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Acids and Particulate Matter and Mercury, Oh My! An Examination of the Major Impacts of Coal on the Environment

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Introduction and Rationale

In December of 1952, a fog unlike any other descended upon the city of London. But this fog wasn't just made up of condensed water droplets. It was full of black particulate matter and sulfur dioxide particles at levels that would be considered astronomical by today's environmental standards. By the time the fog finally lifted, more than 4000 people had died and more than 100,000 were made ill in what was called the Great Smog of London (Figure 1a). Coal being burned in domestic fire places in the city and in coal-fired power plants in the greater London area produced high levels of pollution, which interacted with the surrounding air and water vapor to form the fatal fog.[1] And even though there are much tougher environmental regulations and many developed countries are moving away from coal in favor of cheaper and cleaner natural gas or renewable energies, it still accounts for around 27% of energy production globally. Coal will continue to represent a large portion of the global energy portfolio through 2040 as developing countries turn to it as a cheap and readily available source of energy for their growing economies and populations.[2] For these reasons, coal pollution is still an important environmental issue, as demonstrated by intense smog events occurring in northern China as a result of coal combustion to produce electricity (Figure 1b).

a b

Figure 1: a) Smog conditions in Trafalgar Square, London, 1952.[3] b) Beijing's central business district, 2013.[4]

Because of coal's staying power it is important for students to be familiar with its severe environmental implications, including the impact of mountaintop removal mining, acid-mine drainage, acid deposition, particulate matter pollution, and mercury pollution. It is also important for students to understand the interconnectedness of the environmental problems associated with coal, and this unit aims to bridge the gap between existing curriculum units on energy use, coal mining, and air pollution through hands-on activities and demonstrations.

School Profile and Course Specifics

William Penn High School is a public high school in the Colonial School District in New Castle County, DE. It is the only high school in the district and is the largest high school in the entire state, serving over 2,000 each year across grades 9-12. The district is considered suburban/urban fringe and serves a diverse population in terms of both race and family income levels. There has been a resurgence in jobs in the district, mostly in the industrial sector. This has created a demand for employees with job-specific skill sets, experience, and certifications. As such, William Penn has focused on the growth of Career and Technical Education programs that provide opportunities for students to experience a vocational-type education while still being provided with the traditional college preparatory education typical of public schools.

Such a shift has allowed the school to retain students who may otherwise attend one of the several area Vo-Tech schools. William Penn also offers 25 Advanced Placement courses, the greatest number of any school in the state. This dual focus on college and career readiness has greatly improved the school culture and the school's image in the community, which has translated to the growth in the student population. Students entering William Penn chose a degree program to specialize within one of three college academies: Business, Humanities, or STEM. Degree programs within the Business College Academy include Air Force JRTOC, Business Administration, Culinary Arts, Financial Services, and Accounting. Degree programs with the

Humanities College Academy include Behavioral Sciences, Communications, Teacher Academy, Legal Studies, International Studies, and Visual and Performing Arts. The STEM College Academy offers degree programs in Agriculture, Allied Health, Computer Science, Construction, Engineering, Manufacturing, Mathematics, and Science. In order to graduate, students must complete three consecutive years of coursework in their chosen degree program.

This growth in student population and interest in the sciences helped me justify the need for adding AP Environmental Science (APES) to the course catalog in the 2016/17 school year. Students enrolled in the Agriculture degree program can now specialize in the Environmental Science pathway, which requires them to take two years of on-level environmental science before enrolling in APES as their capstone course. I am now teaching the course for the fourth year, and this is first year I have a group of students who are in their final year of the Environmental Science pathway. At this point I feel comfortable enough with the course curriculum to identify areas for improvements. One such area of need is in making connections between units. The way the course is written, each topic exists in a vacuum, independent of others. However, the way that students are tested by the College Board requires them to have a more holistic understanding of the inter-related nature of environmental science.

Learning Objectives

One of the biggest disconnects in the course is between the chemical nature of pollution and the actions that produce that pollution. For instance, students learn about natural resource extraction in one unit, fossil fuel formation and use in another, and fossil fuel-linked pollution in still another. Yet on the AP exam they may be asked a Free Response Question that requires an integrated understanding of all of that material. In this unit, a bridge between these topics is explored by examining coal mining, coal combustion, and the various types of pollution produced by both processes. Students pay special attention to mountaintop removal mining and its environmental impacts, particulate matter pollution and its impacts, acid rain, formation and its impacts, acid mine drainage, and mercury pollution. Students complete several hands-on activities to advance their knowledge, including demonstrating the impacts of coal mining on a model ecosystem, examining the effects of acid-mine drainage and acid-deposition on plant life, and measuring and categorizing particulate matter pollution. Finally, as part of their AP exam preparation, students are charged with writing, answering, and scoring an inter-related Free Response Question (FRQ) as their summative assessment for the unit. Although the emission of carbon dioxide from coal-fired power plants is a significant source of climate change and a major environmental impact, students do not explore this topic this unit since the College Board considers that an entirely separate topic of the APES course.

In order to satisfy these learning objectives, I use two dimensions of the three-dimensional Next Generation Science Standards (NGSS) framework. I employ several Science and Engineering Practices (SEPs): students obtain and evaluate information about the mining and combustion processes; they plan and conduct investigations to learn about the various pollutants associated with coal mining and combustion, and construct explanations and analyze and interpret data along the way. Finally, students argue from evidence and use mathematical thinking to write and score their own FRQ on the topic. In order to provide the proper context for their learning, students use the following Crosscutting Concepts in this unit: energy and matter, cause and effect, and scale, proportion, and quantity. I do not cover specific Disciplinary Core Ideas since those represent specific content – instead I cover the learning objectives set by the College Board.

Content Objectives

This unit is broken into three key sections. The first section is on the basics of coal, including how it forms, its distribution in the United States and worldwide, an overview of how it is mined, and how coal is used to generate electricity. The next section covers the specifics of mountaintop removal mining, and last section covers air pollutants and water pollution associated with coal mining and combustion. The latter two sections represent the majority of the content presented in this unit, as I cover natural resource extraction more generally in a separate unit.

