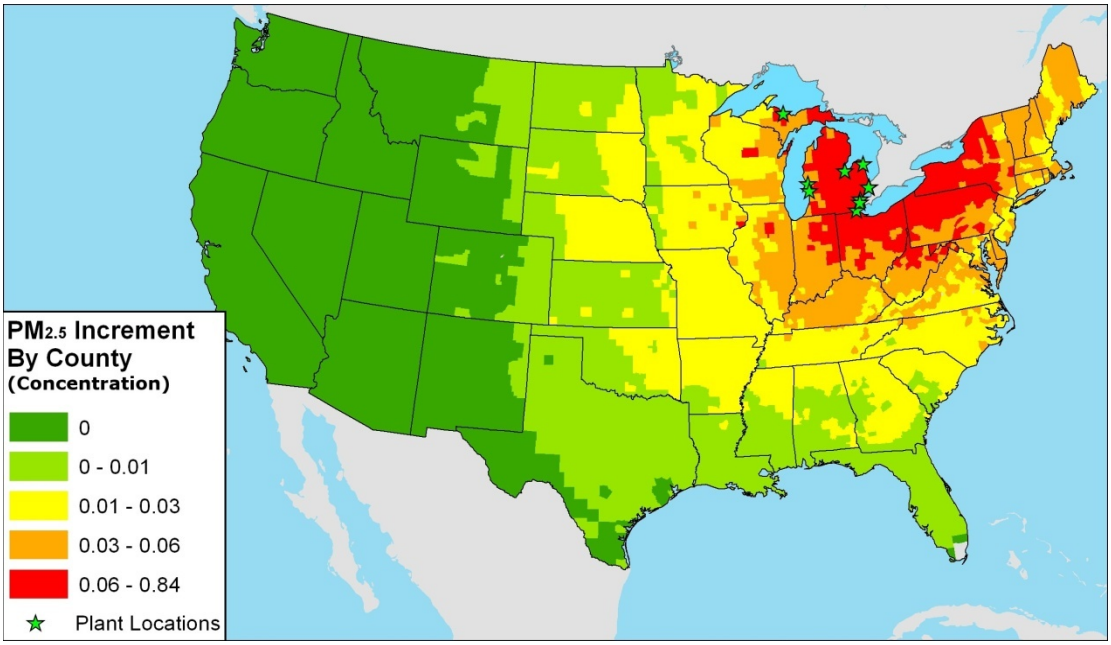


Figure 11 Annual Average Concentrations of Fine Particulate Matter ($PM_{2.5}$) Estimated for Counties of the Contiguous United States as a Result of Emissions of Primary $PM_{2.5}$, Sulfur Dioxide, and Oxides of Nitrogen from 11 Coal-Fired Power Plants in Michigan (EH&E, 2011).

5.0 CONTROL OF HAZARDOUS AIR POLLUTANTS FROM COAL-FIRED POWER PLANTS

The forthcoming Utility Air Toxics Rule is anticipated to establish limits for HAPs from power plants that produce at least 25 MW of electricity for sale. The Utility Air Toxics Rule will apply to both new and existing coal-fired power plants. According to the Clean Air Act, these plants are expected to attain HAP emission rates that are on par with the typical best performing coal-fired power plant, defined as the average of the cleanest 12% of the coal-fired power plants. Using the industrial boiler rule as a guide (USEPA, 2011a), subcategories of emissions limits may be established under the Utility Air Toxics Rule based on plant size, type of fuel, type of boiler, utilization, or other factors.

Technologies that are effective at controlling emissions of HAPs from coal-fired power plants are already in use by some power plants as evidenced by emission data gathered by USEPA from samples of both better controlled and randomly selected facilities (USEPA, 2010b). As shown in Figure 12, emissions of mercury, selenium, hydrogen chloride, and hydrogen fluoride were 5 times lower from the better controlled coal-fired power plants compared to the power plants selected at random. A 50% reduction was observed in emissions of the other non-mercury metals, dioxins, and PAHs for the sample of better performing plants in comparison to the random sample of plants.

