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Thesis Committee:

Coal Fires: An Environmental Disaster

An Undergraduate Honors College Thesis

in the

Department of Chemical Engineering
College of Engineering
University of Arkansas
Fayetteville, AR

by

Edward Jenner

For the WERC project the majority of my contribution ended up being manual labor. Though it was not the only work I did, nor the work I intended on doing when I signed up for the competition, it was the work I could accomplish better than any of my other teammates.

My first task for our WERC project was a trivial one, but at the time that was not known. The professor coordinating our research deemed it absolutely necessary that we read a summary of a research summit on coal fires conducted in 2004. One of the sections, 150 pages in length was over remote data sensing of coal fires. In hindsight, the information was completely irrelevant, but our project leader made sure we did it. Each of us read a section about 100 to 150 pages in length.

In the first stages of our experimental research I worked with Dan Miskin to design and build our initial apparatus. Specifically, I drilled holes in the side of our experimental apparatus to allow temperature probes to measure the temperature of the fire. After building the experimental apparatus, I conducted our first few experiments with Dan; I recorded temperature readings from the fire inside the apparatus.

Concurrently to designing and running experiments, I also worked on our WERC paper, writing the economic analysis. My research determined that coal fires could be economically feasible if either government funded, or paid for by carbon credits.

After writing my portion of the WERC paper and designing the initial apparatus, Dan and I worked closely on building, and testing the apparatus that would be used in the WERC competition. One of the most important jobs I had for the WERC project was procuring coal, which I accomplished by taking my brother's pick-up truck to Sebastian Mining LLC and picking up 1200 lbs of coal/rock mixture. After picking up the coal, I shoveled all 1200 lbs into containers while Dan held the containers open for me. Though most of the members of the WERC team could have done this job, I have had fourteen years of manual labor working experience, and thus was able to complete such a task orders of magnitude easier. After I had procured coal, I ran every experiment we conducted with the apparatus. I performed

such tasks as splitting the firewood necessary to start the fire, sifting the coal from the rock for burning, smothering the fire with sand to measure air flow through the sand, and removing the hot embers after the fire was extinguished.

Once we had conducted all of our research at the university, we had to pack up our apparatus to take to New Mexico for the WERC competition. At the competition I set up our apparatus, ran the experiment, and deconstructed our apparatus nearly solo.

University of Arkansas
Open Task - Coal Fires

WERC 2013 Open Task

**COAL FIRES
AN ENVIRONMENTAL DISASTOR
WHAT SHOULD THE WORLD DO?**

University of Arkansas

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Executive Summary

The mission of the Coal Fire Gang (CFG) is to spread awareness about the global issue of uncontrolled coal fires, and to highlight them as a low-hanging fruit of immediate emissions reduction. This report summarizes CFG's research for the WERC competition, for which this topic was chosen as an open task. Beyond raising awareness, CFG modeled, developed and built an experimentation apparatus meant to prove the validity of a relatively cheap extinguishing method which was also novel to the regions in which it could be employed. The apparatus, which simulated an underground coal fire, was used to test a sand and water extinguishing method.

CFG's results on the experimental research side suggest that the sand and water approach to extinguishing coal fires, though requiring attention and labor for long periods of time (up to a few years depending on how long the coal fire has been burning prior to extinguishing activities), is very cost effective. Exact economics of a particular coal fire would have to be determined on a case-by-case basis, depending on the size and age of the fire, but those costs include only sand, water, labor, and heavy equipment to transport the sand around. The proposed extinguishing technique involves capping all exhaust vents of a fire with sand, and then saturating the sand with water. The steam created by the water on contact with the heated ground and coal then expands and flows through the cavity, flowing out of what were originally combustion air influent vents. This flow reversal could significantly reduce the oxygen intake while also removing heat. Over time, as more vents are discovered or created, they can be capped in the same manner.