Coal Basics

Coal Formation

Coal has its origins some 300 million years ago in the Carboniferous Period.[5] During this time, the placement of the continental land masses, comparatively high atmospheric carbon dioxide (CO_2) concentrations, and a warm and wet climate promoted an explosion in the diversity and size of plant life. These conditions can be likened to the tropical and subtropical humid climates found in the tropics today.[6] Large sections of the earth were covered in swamp forests, where large plants captured sunlight and CO_2 and converted it into biomass as they grew. Because this process begins with photosynthesis, coal (and indeed most fossil fuels) has been called ancient sunlight. When those plants died, the organic material in the plants underwent partial decay but still held a great deal of organic content. Over time, rivers and streams deposited sediment rich in this partially decayed organic material.[7] As the climate continued to change, these organic rich layers were buried with inorganic sediments. This material underwent a series of transformations to become peat, an accumulation of partially decayed organic matter.[8] The lignin and cellulose contained in the organic sediment are of specific importance to the formation of peat because they are the toughest parts of plant material and resist decay under normal conditions.[9] However, the anoxic conditions of the shallow basin promoted the decay of these compounds in such a fashion that the nitrogen and oxygen were lost but the carbon preserved.[10] Under specific temperature and pressure conditions, peat can undergo coalification. These conditions were present due to the burial by additional sediment, the overlying water in the basin, and the subsidence of the underlying crust. The first type of coal that emerges from these conditions is called lignite, a low grade, high-sulfur content coal. Additional heat and pressure continue to alter the chemical structure and eventually produce the next two type of coal, bituminous and anthracite. As the coalification process continues the energy content of the resultant coal increases, while impurities such as sulfur decrease. For this reason, anthracite coal is the most prized type of coal.[11] One of the many reasons the Great London Smog had such a negative impact on human health was the burning of low-grade lignite coal with significant sulfur impurities.

Coal deposits in the lower 48 states are shown in Figure 2. Of specific interest to this unit are the bituminous deposits in West Virginia due to the environmental implications of the mining methods used to extract it. As the figure demonstrates, most of the coal in this region is medium volatile bituminous coal, which has more energy content and produces less sulfur when combusted than the lignite, subbituminous, and low volatile bituminous that dominates much of the available coal in the U.S.

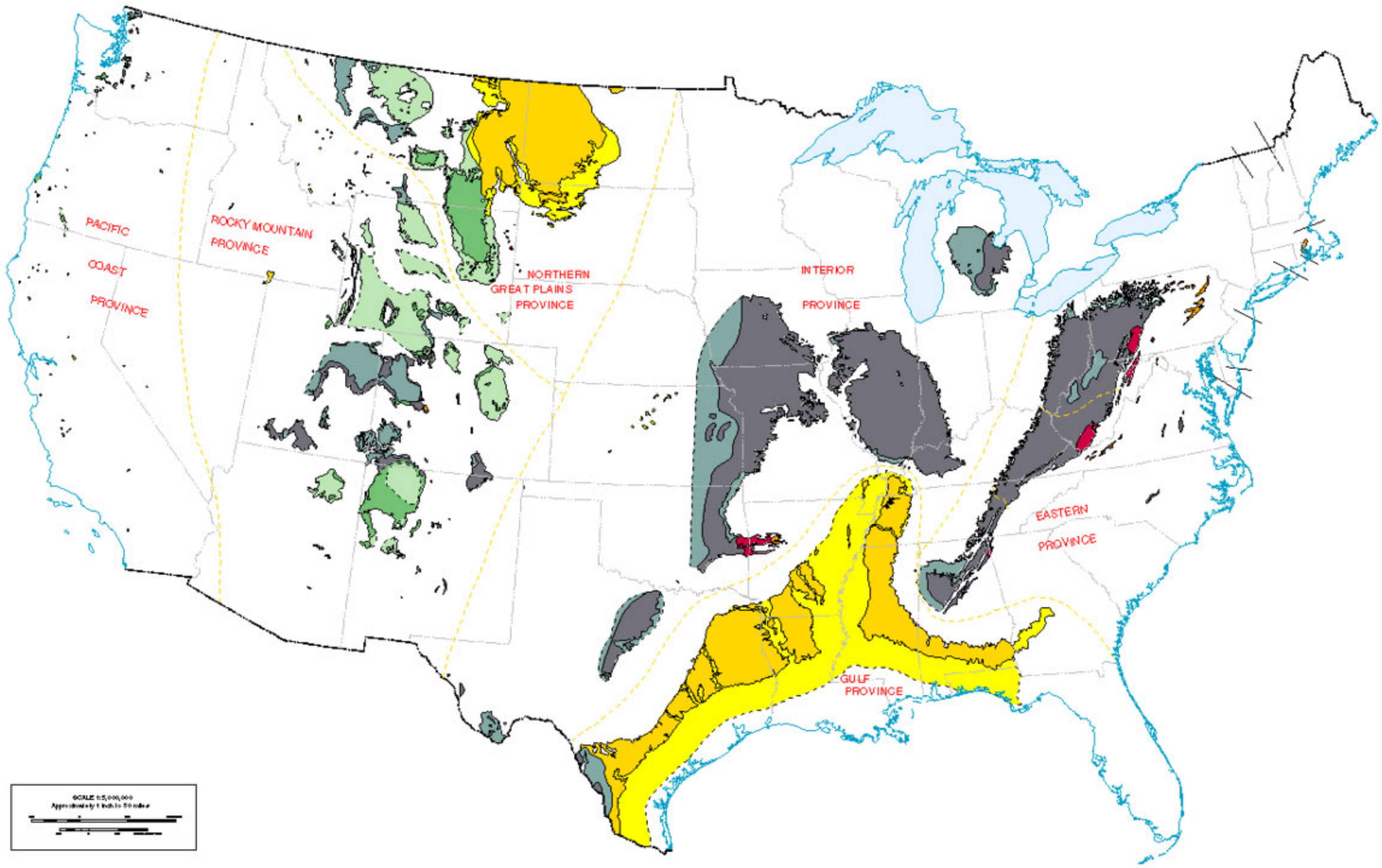

Figure 2: Coal deposits in the lower 48 states.[12] The dark grey and grey-blue deposits are medium and high volatile bituminous coal. The red deposits are low volatile bituminous coal. The two shades of yellow are lignite coal. The two shades of green are subbituminous coal. Most of the active coal mining operations in the U.S. are in medium volatile bituminous deposits (Appalachia) and in subbituminous deposits (Wyoming).

