Chapter 2
Airborne Toxic Chemicals

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Glossary

Air toxic	Substances that are known or suspected to cause cancer or other serious health effects. Also known as Hazardous Air Pollutants (HAPS).
Anthropogenic source	A source of air toxics created by human beings.
Area source	A single source of pollutant that emits less that 10 t per year of one air toxic, or less than 25 t per year of any combination of air toxics.
MACT (Maximum Achievable Control Technology)	Standard that dictates emission limits of a source is set by the best performing 12% of similar sources, if more than 30 similar sources exist nationally. If less than 30 exist, the best five are used to set the standard.
Major source	A single source of pollutant that emits 10 t per year or more of one air toxic, or 25 t per year or more of any combination of air toxics.
Mobile source	A source of air toxics that moves (such as a car, truck, airplane, or boat).

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Definition of the Subject and Its Importance

“Air toxics” is a term that is often used colloquially, but for the purposes of this article it will be used following the specific definition set forth by the US Environmental Protection Agency (EPA). Toxic (or Hazardous) air pollutants are those pollutants that are known or suspected of causing cancer or other serious health effects [1]. Air toxics are defined by the Clean Air Act, which explains what pollutants qualify, how different sources are categorized, and how they are to be regulated [2]. The Clean Air Act (CAA) is the most comprehensive modern legislation concerning air quality in the USA. The original 1970 Act defines “Hazardous Air Pollutants” (HAPS) or air toxics as those substances known or suspected of causing cancer, birth defects, or other adverse health problems. It charges the EPA to “Significantly reduce emissions of the most potent air pollutants” [2]. Initially, the Clean Air Act listed 189 chemicals as toxics; during the revision of 1990 caprolactam was eliminated based on new scientific evidence, leaving 188 [1].

Introduction

It can be said that air pollution is as old as civilization itself. With the discovery of fire, humans started emitting substances into the atmosphere. Ancient Rome had issues with pollution of land, water, and air, including emissions from copper and lead production that were greater than Europe during the nineteenth century [3]. In 1954, smog descended on London, primarily from coal burning, for 4 days and killed 4,000 people [4–6]. Air pollution has been known to affect evolution of species; the most famous example being the peppered moths of England, who evolved a darker color to match soot covered trees near industrial operations [7].

Despite its long history and fundamental importance to environmental health and quality of life, air quality is one of the harder aspects of environmental health to grasp, and even harder to control. Unlike water or soil, air cannot be picked up and held. How it travels from place to place is still the subject of intense scientific research. Human understanding of the air, how pollutants enter into it and travel, and how they ultimately affect human and animal health is still being actively investigated. This chapter will summarize the fundamentals of air toxics, a subset of air pollutants, from both an environmental and human health perspective. The following presents a synopsis of the current state of knowledge and discusses future directions for research in this area. The article will start off with a brief summary of air toxics, where they come from and where they go. Readers are encouraged to consult the numerous air pollution textbooks listed in the references for an in-depth treatment of these topics. Following this background material, three specific toxics, benzene, mercury, and perchloroethylene and their roles in modern living will be discussed. The article will finish with a discussion of future directions for better understanding of the role of air toxics from a sustainability standpoint.

Toxics in the Air

Where Do They Come From?

Any introductory textbook on the topic of air pollution starts with the fundamental knowledge that regulated pollutants are from both biogenic and anthropogenic sources. This information is typically presented in the context of the six major criteria pollutants, which constitute the EPA regulations for ambient air quality. Toxics, however, represent a different set of pollutants and by definition it is not necessarily their ambient concentration that is of main concern. It is important to recognize that while some toxics can be emitted from natural occurrences such as volcanic eruptions and forest fires, by and large, toxics come from anthropogenic sources.

Air toxics can be emitted into the atmosphere in several ways. Attrition occurs through the mechanical wearing of physical objects. Activities such as grinding, polishing, sanding, drilling, and spraying can lead to pollution by attrition. This can be found in activities such as drilling for oil [8], or in a local auto body shop that specializes in sanding and painting cars. Vaporization occurs when a liquid converts into its gaseous form. This can happen under temperature and pressure, or because the liquid is volatile (readily evaporates at normal temperatures). Gasoline is one such volatile liquid that readily evaporates [8]. One of the byproducts of gasoline evaporation is benzene, which is discussed in detail below. The third manner in which many toxics become airborne is through combustion. Combustion occurs when a substance is combined with oxygen in a chemical reaction that creates energy. If a fuel is perfectly combustible, meaning that all of it gets used in the combustion process, the two outputs are water vapor and carbon dioxide. Both of which, while not toxic to humans are greenhouse gasses that can contribute to global warming through the trapping of heat energy from the sun. Most fuels, however, are imperfectly combustible, meaning that they do not burn completely. This leaves byproducts such as benzene, toluene, and formaldehyde [8].