On the economics side, CFG proved that even at conservative estimates of the cost to extinguish fires and the cost of alternative CO₂ sequestering methods, extinguishing coal fires is the for immediate global emission reduction. CFG proposes that coal fires around the world are prioritized ahead of new and expensive technology for emission reduction, and that at the very least the emissions from coal fires are drawn into some regulating system so that they can be tracked and better managed.

Introduction

For generations, mankind has utilized coal as a source of heat and energy. It accounts for approximately 30% of total global energy use, generating 41% of the world's electricity. While the percentage of global energy provided by coal decreased in recent years, the total production of coal continues to increase to meet the rising energy demands of the developing world.¹ It is safe to assume then, that coal will remain an important energy resource for many years to come.

Unfortunately, the same properties that make coal such an important fuel source also make possible the environmental catastrophe known of uncontrolled coal fires. These coal fires can occur in underground mines or at the Earth's surface. Anywhere coal is exposed to sufficient oxygen and an ignition source, a coal fire can occur. The source of ignition can be anthropogenic, due to unsafe or illegal mining operations, or due to natural phenomena such as lightning strikes. Exothermic reactions that occur in coal when exposed to air or water can also lead to self-ignition.² The fires are extremely difficult to extinguish, and represent a hazard to humans, a loss of resources, and a fruitless contribution to greenhouse gas emissions.

The top coal-producing countries in the world are China, the United States, and Australia.³ With such extensive mining operations, these countries are well-known for their coal fires. In China, uncontrolled coal fires rage in more than eleven provinces² with approximately \$125 to \$250 million economic loss in the form of lost coal resources.⁴ In the US, coal mine fires are tracked by the Abandoned Mine Land Inventory System (AMLIS).²³ AMLIS reports that nearly \$180 million has been spent reclaiming land affected by coal fires with nearly \$900 million more allocated for future projects.

In terms of coal fires, Australia is best-known for Burning Mountain, a coal fire first recorded in 1828 and suggested to have been burning for thousands of years.⁵ More recently in February 2014, in the town of Morwell, Australia, a coal seam was ignited in what is suspected to have been a deliberate act. The fire is predicted to burn for several months due to the size of the coal seam. A member of the local council told Newsweek "The town has been choked with smoke. For the first two weeks it was appalling and a constant rain of ash." The town has been evacuated as a result of this fire.⁶

These are some of the larger fires studied for this project, but coal fires are experienced all around the world, on every continent except Antarctica.⁷ Coal fires are truly a global problem.

The Varied Impacts of Coal Fires

Despite the significant negative impacts of uncontrolled coal fires, they receive relatively little media attention compared to other environmental hazards.⁸ At the most basic level, coal fires represent the unproductive loss of valuable non-renewable resource. In China alone it is estimated that up to ten million tons of coal are lost to coal fires each year.⁹ Coal fires have far more wide-ranging effects, however, and cause damage not only to our environment, but also to the communities standing in the path of coal fires.

The gases produced by coal fires often contain from 40 to 50 different components, many of which have negative health consequences.¹⁰ The production of gases such as hydrogen sulfide, nitrogen oxides, and sulfur oxides exacerbate many respiratory and heart illnesses including asthma, chronic bronchitis, strokes, and pulmonary heart disease. Volatile elements like arsenic, fluorine and mercury are commonly released through burning coal and will pollute local water sources and crops. Mercury has toxic effects on the nervous, digestive and immune systems, and on the lungs, kidneys, skin and eyes.¹¹ Pollutants such as carbon dioxide, carbon monoxide and methane are also produced by coal fires and contribute to the yearly growth of carbon dioxide in the atmosphere.