The emissions data illustrated in Figure 12 reflect control efficiencies achieved by a wide range of technologies available to reduce the amount of acid gases, mercury, non-mercury metals, and organic-carbon based hazardous air pollutants in exhaust gas released from coal-fired power plants. A detailed description of those technologies and analysis of their effectiveness for controlling HAPs is beyond the scope of this report. However, an introduction to some of the more common technologies is provided here to aid understanding of the operating principles of these systems and the extent to which they are deployed in coal-fired power plants across the United States.

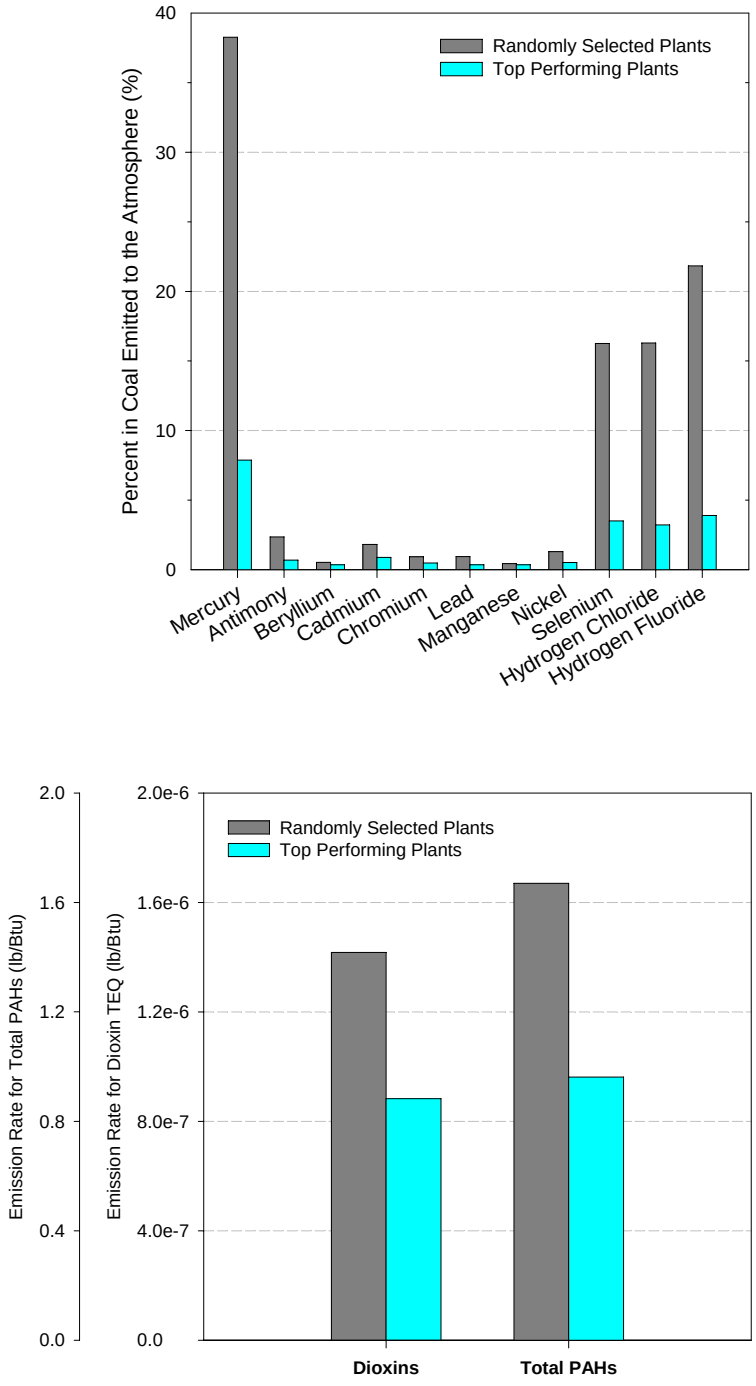


Figure 12. Comparison of Average Hazardous Air Pollutant Emissions from Top Performing and Randomly Selected Coal-Fired Power Plants Selected by EPA (EPA 2010). Abbreviations: PAHs—polynuclear aromatic hydrocarbons; TEQ—toxicity equivalents for subgroups of dioxins and furans.