For a full understanding of the sources of air toxics and regulation, one must first be familiar with the source categories. The main concern for air toxics regulators are routine emissions: Those that are produced as a byproduct of a process, rather than accidental “one time” emissions [1]. Three major source categories exist. *Mobile sources* include any mechanical object that moves (cars, planes, trains, marine, farming equipment, etc.). Over 50% of air toxic released into the atmosphere come from mobile source emissions [9]. In addition to emitting greenhouse gasses, auto emissions also include several air toxics such as formaldehyde, acetaldehyde, 1,3-butadiene, and particulate matter from diesel engines. These are all considered possible carcinogens by the EPA. The EPA estimates that over half of all cancers caused by outdoor emissions are caused by motor vehicle emissions [9].

While motor vehicles contribute about half of hazardous air toxics, air toxics are also released by stationary sources, which are those sources that do not move. Stationary sources can fall into one of two categories: *Major sources* are a single (or point) source that emits 10 t per year of any one listed toxic air pollutant or 25 t of a mixture of any listed air toxic pollutants. *Area sources* are those single sources that emit less than 10 t of one, or 25 t of more than one air pollutant. Area sources may not contribute a large portion of pollution on their own, but coupled with other small sources, such as one might find in a city, area sources can significantly impact air quality. As the population becomes denser, the impact of these small sources on overall air quality becomes greater; since there are more sources of toxics per unit area (such as combustion sources from cooking and heating). The urban poor are especially affected since they tend to live in more highly populated areas, as is the case in Hong Kong, where those more financially well off can live farther from the populous city center [10].

It should be noted that though sources that emit toxics into the atmosphere are of primary concern, a HAP may pollute an indoor area as well, such as coal burning for cooking or heating. Indoor sources present a concern as they can be contained in smaller spaces, and therefore expose those occupying that space (such as industry workers) to high concentrations of toxics. Indoor sources pose high levels of risk in developing areas like parts of China, where coal is used for home heating [11]. The full list of HAPs contains a wide array of compounds ranging from industrial chemicals to agricultural pesticides, which can be present in the air in particulate (solid), gaseous, or liquid (aerosol) form.

Where Do They Go?

Once a pollutant becomes airborne, it can have many potential pathways. It can remain in the air as is, become a component of a chemical reaction and transform, and/or it can be transported short or long distances and then follow another pathway. The complexities of each of these mechanisms depend on numerous factors ranging from the scale of long-term climates to the scale of short-term turbulence occurring within seconds of release. As long as the toxic is in the air, it can affect the global climate or an individual human in a single breath. The complexities of atmospheric interactions of chemicals can complicate efforts to reduce toxics; Each chemical that is emitted into the atmosphere can react differently with other chemicals, to the point that the reduction of one type of pollutant (such as NO_x) can actually increase the production of other pollutants (such as Ozone and aldehydes), depending on solar radiation, climate, and season [12].

The fate of pollutants can be affected by a number of complex physical transformations, including nucleation and coagulation (by which particles grow in size) or deposition through settling or precipitation. Toxics that leave the air and are deposited on the ground can continue to do environmental and health harm by contaminating land and water (including drinking water). Humans can then be exposed by drinking contaminated water, eating contaminated food, or by coming in contact with contaminated soils [8]. Toxics that have settled or precipitated out can also find their way into the food chain. As larger animals eat smaller animals that are contaminated, toxins can accumulate in biologic tissues, resulting in greater concentrations as one rises higher in the food chain. Human consumption of animals higher in the food chain can result in significant doses of toxin. The classic example of this is mercury contamination of tuna fish, which accumulate the toxin through feeding on smaller aquatic life forms [13].