The geomorphological impacts of coal fires on the earth also pose a risk to human health and safety. With coal fires burning at about 600°C,¹¹ the surrounding areas quickly become desolate. The high temperatures destroy vegetation and prevent future regrowth. Land is destroyed by the creation of clinker, sinkholes and cracks. When a coal seam of 10 meters burns, it leaves behind an ash layer of less than one meter thick, causing the overlaying rock to subside into the burned-out cavity. The resulting fractures in the strata allow for air, which supports combustion, to enter the seam and for toxic exhaust gases to escape, perpetuating the fire and poisoning the surrounding air.¹²

In China, the Wuda region, in coal-fire proximity, has experienced a 95% reduction of local vegetation. Cracks in the Rukigou Coalfield, China are several kilometers in length, tens of meters wide, and hundreds of meters deep.¹³

In order to understand the social implications of coal fires, the coal fire in Centralia, PA can be examined. The coal fire was initiated on the outskirts of the town during a 1962 trash burning in an unregulated dump. The fire propagated throughout the complex system of abandoned mining tunnels under and around the town.⁴ In the first two decades of the Centralia fire, several

projects totaling over \$3.3 million were implemented in attempts to control and extinguish the fire, but all were unsuccessful. By 1970 the Federal Government began relocating endangered residents. Lethal carbon monoxide concentrations were measured emanating from boreholes, and the local gas station was ordered to close due to underground fuel tanks overheating.

In 1981 “Concerned Citizens Against the Centralia Mine Fire” was formed to obtain federal aid after a 25-year-old man almost fell into a sinkhole and an elderly man died of carbon monoxide poisoning. The group sought out media attention, and in 1983, the U.S. Office of Surface Mining took action, estimating that extinguishing the fire would cost \$663 million. Instead of moving forward with extinguishing the fire, the US Congress offered \$42 million for voluntary acquisition and relocation of businesses and residences. This created a division amongst the town because many residents wanted to remain in Centralia; it was their home. The federal government’s solution was implemented and between 1985 and 1991, nearly half of the population was relocated. Businesses were closed and Centralia became known as a “ghost town”. Currently less than 5 residents live within the former city limits of Centralia.¹⁴

Coal Fires and Carbon Dioxide Emissions

Carbon dioxide emissions are a topic of concern due to the climate impact of greenhouse gases (GHGs). The breakdown of the sources which emit carbon dioxide and the natural sinks which absorb them are presented in Figure 1. The atmospheric growth of 18.7 Gt/year of carbon dioxide is increasing at a rate from 1-2% every year. In order to reduce these emissions, actions must be taken to eliminate unnecessary sources of carbon dioxide.¹⁵ It is most important to identify the CO₂ sources which can most easily be reduced.

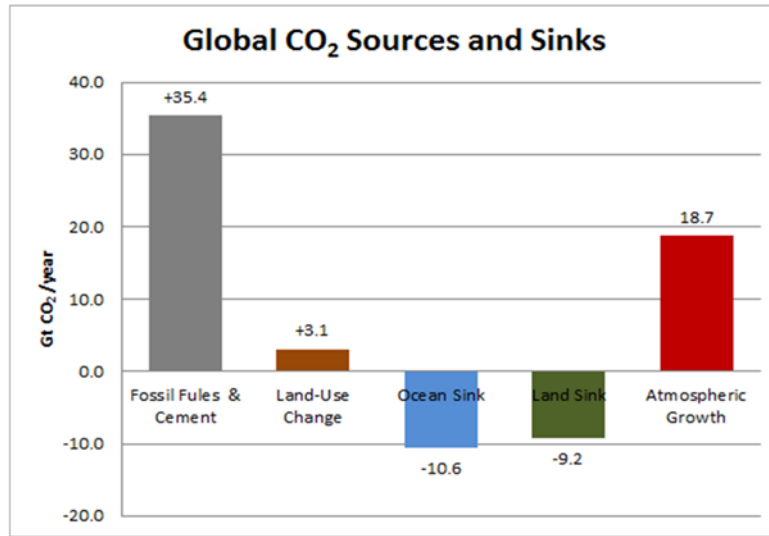


Figure 1. Global Carbon Projects report on carbon dioxide sources and sinks.¹⁵

While measuring the exact emissions from the fires is difficult, it has been roughly estimated that 1% of anthropogenic CO₂ emissions are due to coal fires. Based on this estimate carbon dioxide released from coal fires is 0.35 Gt/year;^{15,16} thus, if coal fires were extinguished up to 2% of the atmospheric growth of CO₂ could be eliminated.