Extracting Coal

There are several different methods of mining coal, categorized as either surface or subsurface methods. Surface methods include contour mining, strip mining, and MTR. Subsurface methods include room-and-pillar mining and longwall mining.[13,14] Students learn about various mining methods in a separate unit of study on natural resource extraction, but present a general review of coal-specific mining techniques. In the various surface mining techniques, the procedure is essentially the same: removal of topsoil, drilling and blasting overlying strata, moving this material (called spoils), drilling and blasting the coal seam with explosives, removing the coal and transporting it away, backfilling with spoils, and reclaiming the area with soil and vegetation.[15] The specific technique is chosen based on the geography and geology of the region. In particularly hilly terrain such as the Appalachian region of the U.S., contour mining or MTR is used since there is limited space to transport and store overburden. In the Midwestern region of the U.S. traditional strip-mining techniques are used. Subsurface mining is also dictated by the geology of the coal seam and surrounding area. Ultimately the thickness depth and angle of the seam, combined with the amount of gas in the subsurface dictate whether the coal is extracted using room-and-pillar or longwall techniques. In room-and-pillar mining, large "rooms" are created as coal is extracted. "Pillars" of coal may be left in place to hold open the space and engineered supports are added to prevent collapse of the overlying strata. Longwall mining involves the cutting of long stretches of rockface and extracting the coal, leaving no support pillars in the area. As mining advances the roof of the previously mined section is allowed to fall.[16]

Surface techniques are most economical and effective for relatively shallow deposits, while subsurface mines are often the better choice for deeper deposits. In some cases, a combination of the methods is used. In general, surface mining has advantages over subsurface mining, including higher recovery rates, health and safety statistics, and lower amounts of pre-combustion processing. Because of these factors, surface mining tends to be significantly cheaper than subsurface mining.[17] Mountaintop removal mining is discussed in more detail below as it is a central focus of this unit.

Producing Electricity from Coal

It is critical to understand that the coal that comes out of the ground isn't a direct source of electricity. I can't power my laptop by plugging it into a chunk of coal. The production of electricity from coal involves the combustion of pulverized coal in order to produce steam from water. This steam then turns a turbine which turns a generator. As the name implies, this device generates electricity. The electricity is then transported along the electrical grid. This is demonstrated in Figure 3. The grid is a network of interconnected transmission lines that distributes electricity from power plants or other electricity-generating sources to users of electricity such as homes or businesses.[18]

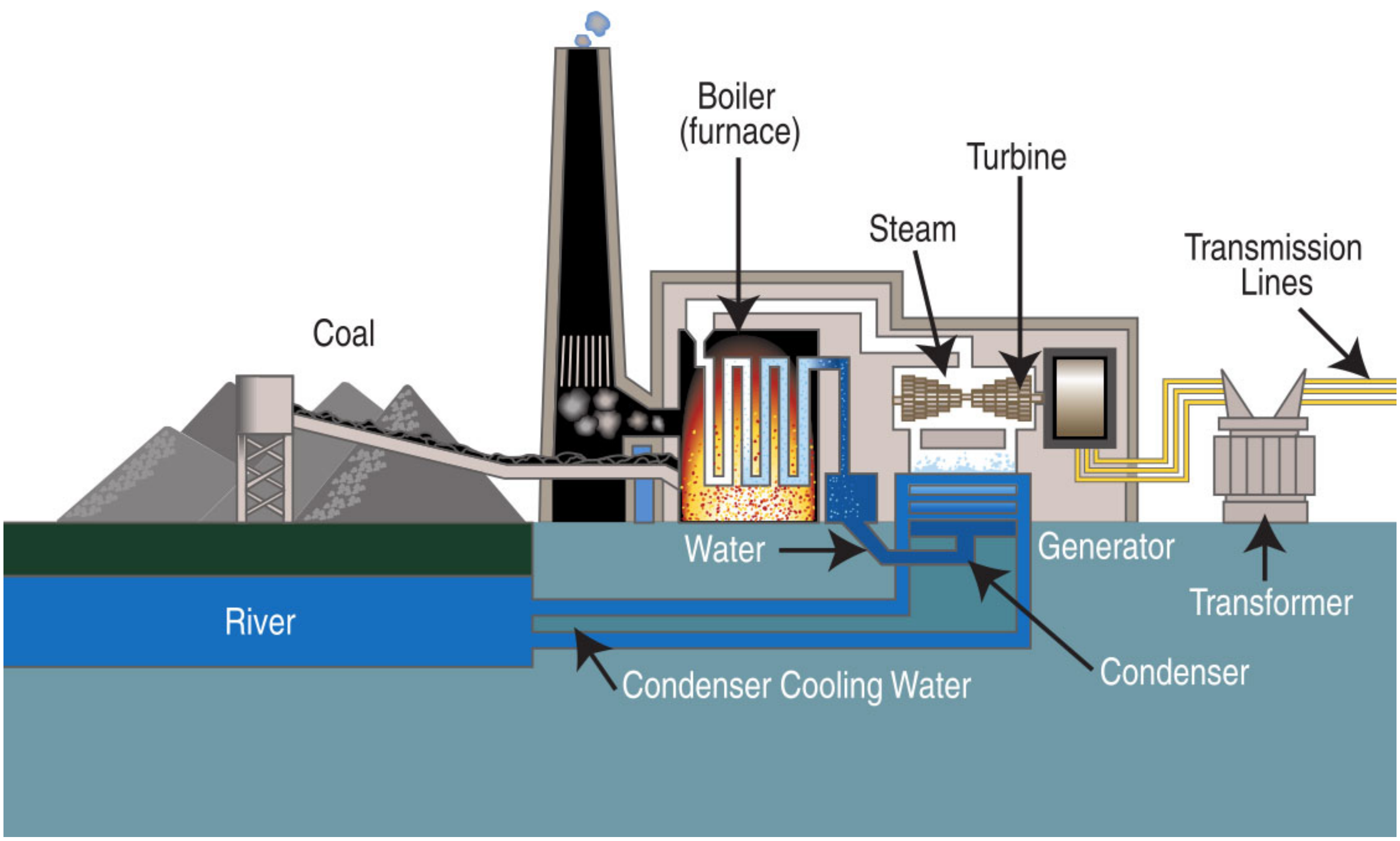

Figure 3: Diagram of how a coal-fired power plant generates electricity.[19]

As simple as it sounds there are several issues with using coal as a source of electricity. First, the coal must be mined, refined, and transported to the power plant. Second, the global average efficiency rate of coal-fired power plants is between 30 and 40 percent. This means that if 100 units of coal are burned in a power plant, only 30-40 of those units get converted into electricity. The remaining units are converted to waste heat.[20] Finally, there are several pollutants that originate from coal combustion, including mercury, sulfur, and CO_2.[21] Mercury and sulfur emissions are addressed below, while CO_2 is covered in a separate part of my course that specifically focuses on the causes, mechanisms, and impacts of anthropogenic climate change.