The interactions between air toxics and the atmosphere is multilayered and dynamic, factors such as time of day, season, wind directions, and temperature can affect what happens to a toxic after it is released into the air. Concentrations of mercury, for example, increase in Korea during winter and at night because of increased coal burning. In contrast, in some areas of China, gaseous mercury concentrations increase in summer because high solar radiation transforms mercury trapped in soil into a gaseous form [11]. Some studies have shown that air toxics tend to have periods of low ambient concentrations that are followed by sharp spikes in output. Logue, Huff-Hartz et al. found that over 50% of the toxics measured by their high time resolved methods occurred during spikes in emissions of short duration; and that different areas (such high traffic areas, areas next to industrial sites, and general city buildings) can have very different release profiles, even if they are in close proximity (in this case 13 km) from one another [14]. Further examples of the importance of microclimates include Raymer et al. who showed that exposures to aldehydes (which are toxics formed from combustion engines, cigarette smoking, oil frying) have been shown to vary widely in different microenvironments, being higher in restaurants but lower in gas stations in the same city [15]. Similarly, areas of high automobile traffic have been shown to equate with high levels of air toxics [16]. With timing and specific location being an important part of the exposure equation, individual human movement patterns are an important part of one's risk for exposure to air toxics [16]. Two individuals living in the same city, or even the same block, can have different exposures depending on when they are present in that block relative to the time of day that an exposure might be taking place.

Though two individuals living in the same city might be exposed to different levels of toxics, they are both likely to be exposed to worse air quality than their rural counterparts. Cities, where most anthropogenic sources are centered, present unique air quality challenges that go beyond the mere high concentration of toxic pollutants due to population. The physical layout of a city affects the air that moves within and around it. The buildings in large cities create a larger surface area to collect heat in the daytime, which they reradiate at night. Warm pollutant filled air concentrates in locations with high numbers of tall buildings (usually at a city's center). That air rises and spreads out over the city, cooling as it moves. As it reaches the city's edge it is drawn back in to fill the void left by the rising warm air in the center. The result is a convection current that circulates pollutants within the city [8]. Though particular microclimates within a city will have their own levels of air toxics based upon what is occurring locally [15], the overall air quality in a city can be worse than it is in less populated areas because of the properties of the physical landscape.

Regulation and Monitoring

As one might imagine, addressing the potential health implications of almost 200 different compounds, all with different sources, means of transport, fates and health effects presents a complex problem. During attempts to regulate air toxics, the EPA has tried several strategies. From 1970 to 1990, the EPA attempted to set standards and regulate each of the 189 toxic air chemicals based on the individual health risks that were posed by each one. The strategy was to identify all of the pollutants that could cause "serious and irreversible illness and death" and reduce the emissions of each to a point that provided a margin of safety to the public. Issues arose with this approach however, as the EPA attempted to create policy based on incomplete scientific evidence; pinpointing the level of reduction needed to avoid health effects proved to be easier said than done! How risk was to be assessed and the level of acceptable risk that should be incurred by the public for each of the pollutants created an inefficient and slow system that only saw regulation of seven pollutants in 20 years [1].

In 1990, with the revision of the Clean Air Act, congress charged the EPA to implement a new system of regulation using a technology-based approach called "Maximum Achievable Control Technology" or MACT. The MACT standard dictates that the emissions limits of a certain toxin be set by the average emissions of the best performing 12% of similar sources, if there are more than 30 sources nationally that are in the same category. If there are less than 30, the average emissions of the best five are used as a standard [1]. Since air toxics may still be harmful even at the emissions levels of the best emitters, the EPA is able to assess how well current technologies reduce risks and has the power to implement additional standards to deal with any remaining risk posed by generation of toxic pollutants. The EPA must explore the remaining health risks posed by a pollutant 8 years after issuing the MACT standard [1].

The 1990 amendments to the Clean Air Act also eliminated caprolactam as a HAP. This shows that the understanding of pollution and regulation is always changing and that the links between regulations, reductions of pollutants, and the health effects of pollutants are still being actively explored [17–20].