One of the efforts to reduce carbon dioxide emissions has been the sequestering of carbon dioxide, often from coal-fired power plants. Since 2005, the US Congress has authorized \$6.9 billion to develop carbon-capturing technology. The process of carbon capture and storage, however, is still too expensive to be an economical method for GHG reduction.¹⁷ Technologies being investigated as funded federal research are estimated to sequester CO₂ at a cost of \$38 to \$107 per tonne of captured CO₂. Many of these projects since their inception have been cancelled or delayed as a result of limited project funding. Many CO₂ sequestering projects will only become viable if carbon taxation occurs or subsidies from governments.¹⁸

With realistic carbon capture and storage programs failing to be economically viable, other means to reduce carbon dioxide emissions must be evaluated. Projects to extinguish coal fires such as the one in Centralia, Pennsylvania, have estimated costs that exceed \$600 million, making it unreasonable to extinguish the Centralia fire. However, a large number of existing coal fires are not unreasonable to extinguish. In 2003, in North Dakota 8 coal fire sites ranging in size from 1/10 of an acre to an acre in size were extinguished by a \$37,000 grant from the Office of Surface Mining, Casper, Wyoming.¹⁹

Determining the cost to extinguish coal fires is difficult because each fire has a unique location, geometry, size, and set of available local resources. The total cost of unresolved projects in the United States to extinguish coal fires is estimated to be \$900 million.¹⁵ Evaluating coal fires in countries such as China and India on an individual basis may reveal that extinguishing coal fires would be a cost effective way to meaningfully reduce global carbon dioxide emissions.

Global Response to Coal Fires

Coal fires are also a common problem in India, most notably throughout the Jharia coalfield. Around “\$12 billion in high-grade coking coal, used in steel production, sits below Jharia,” and the coal fires that burn in the region jeopardize the population of the region.²⁰ The Indian government’s response was a relocation plan worth \$1.4 billion, approved in 1996. However, as of 2012, of the 90,000 residents of the Jharia region only 1,150 families had been relocated. The cause for this slow relocation process is likely due in part to misallocation of funds combined with diminutive relocation packages.²⁰

In China, the Sino-German Coal Fire Research Initiative was begun in 2003 to address the lack of knowledge about coal fires in China and to develop an appropriate response. The Initiative—championing “Innovative Technologies for Exploration, Extinction, and Monitoring of Coal Fires in North China” –was divided into two phases. The first phase focused on investigation and study of the fires, while the second had a stated goal of “bridging the science, economics, and politics of coal fires.”²¹

One of the most interesting economic incentives which the Sino-German study has highlighted is the Clean Development Mechanism (CDM) of the Kyoto Protocol. Defined in Article 12 of the Protocol, the CDM allows “a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol (Annex B Party) to implement an emission-reduction project in developing countries.”²²

In the US, the governmental response to coal fires is regulated by the Surface Mining Control and Reclamation Act (SMCRA) of 1977, which established a “program for the regulation of surface mining activities and the reclamation of coal-mined lands.”²³ This act also created the Office of Surface Mining (OSM). Under this legislation, “Mine operators are required to minimize disturbances and adverse impacts on fish, wildlife and related environmental values and achieve enhancement of such resources where practicable.”²³

The SMCRA introduced a permitting process for coal mines built after 1977. One of the requirements of this permitting process is that the company requesting a permit must develop a plan for reclamation after mining operations have ceased and provide a deposit of the amount required for reclamation.²³

Based on SMCRA, extinguishing a coal fire is the legal obligation of the mine owner, subject to enforcement (permit withdrawal, fines, etc.) by the OSM. SMCRA was not retroactive, so mines already functioning were not required to go follow the new permit process. In 1977, there were an estimated 1.1 million acres of abandoned coal mine sites in the United States.²⁴ To deal with these abandoned mine lands, the SMCRA set up the Abandoned Mine Reclamation Fund (AMRF), and implemented a tax on coal producers in the US. This money goes into the AMRF ‘to be used to finance the reclamation of abandoned coal mine sites.’²⁴