Mountaintop Removal Mining

Mountaintop removal mining (MTR) is of particular interest given the proximity of such mining operations in Appalachia. I use the analogy of a layer cake when discussing MTR with students: just as in a layer cake there are alternating layers of frosting and cake, there are mountains with a layer of rock, layer of coal, layer of rock, layer of coal, etc. To get at the layer of coal, MTR removes the overlying rock using explosives. The layer of coal is then extracted and the process is repeated until the coal layers are exhausted. The rock removed during the process, called the overburden, is typically dumped into valleys between mountains. When the mining operation is complete, this material is sometimes replaced on what is left of the mountain. In other situations where valley fill is not possible, the overburden is hauled away. I present the environmental hazards associated with MTR later in this unit. MTR is favored by the mining industry because it involves less manpower and financial risk compared to traditional strip and subsurface mining techniques.[22] MTR became the primary method of coal mining in Appalachia in the 1990s as the industry needed a way to cheaply extract the low-sulfur coal located in the region. This shift was brought about by stricter EPA regulations on sulfur emissions aimed at reducing sulfur dioxide emissions and associated acid deposition after decades of environmental degradation associated with the burning of low-grade coal.[23]

Environmental Impacts

The environmental impacts of MTR are quite dramatic. In fact, these mining operations can be seen on satellite images due to their scale and dramatic impacts on land cover (Figure 4). What was once covered by dense forest ends up being bare rock.

Figure 4. a) Satellite view of Central West Virginia. b) Zoomed in view of MTR sites (upper left and right corners and center bottom). c) View of a single MTR operation. Individual images courtesy of Google Maps.

The major environmental impacts of MTR include deforestation and habitat loss (as seen in Figure 4), burial of stream headwaters by overburden, leaching of hazardous material into ground and surface water, and release of particulate matter and sulfur species into the atmosphere.[24] The burial of stream headwaters presents several environmental challenges, including alterations to surface and subsurface flow, habitat loss, changes to downstream channel morphology, and reductions in stream biodiversity.[25] It has been reported that 90% of streams below valley fill MTR operations were “impaired” by Clean Water Act standards. Specific impacts include a reduction in macroinvertebrate species and number of individuals, disappearance of fish species, and reductions in salamander species. The use of explosives to remove the overburden and mine the coal seams releases a great deal of particulate matter into the atmosphere, which can cause upper respiratory illness and, in some cases, can lead to cancer.[26] Sulfur species can enter the atmosphere when sulfate from mining runoff is reduced by bacterial species into hydrogen sulfide gas. Sulfate aerosols from the mining operation are also released into the atmosphere.[27] Particulate matter and sulfur pollution are discussed in more detail below since they are not exclusively associated with MTR, but with coal mining and combustion more generally.

Particulate Matter

The combustion of coal is a leading source of toxic air pollution globally.[28] Particulate matter (PM) is a major component of coal pollution, and is a complex mix of fine particles and liquid droplets and may include acids, organic chemicals, metals, and soil or dust particles.[29] PM originates in two ways: the first is direct emission of particles from combustion reactions, construction sites, unpaved roads, etc. The second is through atmospheric reactions of primary pollutants such as SO_2, and nitrogen oxides (NO_x) that are emitted from power plants, industrial operations, or from automobiles.[30] In terms of PM related to coal, both types of PM are emitted. A great deal of primary PM is emitted in the mining process through blasting of rock and transportation of materials to and from mines on unpaved roads. The composition of this PM is distinct from secondary PM, and is mostly dust, silica, and elemental carbon. Secondary PM is also produced as coal-fired power plants emit SO_2 that reacts with atmospheric constituents. As discussed above, some of this material settles out of the atmosphere through dry deposition and some goes on to become acid rain.[31]

Health Impacts

There are several categories of PM based on its aerodynamic equivalent diameter (AED). Typical size categories are less than 10 µm, 2.5 µm, and 0.1 µm (PM_{10}, $PM_{2.5}$, and $PM_{0.1}$). PM with an AED greater than 10 µm has the shortest suspension half-life and will typically be filtered out by the nose and upper respiratory system. The smaller particles have longer suspension half-lives are not as easily filtered by the human respiratory system. The ultrafine particles pose a more significant health threat even though they represent a much smaller fraction of the total mass of PM pollution.[32]

Several studies have shown that the specific impacts of PM pollution vary by AED, but in general such impacts include cardiovascular, cerebrovascular, and respiratory diseases.[33] There is also strong emerging evidence for PM-related lung cancer, as evidenced by the declaration of PM as a Group 1 carcinogen by the International Agency for Research on Cancer.[34] Impacts on the cardiovascular system are thought to be related to inflammation brought about by PM exposure. There are also links to problems with changes to coagulation of blood and platelet activation. In general, there are strong links between PM exposure and ischemic heart disease, congestive heart failure, and acute myocardial infarction.[35] Exposure to PM has also been linked with cerebrovascular health effects. The mechanisms, risk factors, and features for PM-related ischemic cerebrovascular disease are similar to those for cardiovascular disease. However, the specific links to PM-related strokes and other cerebrovascular diseases are less well understood than with PM and cardiovascular disease.[36]

It should come as no surprise that exposure to PM can lead to respiratory illness, especially for the $PM_{2.5}$ and $PM_{0.1}$. However even PM_{10} can lead to or exacerbate existing respiratory illness. Like with cardiovascular issues, there seems to be a strong link between PM_{10} exposure, inflammation, and respiratory illnesses. Several studies have linked exposure to PM with an increase in inflammation as an immune response. In some cases, excessive inflammation leads to an increase in reactive oxygen species, nitrogen species, and release of cytokines. Taken as a whole, chronic inflammation due to PM exposure has been shown to lead to morphological changes in respiratory pathways, asthma, and chronic obstructive pulmonary disorder.[37]