In order to evaluate toxic levels and create appropriate regulations, there must be an understanding of how much toxic is being emitted and how it behaves in the environment. Understanding how air toxics behave, the concentration level at any one time, and how and when an individual might be exposed is an evolving science. Both direct sampling of air quality and modeling of air toxics based upon preexisting data (or a combination of both) are used. The Environmental Protection Agency does not monitor the entire USA in order to gain an understanding of the concentration of air toxics; rather they receive reports from industries who account for their own emissions, which are compiled in the Toxic Release Inventory Report [21]. These emissions data are combined with data such as the rate of toxic release, the location, the height of the release, the nature of the pollutants with respect to decay and longevity, wind speed, and wind direction. This information is then broken down by census track and used in models such as the Assessment System for Population Exposure Nationwide (ASPEN) in order to estimate the level of pollutants in a given area of USA [18, 20, 22]. The success and accuracy of a model depends upon the assumptions made and the inputs used, and different modeling techniques can produce different results for the same area [16].

Direct sampling of toxics can also take different forms. Some techniques, for example, collect an average concentration over a period of time, such as 24 h. Others are able to sample at more regular intervals, allowing a profile of different concentrations during different times of the day [14]. In addition, there may be several different sampling technologies for one pollutant, such as is the case with mercury [11]. *When* sampling occurs is also important: Concentrations can vary both by season, and by time of day. Sampling can help to test the validity of models, and help to determine what factors can make a model more accurate [18, 23].

The difficulties in monitoring and sampling air toxics have led to recent controversy. In 2009, USA Today and scientists from University of Maryland and Johns Hopkins tested the air outside 95 schools nationwide and found that seven schools had high enough levels of toxics such as benzene and chromium to elevate risks of cancer, and 57 schools had levels that were higher than their respective state guidelines. The article created a public outcry, and in response to the article, Louisiana and Pennsylvania conducted their own short-term monitoring and found that levels were not high enough to pose a health threat. This led to questions about how areas are monitored, the duration of monitoring, and whether the health threats existed or not [24, 25].

Monitoring and Regulation of hazardous materials is complex. The ways in which air toxics behave in the atmosphere are not always completely understood, and monitoring and modeling air toxic behavior is subject to several variables that can lead to different results. This can lead to controversy about the level of exposure (and thus risk) of the general public. In order to regulate such a complex issue, the EPA has taken a technological approach, based upon the level of control possible, which allows them to establish regulations despite incomplete knowledge about distribution and health effects.

The Toxic Cycle: Specific Examples

Mobile Sources: A Balancing Act

As mentioned above, mobile sources, most notably automobiles, represent a major contributor to air toxic emissions in the USA. Of high concern is benzene. Benzene is a colorless liquid with a sweet odor. It evaporates rapidly and is used in plastics, resins, and synthetic fibers. It also naturally occurs in crude oil and is present in gasoline when it is refined. The benzene that exists in gasoline can become airborne when gasoline evaporates or vaporizes. Most benzene, however, comes from incomplete combustion of other naturally occurring compounds in gasoline, namely, toluene and xylene [9]. Inhaling very high levels of benzene can cause death. At slightly lower levels, it can cause drowsiness, confusion, and increased heart rate. Most seriously, it has been linked to leukemia of the blood called AML, which is a byproduct of benzene's effect on blood cells and bone marrow [9, 26]. Children are of particular concern with respect to air toxics because their bodies are still growing, and air toxics can affect them developmentally [18, 20]. In a study by Whitworth et al., census tracks with the highest levels of air benzene based on ASPEN also had the highest levels of leukemia in children. Other studies have found that concentrations of benzene and 1,3-butadiene exceed EPA health benchmarks at hundreds of locations across the USA [18], making benzene a serious health threat.

In order to eliminate air toxics, including benzene, from gasoline, the 1990 revision of the Clean Air Act mandated that highly polluted cities use reformulated gasoline; which is required to be less likely to vaporize, and have lower levels of benzene and aromatics. In addition, in many states, gasoline pumps are required to have vapor recovery nozzles, in order to trap gasoline vapor that may evaporate during refueling [9]. Reformulation of gasoline to eliminate benzene has been successful. California saw reductions in benzene emissions of 54% in the mid-1990 s, corresponding with the introduction of reformulated gasoline [17].

Another requirement of reformulated gasoline is that it burns more efficiently. This last requirement is accomplished by adding compounds that oxygenate the gasoline, which allow gasoline to burn more completely and efficiently. Two such compounds are ethanol, and MTBE or methyl tertiary butyl ether. The goal of the increased efficiency is to reduce the production of carbon monoxide, a cause of smog and to conserve oil, which is a nonrenewable resource. Thus it serves several purposes [27].