Money from that fund is distributed by the OSM to state-level regulating systems expressly for the use of reclamation and reduction of abandoned mine hazards. In 2012, for instance, OSM announced the fund received more than \$485 million, and that money was distributed to states like Kentucky, which received \$47 million for reclamation activities.²⁵ OSM has a list of problem areas which are publicly available in the form of the AMLIS. Each abandoned mine land area is documented here, along with its size, description of environmental problems, projected cost of reclamation, expenditure to date, as well as several other useful parameters. The OSM distributes money to states to deal with these projects, and they are prioritized by hazard threat. Though coal fires burn in the US today, this system ensures they will eventually be addressed, and provides money to do so through taxation.²⁴

Economic Analysis of Coal Fires

Understanding the economics of coal fires requires an understanding of their associated costs: the cost of extinguishing the fire, the value of coal lost, and the cost to the environment, now directly measurable in carbon credits. Before reviewing the potential costs of coal fires, it is beneficial to cover the costs of extinguishing fires.

While the Centralia fire was estimated to cost over \$600 million to extinguish and the fires in North Dakota cost as little as \$37,000¹⁹ to extinguish, the twelve coal fires in the Wuda mining area were extinguished for \$54 million total. Since 2004, a Chinese government-funded firefighting organization has extinguished twelve of the eighteen major fires in the Wuda area.²⁶

These fires were extinguished by injections of water, ash, and colloids while covering the burning area with loess and gravel to prevent further fire propagation. When these large-scale extinguishing efforts started in 2004, there were 159 hectares burning. In 2005 this area was reduced to 113 hectares, but a surge in illegal mining activity resulted in several new fires and the affected area grew to 227 hectares in 2010.²⁶

The most straightforward cost is the value of the lost coal. Coal costs have fluctuated greatly over the past decade, but as a whole has risen approximately \$1.74 per year per tonne. The current cost of coal is approximately \$65 per tonne.²⁷ It is estimated that in China, 10 million tons of coal are burned in uncontrolled coal fires each year, resulting in a yearly loss of \$650 million worth of coal.⁹ With the GDP of China at \$8 trillion, this loss is a small percentage of the total GDP. Thus, larger efforts are not being made to extinguish all fires because they are a proportionally small economic problem.

The cost of coal fires to the environment is more difficult to quantify with certainty. Though private companies and individuals started making strides to be carbon neutral as early as 1997,³¹ carbon credits were first used internally in Britain.³¹ The market developed in the UK served as a template for other markets. Soon after the ratification of the Kyoto Protocol in 2002,³¹ the carbon market swelled to \$64 billion by 2007. In 2008, the Chicago Climate Exchange (CCX) collapsed due to a large number of governmental free allowances³² driving down the demand for credits, while many startup companies made credits widely available, driving up supply.³³ Carbon trading systems have been more successful in markets outside the US.

Currently, carbon credits are largely generated through offset retail providers who then sell the credits to companies to reduce their carbon footprint, meet quotas, or industry regulations. Terrapass, Carbon Fund, and Native Energy are such companies that engage in reforestation projects, implementation of solar or wind energy, hybridization of large trucks to electric/gas, or others and currently sell credits at approximately \$12 per tonne of CO₂.^{34,35,36} With the quantity of CO₂ released from uncontrolled coal fires estimated to be 0.35 Gt/year, coal fires would be worth \$4.2 trillion in carbon credits.

In the US, companies operating in a carbon market are doing so voluntarily. Volunteer markets are begun by private investors or eco-investing firms such as Eco-securities. Most members of volunteer markets participate partly due to an anticipation of future government legislation regulating emissions. Some companies tax themselves internally for their own CO₂

emissions.³⁷ Companies such as ExxonMobil, Microsoft, and BP have already priced their own emissions and spend money on emission-reduction projects to offset them.³⁷