Because $PM_{2.5}$ can penetrate more deeply into the respiratory system, it has been linked with the development of lung cancer. $PM_{2.5}$ also tends to have greater proportions of mutagenic species, making cancer a more likely outcome of exposure than the mostly biological and mineral composition of PM_{10}. In fact, cancers of the respiratory system (including the trachea, bronchus, and lungs) accounted for seven percent of total mortality due to $PM_{2.5}$ exposure in 2010. More research is needed on the explicit links between PM and various types of cancer.[38]

Coal workers' pneumoconiosis, more commonly known as black lung disease, is a unique impact of PM. As the name suggests, it is common in coal miners and others who work in the coal industry. It occurs as coal dust builds up in the lungs, leading to inflammation, formation of scar tissue, and death of lung cells. Black lung disease is a progression and often goes unnoticed or undiagnosed since symptoms mimic more common respiratory illnesses. Unfortunately, it is uncurable and in its most advanced stage is often fatal. And though the number of deaths attributed to black lung disease has fallen since 1990, recent studies have shown a resurgence in cases.[39]

Acid Mine Drainage

Acid mine drainage (AMD) forms when sulfide minerals are exposed during mining or other large-scale excavations. These minerals oxidize when exposed to air and water and are converted into sulfuric acid, metal ions, and sulfate. These new chemical species can then enter surface water or groundwater where they can have serious ecological impacts.[40] The chemical makeup of AMD varies, but it generally has a pH ranging from 2 to 8, and consists of group II metals, transition metals (especially iron and aluminum), and either bicarbonates or sulfates.

AMD forms in four steps: 1) oxidation of pyrite by atmospheric oxygen, making sulfate and ferrous iron, 2) conversion of ferrous iron to ferric iron, 3) hydrolysis of iron leading to the formation of iron hydroxide, and 4) additional oxidation of pyrite by ferric iron. Because oxygen is not the oxidizer in the fourth step, this process can be self-perpetuating so long as sufficient pyrite is available. The second step in the process is considered rate-limiting and controlled by the presence of specific bacteria.[41] Other sulfur-bearing minerals can undergo similar oxidative reactions leading to the formation of AMD, including pyrrhotite, chalcopyrite, arsenopyrite, sphalerite, and galena.[42] AMD is a worldwide concern because of the sheer number and distribution of coal mines. Studies have shown AMD-related damage in Asia, New Zealand, Europe, South America, Canada, and the United States. In the eastern U.S. alone, 10,000 km of streams/rivers and 77 hectares of lakes/reservoirs have been damaged by AMD.[43] Specifically, AMD is problematic where abandoned mines are left without reclamation and are exposed to air and water or where mine waste breaches containment. This is more common in countries with weak environmental regulations or enforcement of those regulations. Recently AMD has devastated water bodies in South Africa where coal accounts for over 90% of the country’s electricity generation.[44,45]

Environmental Impacts

AMD has several different environmental impacts. Constituents of AMD can be directly toxic to aquatic and terrestrial organisms. AMD can alter the biogeochemical nature of habitats, stain stream sediments, disrupt nutrient cycles, and render water unfit for domestic, agricultural, or industrial use.[46] The low pH of most AMD has several ecological consequences. Terrestrial plant species are impacted as nutrient availability changes in response to the presence of acids. Aquatic organisms typically experience sub-lethal toxicity as the pH decreases, but below a certain threshold pH (around 5 for many sensitive organisms), organisms begin to die off or migrate elsewhere if possible. Perhaps more importantly, acids tend to mobilize heavy metals. In plant life, exposure to or uptake of heavy metals causes oxidative stress that can lead to cell damage and morphological changes. At high enough levels, metals can cause plant death. In aquatic organisms, many metal species can cause immediate toxicity. Such metals include cadmium, copper, lead, and zinc. Other metals species stunt growth, reduce reproductive success, and lead to deformities in offspring. In humans, heavy metals are known to disrupt metabolic functions, accumulate in vital organs, and block absorption of other minerals.[47]

Acid Deposition

There are four main processes in acid deposition (Figure 5). First, SO_2 and NO_x are released into the air from combustion of fossil fuels. The combustion of coal in coal-fired power plants is a significant source of SO_2. Once in the atmosphere, this material reacts to form acid particles that can travel long distance via atmospheric circulation patterns. Eventually they fall to the earth through wet and dry deposition. Wet deposition occurs when the particles fall during rain and/or snow events, while dry deposition occurs as dust particles settled out of the atmosphere. Once into terrestrial or aquatic ecosystems, the acid can have harmful effects.