Studies of the effectiveness and side effects of ethanol and MTBE gasoline have shown that the addition of these compounds does reduce CO emissions, but increases the concentrations of formaldehyde and ethyl-aldehyde [27]. Formaldehyde is one of the 188 EPA air toxics [28]. In addition, MTBE itself has been named as a health concern, causing irritation and nervous system effects [26]. Health concerns caused California to phase out MTBE in favor of ethanol as an oxygen booster [17]. The story of MTBE makes an important point about the efforts to lessen the impact of the industrial way of life on the environment, so that mankind sustains itself into the future. Interactions between chemicals and the atmosphere are complex, and adding something new to the equation can have unforeseen consequences, even if the original aim was to reduce the levels of a harmful substance. MTBE was introduced to help reduce smog, but it also increases levels of some air toxics, and has health concerns of its own.

The phase-in of reformulated gasoline highlights another issue in regulation; the economic, and by extension, political trade-offs inherent in regulating an industry: The phase-in of reformulated gasoline in California has led to higher gasoline prices for consumers, as well as disadvantaged smaller refiners who have had more trouble in meeting the regulations in relation to larger refiners [29]. Thus the regulation of air toxics can, and does, become a political and economic issue.

The most transformative solution to the problems of air toxics from gasoline is to simply greatly reduce or eliminate the use of gasoline altogether. In 2010, cars that run on both electric and gasoline power (i.e., hybrids) are gaining greater market share, and automotive manufacturers, both large and small, are designing and constructing vehicles that run exclusively on electric power. A complete transition from gasoline to electric power creates its own obstacles, however. Battery technology is one of them. Traditional lead acid batteries are inexpensive, but are heavy and cannot hold enough power for electric vehicles to be practical. Nickel-metal hydride batteries have more power but can become permanently damaged if over discharged. Lithium ion batteries, a newer technology, can store a good deal of power and are not affected by discharge, but some use cobalt, which is highly toxic [30]. Thus the ideal battery technology is yet to be developed, and existing technologies have inherent trade-offs between efficiency, cost, and environmental impact.

Technology development is not the only obstacle to changing the automotive landscape: The use of Electric cars could be a benefit to energy companies, allowing them to gain revenue as cars charge at night (when little electricity is being used elsewhere). The integration of electric vehicles, however, would necessitate a fundamental change in power infrastructure, which would take time and serious amounts of coordination between industries, such as the power generation industry and the automobile industry, two industries that have never worked together very closely [30]. This brings up a very important issue when talking about sustainability. The challenges and obstacles to sustainable practices are not just limited to developing technology, but are also problems of coordination, commitment and political will, and balancing the trade-offs inherent in changing from one system to another.

Perchloroethylene: Keeping Things Clean

A common site in cities (and suburbs) in the USA is a local, small neighborhood dry cleaner. In fact, there are about 27,000 free standing dry cleaners within the USA [31]. Many people, when entering a dry cleaners, will notice a particular odor; both in the establishment, and on their newly cleaned clothes. That odor is Perchloroethylene or PERC. It historically has been the most common chemical associated with dry cleaning. PERC has been linked to liver and kidney tumors in rats and is considered by the EPA to be a carcinogen. In high concentrations (such as that associated with occupational exposure) it is associated with dizziness, confusion, nausea, difficulty in speaking, unconsciousness, and death [26]. Exposure to PERC can happen from inhaling the chemical directly or ingesting contaminated water. Once in the body, it can be stored in fat cells, and releases itself slowly into the blood stream [26].

The case of PERC provides a good example of how an air toxic is regulated, the different categories of emitters, and how technology provides the basis for guidelines. The 1990 revision of the Clean Air Act required regulation based upon available technology (MACT). The first rules for PERC dry cleaners were laid out in 1991, revised and finalized in 1993 and updated in 2005–2006 as technology improved and health effects were better understood. In regulating the industry, the EPA divided dry cleaners into three groups. The first were major sources (those that produce more than 10 t of PERC per year), the second were smaller area sources that were free standing or in shopping plazas, the third (which was a category that was not originally differentiated in the 1993 guidelines, but believed to cause a greater health threat) were dry cleaners that exist as part of residential buildings [31].

In 2005, the EPA estimated that nine million people lived within 6 miles of a major source of PERC [32]. The main strategy for the large cleaners (the major sources) is the requirement to use state-of-the-art recovery systems that do not permit PERC to be released into the air, but rather trap and filter it. They are also required to implement advanced leak detection practices to ensure that systems do not leak PERC into the atmosphere accidentally [31].