The last and most variable cost is that of extinguishing the fires. Unfortunately the extinguishing cost of each fire varies with the location, size, age, and coal quality. The fires require case-by-case analyses to determine exact extinguishing cost. A study of uncontrolled coal fires by the University of Maryland estimates coal fire-extinguishing could cost from \$0.55-\$5.5 per tonne of CO₂ emission reduced.³¹ In China, many coal fires are surface fires or close to the surface,³¹ which means excavation is a valid extinguishing method. Despite being a relatively cost-effective method, many coal fires are in rough terrain where excavation equipment function poorly. Excavation of the most difficult sites would have to be performed by laborers with hand tools, and would be much more dangerous and costly. Though this method may seem unreasonable, sixty-eight coal fires have reportedly been excavated and extinguished by hand with shovels and water buckets.³¹

Coal burnt in power plants also produces emissions, and so it is not solely from an emissions standpoint that the fires should be extinguished. Coal fires cause many problems other than accelerating global warming, and though coal burnt in a coal-fired power plant also emits emissions, those emissions are a trade-off for energy production. This is opposed to coal fire emissions, which eliminate the future possibility for energy production. Emissions from power-plants, further, are more easily regulated as well, and so those emissions can be tracked, responded to, and their production mitigated. Coal fires fall outside this system, and so contribute to the global warming problem without being tracked or responded to at all.

Field Research and Case Studies

There have been field-work and extinguishing campaigns in the US which have generated useful information on responding to coal fires. In the US, North Dakota used OSM funds to extinguish several fires as mentioned earlier. Grass fires in 1999 ignited 30 separate coal seam fires ranging in size from 1/10 to 1 acre or more in North Dakota, and the method of extinguishing used was complete excavation.¹⁹ For the coal seams to be extinguished, contractors used excavators and bulldozers to first dig a 4-foot wide “intercept trench” which extended to at least 1ft deeper than the coal seam into the earth. This established a perimeter that the fire would not cross since the fuel had been removed. With the fire quarantined, excavators were then used to

remove burning coal and place it in a “burial trench,” where it was quenched with water until cool to the touch before being buried. After the work of extinguishing was complete, all of the trenches were filled in with topsoil and the surroundings were re-graded. Eight project sites (separate coal seams) were addressed during this study, and all of them remain extinguished.¹⁹ This is a prime example of a response to a surface or near-surface coal fire.

For deeper fires, many other methods have been tried such as compressed-air foam systems (CAFS), which work by injecting “a biodegradable compressed foam containing oxygen-consuming microbes” into the underground seams.³⁸ This method is simpler to employ (it is both faster-acting and lighter than water), and also absorbs toxic gases, making the operation safer, but is much more expensive. Companies such as CAFSCO and Chemguard have attempted to bring to market CAFS technology, but its high price compared to less innovative methods make it less feasible.

In China, enough time has passed to examine the results of large-scale extinguishing activities. The main extinguishing activities were to inject a “high pressure mix of water, coal dust, and ash” into the underground cavities. Then, the entire area was covered with loess, gravel, and rock.²⁶ This was found to be generally effective, with the number of fires reduced from 18 to 6. This number is uncertain, because some of the fires were extinguished, while some of them grew and merged with others. Though the extinguishing efforts were seen as a success (fires were extinguished in the region with high efficiency), the overall area of coal fires in the region almost doubled from 2005 to 2010. Expansion of the fires has been the result of accelerated removal of coal resources, as well as improper sealing of mines left by smaller companies who were forced out of the region.²⁶

Though new methods of extinguishing coal mine fires may be developed (i.e. CAFS), extinguishing any unique fire has to take into account the available resources and methods which have been successful in the past. Our experimental apparatus was devised to test methods that CFG felt would be employable in extinguishing cavity fires, such as those in the Wuda region, as well as large fires in other desertified regions. To develop a robust experiment, it was useful to model the heat dissipation of long-burning coal fires.

Heat and Mass Transfer of Coal Fires

The heat transfer process from coal fires is a complex phenomenon. These fire systems

involve transient mass and heat transfer, reaction kinetics, and fluid dynamics.³⁹ Still, there are a finite number of ways that heat enters and leaves a burning coal seam.