Three major categories of air pollution control equipment are used to reduce emissions of HAPs including systems for acid gases, particulate matter, and mercury (Table 6). A portion of coal-fired power plants in the U.S. already use these technologies. More facilities are expected to install these or similar technologies in response to the new Utility Air Toxics Rule.

Table 6. Currently Available Control Technologies in Use for Reduction of Emissions of Air Toxics from Coal-Fired Power Plants

Control Technology	Which Pollutants Are Controlled?	How Does this Technology Work?	Number of Coal-Fired-Power Plants Using This Technology
Acid Gas Control Technologies			
Wet Flue Gas Desulfurization (FGD) (Scrubbers)	HAPs: Hydrogen chloride Hydrogen fluoride Hydrogen cyanide Mercury Collateral Pollutants Sulfur dioxide Particulate matter	Liquid mixed with limestone is sprayed into the emission, producing wet solid by-products. Sulfur oxides react with limestone to form calcium sulfite and calcium sulfate.	144 (32%)
Dry Flue Gas Desulfurization (FGD) (Scrubbers)	HAPs: Hydrogen chloride Hydrogen fluoride Hydrogen cyanide Mercury Collateral Pollutants Sulfur dioxide Particulate matter	Emissions are passed through a stream of liquid mixed with lime or a bed of basic material such as limestone, forming salts which are captured using PM controls.	64 (14%)
Dry Sorbent Injection (DSI)	HAPs: Hydrogen chloride Hydrogen fluoride Hydrogen cyanide Collateral pollutant Sulfur dioxide	Dry sorbent consisting of Trona, sodium bicarbonate, or lime is blown into duct, reacts with acid gases and is captured in downstream PM controls.	19 (4%)
Fluidized Bed Combustion (FBC)	HAPs: Hydrogen chloride Hydrogen fluoride Hydrogen cyanide Collateral pollutants Sulfur dioxide	Combustion technology more efficient than conventional boilers, air is blown through a bed of limestone and fuel during combustion.	6 (1%)

Continued on the next page

Table 6. Cont'd: Currently Available Control Technologies in Use for Reduction of Emissions of Air Toxics from Coal-Fired Power Plants			
Control Technology	**Which Pollutants Are Controlled?**	**How Does this Technology Work?**	**Number of Coal-Fired-Power Plants Using This Technology**
Non-Mercury Metal Control Technologies			
Electrostatic Precipitators (ESP)	HAPs: Antimony, Beryllium, Cadmium, Cobalt, Lead, Manganese, Nickel, Particle phase organics Collateral Pollutants Other forms of primary particulate matter	Particles are charged with electricity and collected on oppositely charged plates, particles are collected for disposal/further treatment.	333 (74%)
Baghouse	HAPs Antimony, Beryllium, Cadmium, Cobalt, Lead, Manganese, Nickel, Particle phase organics Collateral Pollutants Other forms of primary particulate matter	Emissions passed through fabric filters and collected	157 (35%)
Cyclones	HAPs Antimony, Beryllium, Cadmium, Cobalt, Lead, Manganese, Nickel, Particle phase organics Collateral Pollutants Other forms of primary particulate matter	Use centrifugal force to separate particulate from gas streams.	23 (5%)
Mercury Control Technology			
Activated Carbon Injection (ACI)	Mercury, Arsenic, Chromium, Selenium, Dioxin and other gas-phase organic carbon-based compounds	Powdered activated carbon (similar to charcoal) is blown into the flue gas after combustion, pollutants are absorbed by carbon and removed by PM controls	58 (13%)
Notes: The total number of coal-fired plants (447) and the number using each type of control technology was obtained by merging information from the U.S. Environmental Protection Agency Clean Air Markets Database (USEPA 2009b), USDOE, 2009b, and USEPA, 2010d.			

A notable aspect of the information in Table 6 is that some of the technologies that are effective for control of HAP emissions from coal-fired power plants are also effective at controlling emissions of non-HAP air pollutants such as sulfur dioxide and particulate matter (referred to as *Collateral Pollutants* in the table). As described below, control of criteria air pollutants as a collateral benefit of reducing emissions of HAPs would be an important public health benefit of the Utility Air Toxics Rule.