The guidelines for smaller area sources are based upon the standard of “Generally Available Control Technologies” or GACT. GACT is slightly less stringent than MACT and mandates that firms that emit HAPs use control technologies that are commercially available and the most appropriate considering the economic impact on regulated entities and the ability for entities to comply [33].

As per the GACT standard, new free-standing operations are required to build facilities with closed loop systems (that do not release PERC into the air) and implement advanced leak detection practices. Dry cleaners that already exist have to eliminate what are called transfer machines, those that require PERC soaked clothes to be moved to a second machine for drying, in favor of machines that wash and dry together [32].

Dry cleaning operations that are part of apartment buildings pose a greater risk to the public because people are living in close proximity to PERC emissions; thus more stringent regulations were proposed. According to the rule, all existing dry cleaners have to eliminate transfer machines, and are not able to replace PERC machines when the old ones wear out. PERC machines will have to be phased out completely by 2020 [31].

These regulations are not without costs. For example, implementation of these regulations has been estimated to cost the smaller dry cleaners 7.3 million dollars collectively. Though greater efficiency might save 2.7 million annually, these changes represent an overall net cost to the industry [32].

Dry cleaning of clothes is a service millions of Americans use without giving much thought to the health effects or environmental impacts of the service. Even though a small neighborhood dry cleaner might not cause a large environmental problem on its own; a densely populated area, such as a city, might have tens or hundreds of small establishments. Taken together, they can have a large environmental impact. The regulations are foremost to protect health, and those operations that cause a greater immediate threat (such as residential dry cleaners) are regulated more strictly.

The regulations also attempt to take into account the ability of emitters to follow the regulations in a way that is not detrimental to their business, hence the GACT guidelines for smaller area emitters. Regulations are often a give and take.

Mercury: A Global Toxin

Air toxics are truly a global problem, and a good example of that is the harm posed by human exposure to mercury. Mercury is an element and is naturally occurring in the environment. It can be emitted through geothermal and volcanic activity. The main concern for human health, however, comes from human-made (or anthropogenic) sources of mercury emissions. In adults, mercury exposure can damage the brain, heart, kidneys, lungs, and the immune system. Brain effects can lead to personality changes, shyness, tremors, and hearing and sight problems. A bigger risk comes for children. Fetuses and young children exposed to mercury can develop neurological and developmental disorders that can lead to mental retardation, blindness, seizures, inability to speak, and lack of coordination. It can also cause damage to kidney, liver, and digestive systems [34]. Mercury can be passed from mother to infant in breast milk or from mother to fetus directly during gestation.

Mercury poisoning goes far back into human history: Mercury poisoning can result from exposure during metalworking and gold extraction, and there is evidence of increased mercury concentrations globally during times of high levels of gold mining activity, including the ancient Roman and Incan empires [35]. Small-scale gold working is still a major source of mercury pollution in places such as Africa and Asia [36, 37]. Mining and metal working are not the only industries that historically exposed one to mercury: The term "Mad as a Hatter" comes from mercury poisoning among hatters, who used the element in the creation of hat felt from animal pelts and suffered cognitive effects [38].

Currently, humans introduce mercury into their environment through metal mining, waste incineration, refining, and manufacturing. The largest source of mercury comes from the combustion of coal for electricity generation and heating. In fact 60% of global mercury production in 2000 was due to coal burning [39]. Mercury can exist in several forms: Elemental mercury (Hg^0), divalent mercury (Hg^{2+}), and particulate mercury (Hg(p)). Elemental mercury is the most common form. It can exist in the atmosphere for extended periods of time, a year or more, which means that it can travel large distances, up to 1,000 km from its source. In fact, it has been argued that elemental mercury production in Asia contributes to mercury levels in North America [36]. Mercury occurs naturally in coal. The amount of mercury depends upon the type of coal and its origin. When coal is burned for fuel, elemental mercury, particulate mercury, and divalent mercury can be released. Elemental mercury can oxidize into Hg^{2+} and deposit in waterways and land. Hg^{2+} that is deposited in waterways can become transformed by certain bacteria into methyl mercury (CH_3Mg^+). Though these basics are understood, the details about how mercury cycles through the environment are still under investigation [40].