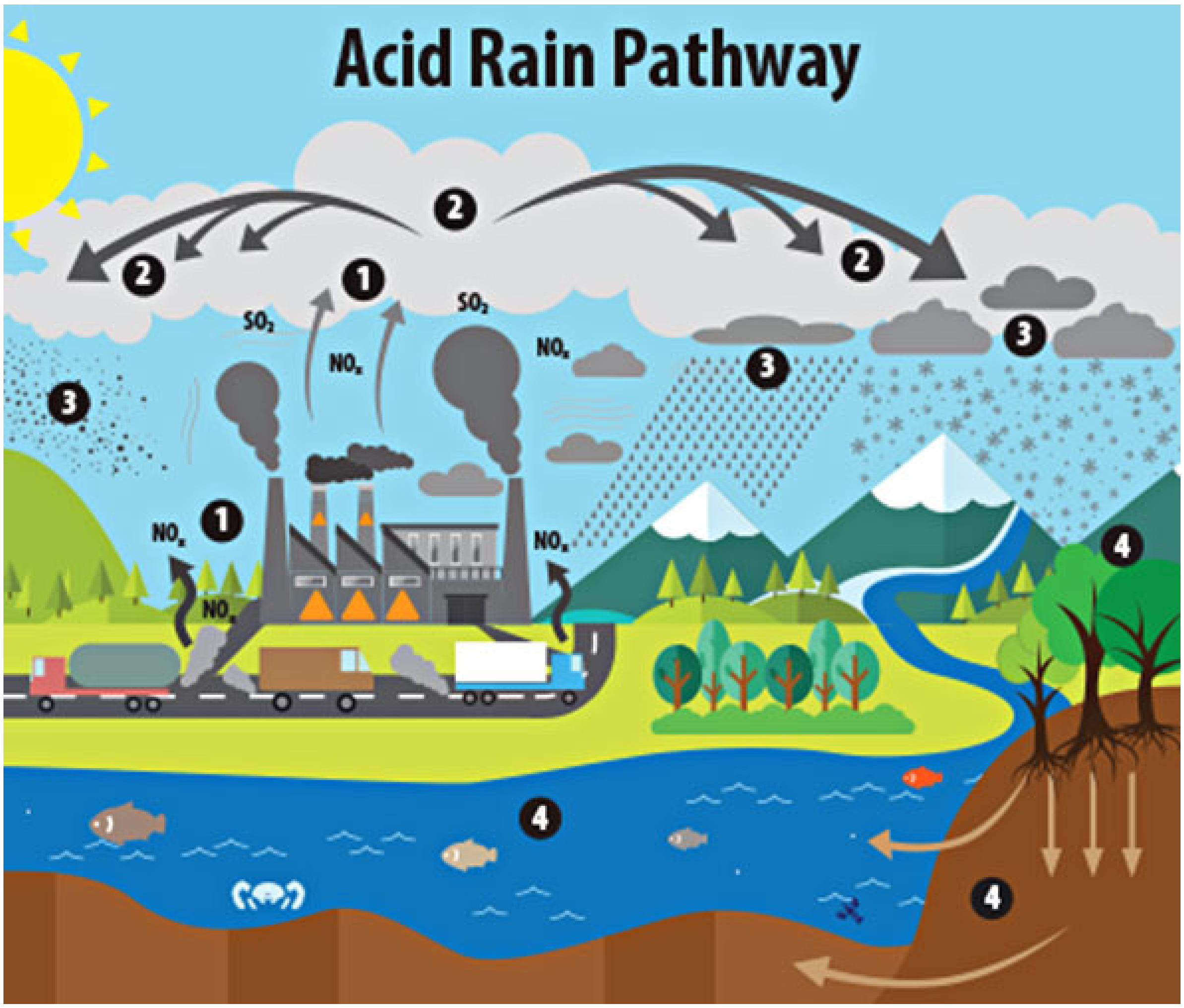

Figure 5: Processes of acid deposition: 1) emissions of SO_2 and NO_x are released into the air, where 2) they are transformed into acid particles that may be transported long distances. 3) These acid particles then fall to the earth as wet and dry deposition (dust, rain, snow, etc.) and 4) may cause harmful effects on soil, forests, streams, and lakes.[48]

Coal combustion is not the only source of the raw materials that lead to acid deposition. Other anthropogenic activities include the combustion of gasoline in automobiles and combustion of other fossil fuels such as oil or natural gas to generate electricity.[49] There are also natural sources that emit these compounds, most notably volcanic activity.

Environmental Impacts

Acid deposition is problematic for some of the same reasons as AMD. The introduction of acids can lower the pH of aquatic and terrestrial environments. For example, as acid rain flows through soil it can leach out aluminum from soil particles and transport it to streams and lakes where it is toxic to aquatic organisms. As discussed earlier, the threshold pH for most aquatic organisms is around 5. Below this, many organisms suffer increasing toxic effects. Acid rain also leaches out nutrients critical for terrestrial plants. In the absence of these nutrients, plant life is greatly diminished, which negatively impacts food chains and can lead to enhanced soil degradation. Less-vegetated soil dries out faster, is less stable, and is more likely to erode since there is less of a root network to hold soils in place during rain or wind events.[50] Many of the most pH-sensitive organisms are critical to ecosystem function and their absence leads to significant ecological decline. Acid rain is especially problematic for environments lacking in buffering capacity – the ability to resist changes in pH. This was evidenced by the decline in sensitive macroinvertebrate, fish and aquatic plant species in Quebec, Canada in the 1980s and 1990s partly as a result of coal combustion in the Midwest of the U.S.[51] This region was particularly vulnerable to the impacts of acid deposition because its lakes and streams are naturally low in dissolved minerals that serve as buffers. Emission standards set by the U.S. and Canada have decreased sulfate concentrations and led to a rebound in aquatic ecosystems.[52]

Mercury Emissions

Small amounts of mercury are contained in the coal burnt in electricity-generating power plants. This mercury settled out of the atmosphere into the sediment or was accumulated into the original plant tissue hundreds of millions of years ago during the Carboniferous. When the resultant coal is burned in coal-fired power plants to generate electricity that mercury is returned to the atmosphere. This is not problematic on its own. But when the mercury settles into water or onto land, several classes of microorganisms change it into methylmercury, a highly toxic and persistent form of the element. Mercury from coal-fired power plants accounts for 44% of all mercury emissions in the U.S. (EPA), the most of any source. Non-coal sources of mercury include but are not limited to gold mining, waste incineration, and chlorine production. Collectively their emissions levels are much smaller and less significant than those from burning coal.[53]

Environmental Impacts

Because methylmercury is highly bioavailable and persistent in the environment, it can be bioaccumulated and biomagnified. Bioaccumulation occurs when an organism takes up a toxin that accumulates in its tissue because it cannot be digested or processed by the body. Bioaccumulated material is typically stored in the fatty tissues of organisms. Biomagnification occurs when the concentration of a bioaccumulated toxin increases up the food chain. This occurs because higher trophic level organisms eat many of the lower trophic organisms. This has the effect of concentrating the toxin at the higher trophic levels and leading to greater toxicity.[54] Because much of the mercury emitted into the atmosphere settles into the ocean, aquatic species tend to accumulate greater concentrations of mercury. This is especially true of shellfish and cold-water fish due to their fatty nature. Anything that eats these organisms is at risk for mercury toxicity, including humans.[55]

In the body, mercury acts as a neurotoxin and can lead to a loss of peripheral vision, pins and needles feelings in extremities, loss of motor function, and muscle weakness. Because it is a neurotoxin it has particular adverse effects on infants and children. Exposure to mercury at developmental stages can lead to long term effects on cognitive thinking, memory, attention, language, fine motor skills, and visual spatial skills.[56]

Strategies

In order to instill in students that science is not merely a body of isolated facts but a systematic process for acquiring new knowledge, I always try to incorporate real aspects of the scientific process into the classroom. The National Research Council (NRC) lays out a framework for how to ensure that under NGSS students have authentic scientific experiences in their classrooms even as they learn the bodies of knowledge of the specific sciences. When implemented properly, this framework of "supports a better understanding of how scientific knowledge is produced and how engineering solutions are produced…help[ing] students become more critical consumers of scientific information."[57] This focus on process, according to the NRC, improves upon previous practices that reduced scientific procedures to isolated aims of instruction, rather than a vehicle for developing a meaningful understanding of the true scientific concept. Additionally, the process of discovering scientific truths allows students to engage in the types of critical thinking necessary to understand why the right is answer is right, and perhaps more importantly, why the wrong answer is wrong.