Coal, especially some bituminous coals can have significant chlorine content, which contributes to hydrogen chloride emissions when this type of coal is burned (Staudt, 2010). Electric utility boilers that fire bituminous coal comprise roughly half of the coal-fired electric generating capacity of the U.S. Many of these facilities are equipped with wet scrubbers that are highly efficient at capturing hydrogen chloride and other acid gases (e.g., hydrofluoric acid). However, a large number of bituminous fueled units are not equipped with scrubbers—having only particulate controls, and could need acid gas controls to meet emission limits set under the Utility Air Toxics rules.

In order to meet the emission standards for hydrogen chloride and hydrogen fluoride, some of the uncontrolled facilities may choose to install wet or dry scrubbers, also known as flue gas desulfurization. Wet scrubbers are more efficient at removing acid gases, but they are more costly than dry scrubbers. Modern wet scrubbers typically reduce sulfur dioxide emissions by about 98%, have higher capture rates for hydrogen chloride, and reduce emissions of primary PM as well. Reduction of primary PM is supported by data in USEPA's Information Collection Request on bituminous coal units equipped with an electrostatic precipitator (ESP) (USEPA, 2010a).

A review of these data showed significant reductions in condensable particulate emissions when comparing the average emissions of units with wet flue gas desulfurization versus those without it, as shown in Table 7. Condensable particulate matter consists of substances, such as many metals, that are a vapor in the hottest portions of an exhaust stack, but rapidly condense to form primary PM. These results are based upon relatively small data sets and may not be representative for all facilities, but the data show a large reduction in condensable PM from the use of this technology.

Table 7. Comparison of Average Emission Rate of Condensable Particulate Matter for Bituminous Coal Facilities With and Without Wet Flue Gas Desulfurization ("Scrubbers")

Emission Rate, pounds per million British Thermal Units			
Control Device	With Wet Scrubbers	Without Wet Scrubbers	Percent Reduction
Electrostatic Precipitators	0.041*	0.009	78%

Source: EPA, 2010a. *These data included units with selective catalytic reduction, which would increase condensable particulate matter somewhat, but typically not more than doubling it.

Because of the cost of wet scrubbers (and to a lesser extent, dry scrubbers), other technologies are likely to be deployed for hydrogen chloride capture from unscrubbed bituminous coal fired boilers. Many unscrubbed facilities may install dry sorbent injection, which is much less expensive to install than a wet scrubber. Dry sorbent injection offers the ability to reduce both hydrogen chloride and sulfur oxides, but is generally less effective at removal of sulfur dioxide than the more costly wet or dry scrubbers.

At one facility, hydrogen chloride and sulfur dioxide were removed using dry sorbent injection with both a baghouse (i.e., fabric filter) and an ESP for particle collection (Davidson, 2010). This study showed that the unit with an ESP, the most commonly used PM control device on power plants, removed 95% of the hydrogen chloride and 50% of the sulfur dioxide. At the Mirant Potomac River Power Plant, equipped with dry sorbent injection and an ESP, roughly 98% of hydrogen chloride and greater than 70% of sulfur dioxide were captured (Kong, 2008). A review of power plant data showed significant reductions in condensable PM emissions when comparing the average emissions of units with dry sorbent injection versus those without, as shown in Table 8. As before, these results are based upon relatively small data sets and may not be representative for all facilities, but the data show large reductions in condensable PM from the use of this technology.

Table 8. Comparison of Average Emission Rate of Condensable Particulate Matter from Facilities With and Without Dry Sorbent Injection (DSI)

Emission Rate, pounds per million British Thermal Units			
PM Control Device	Without DSI	With DSI	Percent Reduction
Electrostatic Precipitators**	0.041*	0.007	83%
Fabric Filters***	0.028*	0.003	91%

Source: USEPA, 2010a. *These data included units with selective catalytic reduction, that would increase condensable particulate matter somewhat, but typically not more than doubling it. ** Bituminous coal *** Powder River Basin coal

Regardless of whether scrubbers or dry sorbent injection is selected, the Utility Air Toxics Rule standards are expected to reduce aggregate emissions of hydrogen chloride and hydrogen fluoride from coal-fired power plants. Because of the physical and chemical properties of the available control technologies, the measures taken to reduce HAP acid gases are also anticipated to lower emissions of condensable PM and sulfur dioxide. These collateral benefits are important because condensable PM and secondary PM formed from sulfur dioxide comprise the majority of fine particulate matter in most areas of the United States.