Methyl mercury is highly toxic to humans and animals, and can accumulate in animal tissue. Through this accumulation (called bioaccumulation) humans can receive large doses of mercury from ingesting several smaller animals that have been contaminated. Consumption of toxic fish is the primary risk of mercury globally. In the USA alone, 48 out of the 50 states had to advise residents to avoid consuming fish from certain bodies of water within their borders [39].

Mercury from coal-fired power plants is a particular problem since rapid development, and the associated need for power generation, has increased coal usage worldwide. Poland, for example, derives 93% of its power from coal and has no legal limitations on mercury emissions, making it the fourth highest emitter in Europe [41]. Asia, because of rapid development, is a source of mercury emissions from all sources, with a large portion coming from manufacturing [36] and coal burning [40].

The primary post-combustion technologies that reduce mercury emissions are not specifically for mercury control, but rather for controls of particulate matter, SO_2 and NO_x [40, 42]. Combinations of control technologies can be successful for mercury reduction. South Korea, for example, has seen a 68% reduction in mercury emissions by using a combination of technologies intended for control of SO_2 and NO_x [43]. Though reductions based on current technologies are possible, the lack of specific controls indicates that the science of mercury control is lacking. Even developed countries, such as the USA, do not have a clear direction in dealing with this hazard.

The path of regulation of mercury in the USA has taken a few interesting turns. In the USA, power plants are the largest emitters of mercury, and the Clean Air Act revisions of 1990 charged EPA to study coal burning in the USA. They found that about a third of the mercury found in coal was being removed by current filters (the ones primarily for SO_2 and NO_x), while the other two thirds were being released into the atmosphere. The EPA was in the process of developing new standards for mercury emissions under MACT until 2004, when they changed course and proposed a cap and trade system instead. In the cap and trade system, the mercury emissions would be limited nationally, and power plants would possess credits for each unit of mercury produced. Plants that produced *less* mercury than permitted could then sell their excess units to another power plant. That plant could then produce more. The cap and trade system has come under fire, however, because though it would reduce emission of mercury nationally, it could create a situation where mercury emissions are high locally, affecting residents of an area disproportionately. It was ultimately struck down by the USA court of appeals, who ruled that the EPA did not follow the proper procedures for delisting mercury as an air toxic; therefore, it was still subject to the MACT standards as laid out in section 112 of the Clean Air Act. Currently the US government is likely to reinstate MACT standards for mercury, but until then, mercury control will be left to the states, many of whom adopted stricter standards than the federal ones [44].

Mercury is a highly toxic substance, and its toxic effects have affected humans for millennia. Mercury produced in one corner of the world can affect another, which can make mercury contamination a political issue. The case of the change in US regulations highlights issues of scale and social justice: The cap and trade system may reduce the levels of mercury nationally, but it may do so at the expense of some local populations. That raises questions of whom regulations benefit (such as more well-off people at the expense of poorer who may live near power generation). It also illustrates the importance of scale when thinking about pollution and regulation: Nationally the levels of mercury might look acceptable, but when the resolution is increased and examined locally some places may have unacceptably high levels. This ties back to the issue mentioned above about how an air toxic is measured, when and where; different levels of measurement can have different results, and the action taken based on those measurements can affect health and outcomes.

Human Health

Many of the health effects of different compounds that are considered air toxics are well established, and can be quite dramatic. In the early 1950s, residents of Minamata Bay, Japan began suffering from neurological illness. Adults began exhibiting symptoms such as blurred vision and difficulty in hearing, reduced ability to smell and taste, clumsiness, difficulty in walking, and mood changes. Children and newborns began suffering from impairments in chewing, swallowing, speech, and movement. All of these individuals were suffering from brain damage due to acute poisoning with methyl mercury. Contamination came from a local acetaldehyde plant (acetaldehyde is used in the making of plastics). The residents became ill from eating fish and shellfish that had stored mercury in their bodies through biomagnification. Estimates put the number affected since the 1950s at 200,000 and these acute cases of illness have been unequivocally linked to mercury [45].