This emphasis on developing a strong evidence foundation supports student understanding of fundamentals of scientific truths instead of the traditional model of asking for rote memorization of facts that didn't serve students well in their post-secondary education or in the workforce. In fact, the NRC designed the NGSS model with this specifically in mind, citing that in the past "rather than learning how to think scientifically, students [were] generally being told about science and asked to remember facts," whereas the new standards focus on student understanding by "linking concepts and practices that build coherently over time throughout K–12, thereby helping to ensure that students who meet the NGSS will be prepared to succeed in science courses in both 2- and 4-year institutions."[58] The presentation of content in this unit is phenomena-based, another hallmark of NGSS that helps students deepen their content understanding. In this unit, I make use of a flipped classroom, hands-on learning, and the Learning Focused strategy of Higher Order Thinking in order to engage students in the content presented above.

Using a Flipped Classroom

Because I have so much material to cover in advance of the AP exam and I don't dedicate class time to lecture or direct instruction, students must come to class with the background information already under their belt. This model, known as the flipped classroom, frees up time in class to be spent on authentic science experiences through lab experiments, collaborative learning, and peer review. Effectively using the flipped classroom model requires a great deal of advanced planning by me and buy-in from my students. It involves more than just assigning readings and expecting students to complete them. Students need to find value in the at-home assignments and then be held accountable for completing them. In order to promote engagement with the flipped materials, I have brief daily quizzes based on the previous night's material. I allow students to use their notes and annotations to my outlines on these quizzes. For highly motivated students, this strategy works well. Less intrinsically-motived students often struggle early on with this model until they begin to see the value in coming to class prepared.

Hands-on Learning and NGSS Practices

In my classroom, I am more a facilitator of learning than I am a source of information and correct answers. To that end, my teaching toolkit is full of strategies that get students *doing* science rather than *learning* science. I employ a wide range of the NGSS SEPs in my classroom. In this specific unit, I will ask students to obtain and evaluate information, plan and conduct investigations, analyze and interpret data, construct explanations, engage in argument from evidence, and use mathematical thinking. The biggest challenge I find when employing the SEPs is wanting to interject. But it is important for me to limit my interruptions and let students struggle and find solutions. Like with the flipped classroom, this has to be managed and not every student is going to be successful right away. But by not giving in to student demands and providing answers right away, I hope to train them to think creatively, work together, and develop their scientific "muscles" for use on the AP exam in May.

Higher Order Thinking

Like the flipped classroom and NGSS SEPs, Higher Order Thinking is a strategy that challenges students to go above and beyond. As this is an AP course, I do not shy away from challenging my students to analyze, reason, and apply information to different scenarios. Higher Order Thinking is a hallmark of my classroom and often bleeds into everything I ask my students to do, including as they design and conduct experiments, analyze and interpret data, communicate information, and engage in evidence-based argument. By forcing students to go beyond rote memorization or simple representation, students become better critical thinkers. By using this strategy, I train my students to compare and contrast, determine patterns, analyze relationships, evaluate information, and propose solutions. These are all skills espoused by the NRC framework and the College Board. Not using this strategy to challenge my students would do them a complete disservice.

Classroom Activities

Hands-on Activities

The majority of this unit involves students completing hands-on activities, including three separate labs. Because there is little time dedicated to content delivery, students are expected to have completed all assigned readings, notes, and checks for understanding prior to coming to class. By doing this, students satisfy the SEP of obtaining, evaluating, and communicating information. Specific instructions and deliverables for each of the following activities are freely available by emailing michael.doody@colonial.k12.de.us.

Cookie Mining Lab

In this lab, students simulate the impacts of MTR by attempting to mine chocolate chip ore from a cookie. However, there are several principles to consider as students mine their cookies. First, not all land is equal – some has more ore, some is harder to mine, etc. To mimic this, I give students the option of buying different types of cookies (one standard chocolate chip cookie, one soft chocolate chip cookie, and one chunky cookie). Students also purchase mining tools (paperclips, toothpicks, and popsicle sticks) and cannot use their land. Before mining students must record their cookie's topography as well as their initial environmental impact. I give students seven minutes to mine their cookie. When time is up, students have an additional two minutes to reclaim their land and return the cookie to its original topography. When the reclamation period is up, students trade places with a partner and complete two assessments. The first is of the additional environmental impact of the mining operation. Failure to clean up the site results in environmental penalties in addition to damaging the surrounding ecosystem. Violations are recorded in a data table. Students also complete a secondary assessment of the indirect impacts of their mining operation. Their mining grid contains streams, forested land, deer habitat, fertile topsoil, and scenic vistas. Students fellow a specific set of rules to determine if the mining operation degraded any of these attributes. For instance, if students pollute the headwaters of a stream, all of the connected water downstream is degraded. Likewise, if students degrade too much forested land, the deer habitat is degraded. The degradation of natural attributes does not count against the students financially, but opens their eyes to the far-reaching impacts mining can have on ecosystems. The second assessment is of the amount/quality of the ore mined from the cookie. The money earned from mining is recorded in the same data table from above. Students determine whether they earned a profit from their mining operation. Finally, students are asked a series of analysis questions that force them to apply their knowledge of mining and its environmental impacts and consider competing environmental and economic principles. In this way, students analyze and interpret data, and construct explanations. This lab can be completed in one ninety-minute class period.

Tube Sock Pollution Lab

To model PM pollution, students will secure tube socks to various vehicles in the school parking lot and then analyze the socks under microscopes for evidence of various PM types. To complete this lab, students will secure new white tube socks to the exhaust pipe of a car and let the car run in idle for five minutes. Once the sock is removed it can be cut into sections and placed under a dissecting microscope to identify regions with significant pollution. These smaller sections can be further examined under higher magnifications using a traditional microscope. Students then quantify the amount of pollution on their section and compare data with their peers. This activity challenges student to analyze and interpret data and use mathematical reasoning to construct explanations about the nature of PM pollution.