The public health benefits of additional PM and sulfur dioxide controls could be substantial. The potential value of collateral benefits from the Utility Air Toxics Rule is indicated EPA's recent Regulatory Impact Analysis for MACT on industrial boilers (USEPA 2011a). In that analysis, EPA estimated that public health benefits of at least $22 billion to $54 billion would be achieved by MACT controls on industrial boilers. In comparison, the costs of controls were estimated to be $1.4 billion. EPA attributed over 90% of the public health benefit to reductions in sulfur dioxide emissions, presumably achieved as a by-product of acid gas controls on those boilers. With a benefit-cost ratio of at least 16 to 1, the public health and economic value of controlling acid gas emissions from those boilers is clear. Although not quantified directly, technologies that control acid gas emissions may also reduce emissions of hazardous metals like mercury and selenium, which are not as effectively controlled by conventional particle technologies. (USEPA, 2010).

While there has been some debate over whether collateral benefits can be considered in rulemaking for HAPs, the Clean Air Act states that EPA is authorized to consider the collateral benefits of controlling sulfur dioxide and other criteria pollutants when establishing National Emission Standards for Hazardous Air Pollutants. This aspect of the law was recently affirmed. After consideration of extensive public comments on this subject EPA concluded it knows of "no principle in law or common sense" that precludes the Agency from considering collateral environmental benefits when acting to regulate HAP emissions under the Clean Air Act (USEPA 2011b).

6.0 CONCLUSIONS

The U.S. Environmental Protection Agency (EPA) will propose new limits on emissions of selected hazardous substances to the atmosphere from utilities that burn coal and other fossil fuels. The proposal will set new limits on emissions of hazardous air pollutants, 187 chemicals identified by EPA according to criteria established by Congress. This is the first time that emissions limits for HAPs will be required on all medium and large-scale power plants. The new limits are to be based on emission rates that can be achieved by the use of maximum available control technology, referred to as MACT. The set of regulations and impending limits for electric generating stations is known as the *Utility Air Toxics Rule*.

Environmental Health & Engineering, Inc. was retained by the American Lung Association to prepare a summary of hazardous air pollutant emissions from coal-fired power plants that would be a useful resource for the general public. The major conclusions of the summary are as follows:

- Hazardous air pollutants emitted to the atmosphere by coal-fired power plants cause a wide range of adverse health effects including damage to eyes, skin, and breathing passages; negative effects on the kidneys, lungs, and nervous system; increasing the risk of cancer; impairment of neurological function and ability to learn; and pulmonary and cardiovascular disease.

- Exhaust gases discharged to the air by coal-fired power plants are reported to contain 84 of the 187 hazardous air pollutants identified by EPA.

- With total emissions of 386,000 tons of HAPs annually, coal-fired power plants account for 40% of all hazardous air pollutant releases from point sources to the atmosphere, more than any other point source category.

- Hazardous air pollutants released from coal-fired power plants influence environmental quality and health on local, regional, and continental scales.

- Public health risks of exposure to mercury in food and metals in airborne fine particulate matter are among the most notable health and environmental impacts associated with emissions of hazardous air pollutants from coal-fired power plants.

- Hazardous air pollutant emissions from a sample of coal-fired power plants selected because of their use of multiple control technologies were 2 to 5 times lower on average than from a random sample of plants selected by EPA.

- Controls on acid gas and non-mercury metal emissions are likely to reduce emissions of sulfur dioxide and primary particulate matter. As a result, controlling hazardous air pollutant emissions is expected to generate substantial public health and environmental benefits.

- Use of more effective control technologies by more coal-fired power plants as a result of the Utility Air Toxics Rule is expected to reduce the public health and environmental impacts of electricity generated by combustion of coal.

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