The results of air toxics in lower doses (the type one might encounter living next to a dry cleaner, or living in a heavy traffic prone area) is much more difficult to understand and to illustrate. Knowing that chemicals like benzene and PERC have carcinogenic effects in laboratory animals and during heavy occupational exposures is not the same as claiming that the average residents of a city are at greater risk for cancer because they live in a high traffic area. The relationship between toxics and illness is not always clear-cut. Benzene is one of the best understood of the air toxic carcinogens, and the effects have been well explored in animal research as well as in humans who are exposed to benzene in occupational concentrations. Less is known, however, about the relationship between ambient concentrations and cancer, especially in children. Whitworth et al., for example, used EPA models of benzene levels and census track to show that census tracks that have the highest levels of benzene also have higher incidence of childhood leukemia [20]. On the other hand, Reynolds et al. found that traffic density (which is a predictor of benzene and butadiene levels) did not correlate with childhood leukemia rates [46]. Thus even though the health effects of benzene are well established, the effects of environmental concentrations on populations are more difficult to pinpoint. With respect to mercury, Lewandowski et al. note that correlations have been found between mercury levels and autism in 2002, for school districts in Texas, but that these correlations were not found for 2005 and 2006, calling into question the original correlations [47]. Understanding the health effects is an important issue since policy and regulation decisions are made, at least in part (remember the EPA can create stricter regulations based on health effects) upon the impacts on human health. Understanding how these effects unfold in real-world situations is crucial to assessing local impacts of pollutants, the benefits of regulation, and the need for new cleaner technologies.

The health effects of air toxics cannot be completely decoupled from general problems of air pollution. Often, sources of pollution, such as power plants and automobiles, release more than one harmful substance. In addition, multiple sources will cluster in certain areas, such as cities (many cities have power plants, drycleaners, and cars!). In areas that are developing quickly and do not have strict environmental controls, such as parts of Africa, individuals may be exposed to mercury, lead, pesticides, contaminated water, and various air toxics simultaneously [48]. Air toxics and other forms of pollution are also part of larger issues of health and illness: Factors such as several environmental pollutants, nutrition, levels of stress, and poverty interact and can be considered to affect health synergistically, with each problem causing the others to become more dangerous and vice versa [49, 50]. The impacts of toxics are complex and intertwined with the fates of other pollutants and linked to other aspects of human health and well-being. While it is important to understand how a particular toxin reacts, and how it may affect health, it is important not to lose sight of the larger system and the interactions that play a role in determining who and what is ultimately impacted.

Future Directions

The regulation of air toxic chemicals is an evolving science. Not all aspects of transport and fate are completely understood (mercury is a good example of this). The activities that produce air toxics are part of the activities of daily life, and are difficult to terminate. People all around the world still need to get from place to place, and power must be generated. These needs have to be balanced with the impact from the consequences of these actions. The immediate strategy is to make current technologies (coal burning, gasoline automobiles, dry cleaning establishments) as clean as they can be. This presents challenges since the way in which toxics behave in the environment is not always completely understood (as is the case with mercury), regulations have costs to consumers and producers, and monitoring for toxics is still an underdeveloped science. In some cases, such as the push for cleaner burning fuels, attempting to solve one problem (higher efficiency) leads to another (higher levels of volatile aromatics such as benzene). Some toxic-generating activities may be supplanted with newer technologies in future. This presents challenges as well. Changing from gasoline to electric powered cars will necessitate a change in the infrastructure that supports the automobile, and will create the need for collaboration between very different industries. Alternative sources of power, such as nuclear, have their own drawbacks in risks and wastes generated. Even alternatives such as wind have opponents who are concerned about the space needed to house wind generation and the impact on the aesthetics and enjoyment of land [51]. There are political issues at play as well. Much of the reason for the increase in coal burning is that it is a relatively inexpensive means of power generation for countries that are expanding rapidly. Many in those countries argue that they cannot afford to implement stringent environmental control technologies at the expense of the development that they need. The picture becomes more complex with toxics such as mercury, which can travel half way across the globe, so that the energy choices made by one country may affect another.

The way forward is likely a mixture of better monitoring and regulation of current technologies, as well as implementation of newer technologies that have less environmental impact. Many of these will likely exist in tandem (as is seen today with gasoline cars and gasoline electric "hybrid" cars). In order to create a way forward that is sustainable, solutions must be found that can benefit most people. The concerns of developed countries, developing countries, industry, and citizens must be considered, with the overall health and well-being of humans everywhere being the foremost concern. Cooperation between corporations and governments, as well as long-term thinking will be key to meeting these challenges.

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