Ideally, students test cars of different ages and engine types in order to show how PM pollution varies. An ideal sample set includes a diesel engine, an older car, a newer car, and a hybrid or electric car. To satisfy this, I complete portions of the activity ahead of time and have students simply test older and newer cars in our school lot. Though this is not directly related to the PM pollution from burning coal, it is close enough and a powerful demonstration for students. This lab takes two ninety-minute periods.

Effects of Acids Lab

To demonstrate the effects of acids (from acid deposition or AMD), students construct model ecosystems with an unconfined aquifer, a lake, farmland, and unique topographical features using plastic containers, clay, soil, fast-growing plants, tap water, and dilute acids. In order to satisfy the plan part of the plan and conduct investigations SEP, students are given their materials and tasked with setting up the ecosystem without much guidance from me. Students are split into several groups of three students, and each group receives slightly different instructions and materials from me. For instance, one group acts as the control. Another group receives soil with a greater buffer capacity. Other groups may receive different acid types or concentrations. Each group is charged with getting their plants to grow and must collect the following data during the experiment: plant growth (height in cm), soil pH, and water pH. After collecting data for five class periods, students compare their data and discuss the impacts of acid on their ecosystems, drawing from their lab experience and their content knowledge from reading in the textbook. In addition to planning and carrying out the experiment, students analyze and interpret data and construct explanations in this lab.

The initial set up of this experiment takes about forty-five minutes, and students need about ten minutes in class after that to collect their data. On the final day of the experiment, students need about thirty minutes to discuss their results and breakdown their specific experiment. They answer a series of analysis questions as homework.

Write Your Own FRQ

In order to prepare students for the AP exam, I typically assign an FRQ at the end of each major topic. However, since the College Board redesigned their exam format and a great deal of previously released questions are no longer applicable, I am challenging my students to write their own questions. Students are given this assignment over parts of three class periods. On the first day, students collaborate with one another to discuss the elements of an FRQ, the different aspects of coal mining and environmental impacts, and write a first draft of their question. I provide students with reference questions and rubrics for similar topics to get them started on this process. On the second day, each student revises their first draft and then creates a rubric for their question. At this point, I give students approval or guidance on how to modify their question. There are three requirements that students must meet in order to have their question approved: 1) the question must have multiple parts, 2) there must be some quantitative analysis involved in answering the question, and 3) the question must integrate content from previous units in some way. On the last day of the unit, students trade with a partner so that they answer a peer's question. The author of the question then evaluates their peer using the rubric they wrote and assign them a grade, which I validate and correct if necessary. The use of Higher Order Thinking on this assignment is wrapped up in students constructing explanations, thinking mathematically, and engaging in argument from evidence.

Appendix: Implementing District Standards

This unit covers all or significant portions of the following Learning Objectives as outlined in the 2019 APES Course and Exam Description:

ENG-3.D: Identify where natural energy resources occur.

EIN-2.K: Describe natural extraction through mining.

EIN-2.L: Describe ecological and economic impacts of natural resource extraction through mining.

ENG-3.E: Describe the use and methods of fossil fuels in power generation.

ENG-3.F: Describe the effects of fossil fuels on the environment.

STB-2.A: Identify the sources and effects of air pollutants

STB-2.H: Describe acid deposition.

STB-2.I: Describe the effects of acid deposition on the environment

The aim of this unit is to have students cover this diverse array of learning objectives through hands-on activities and investigations. Through their independent reading students will be able to satisfy some aspects of each of the above objectives. Select standards are investigated in depth through classroom activities. The Cookie Mining lab helps students satisfy learning objectives EIN.2-K and EIN.2-L. Learning objectives ENG-3.E and STB-2.A are met when students complete the Tube Sock lab. The Effects of Acid lab helps students satisfy learning objectives STB-2.H and STB2.I. The remaining objectives are met through readings and online lectures.

Endnotes

1. (Excell 2015)
2. (Berners-Lee 2019)
3. (Stobbs 2008)
4. (钉钉 2013)
5. (Beerling and Woodward 1998)
6. (Kidston 1901)
7. (Bird 1997)
8. Ibid
9. Ibid
10. (Orem 2014)
11. Ibid
12. (Tully 1996)
13. (Friedland and Relyea 2019)
14. (National Research Council 2007)
15. Ibid
16. Ibid
17. Ibid
18. (Friedland and Relyea 2019)
19. (Tennesee Valley Authority 2016)
20. (World Coal Association 2019)
21. (Friedland and Relyea 2019)
22. (Copeland 2004)
23. (Holzman 2011)
24. Ibid
25. (Giam, Olden and Simberloff 2018)
26. (Holzman 2011)
27. Ibid
28. (Xie, et al. 2006)
29. (Anderson, Thundiyil and Stolbach 2012)
30. (United States Environmental Protection Agency 2018)
31. (Aneja, Isherwood and Morgan 2014)
32. (Anderson, Thundiyil and Stolbach 2012)
33. Ibid
34. (Hamra, et al. 2014)
35. (Anderson, Thundiyil and Stolbach 2012)
36. Ibid
37. Ibid
38. (Hamra, et al. 2014)
39. (Valdamis 2018)

40. (Skousen, Ziemkiewicz and McDonald 2018)
41. (Lehigh University 2011)
42. (Simate and Ndlovu 2014)
43. (Skousen, Ziemkiewicz and McDonald 2018)
44. (Burkhardt 2019)
45. (McCarthy 2011)
46. (Skousen, Ziemkiewicz and McDonald 2018)
47. (Simate and Ndlovu 2014)
48. (United States Environmental Protection Agency, Acid Rain Pathway 2019)
49. (Friedland and Relyea 2019)
50. Ibid
51. (Hopkin 2005)
52. (Government of Quebec 1999)
53. (United States Environmental Protection Agency, Basic Information about Mercury 2019)
54. (Friedland and Relyea 2019)
55. (United States Environmental Protection Agency, Health Effects of Exposures to Mercury 2019)
56. Ibid
57. (National Research Council 2012)
58. Ibid

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