The combustion of coal is largely dependent on the availability of oxygen to feed the fire. Clearly a surface coal fire is exposed to the atmosphere and has an ample supply of oxygen. However, an underground fire can receive sufficient oxygen via soil permeability to the atmosphere if the fire is close enough to the surface. Deeper fires may receive most or all of their oxygen from air flow ingress via cracks in the surrounding bedrock, and via open shafts and tunnels in the case of mine fires.⁴⁰ Because underground coal fires frequently cause land subsidence, the longer a fire burns the more likely it is to create new fissures, supplying itself with more oxygen.

The quickest route of heat dissipation, particularly for an underground fire, is the emission of heated air and combustion gasses through open fissures, arising from the chimney effect of the density difference between the atmosphere entering the coal fire cavity and the lower density of the combustion gases exiting the coal fire cavity. Another mechanism is the direct conduction of heat from burning coal to the surrounding soil and bedrock.⁴¹ Some of the heat from the off-gases is also transferred into the ground before the gases escape, which contributes to the conductive heat transfer mechanism and helps heat the ground around a fire.⁴² The conducted heat that reaches the surface of the ground is dissipated by convection and radiation.

Ultimately, the goal of modeling burning coal seams, particularly those underground, is to provide an accurate and low-cost way to determine how a fire is behaving so that an effective firefighting plan can be created. Sophisticated models of coal fires have been developed over the last decade, notably within the context of the Sino-German Coal Fire Research Initiative.⁴³ A particular issue for these models is the wide variety of timescales on which a coal fire exists. The reaction kinetics and some of the gas flows occur during very short time intervals, whereas the reaction-front propagation can proceed over long periods. These discrepancies can significantly affect the stability of a dynamic model and thereby lower its accuracy.⁴¹ Progress has been made in addressing this issue, though, and models are continuing to be improved and implemented in efforts to eliminate coal fires.

As part of the current work, a relatively simple model was developed to study the heat transfer into the ground beneath a burning coal seam, and to investigate how that built-up thermal energy then affects the cooling of the seam after the fire is extinguished. The model is a one-dimensional application of Fourier's law that has been discretized in time and space. Even though

the geometry of the model is quite simple, this numerical approach allows the user to easily input variations in the initial conditions (e.g. the initial temperature gradient below the coal seam) as well as to implement the sudden changes that occur when a coal fire is extinguished.

The user inputs the initial temperature(s) of the ground beneath what is assumed to be a plane of burning coal. The temperature of the burning coal seam is input and is assumed to stay at a constant value while the fire is active. The relevant properties of the surrounding rock, i.e. density, heat capacity, and thermal conductivity, are also input. These properties are assumed to be constant throughout the conduction medium, though it would not be difficult to alter the model so that they vary with depth or even time.

The governing equations for the model are:

$\frac{dT_1}{dt} \approx 0$	(isothermal top boundary)	(1)
$\frac{dT_1}{dt} \approx \frac{2k(T_2 - T_1)}{\rho C_p \Delta x^2}$	(adiabatic top boundary)	(2)
$\frac{dT_i}{dt} \approx \frac{k(T_{i-1} + T_{i+1} - 2T_i)}{\rho C_p \Delta x^2}$	(internal nodes, $i = 2$ to $N-1$)	(3)
$\frac{dT_N}{dt} \approx \frac{2k(T_{N-1} - T_N)}{\rho C_p \Delta x^2}$	(adiabatic bottom boundary)	(4)

where k , ρ , and C_p are the thermal conductivity, density, and heat capacity of the bedrock, respectively. Δx is the node size and T_i is the temperature of the i^{th} node.

It is important to note that the burning interface in this model is assumed to be stationary. Because coal fires naturally move along a coal seam as time progresses, this model has limited usefulness over long periods of time; eventually the burning interface moves far away from the original position and the one-dimensional model at that spot breaks down. Still, the speed of a coal fire reaction front tends to be relatively slow, on the order of 10 to 100 meters a year⁹, so the model is likely applicable for burn times up to a year or two.

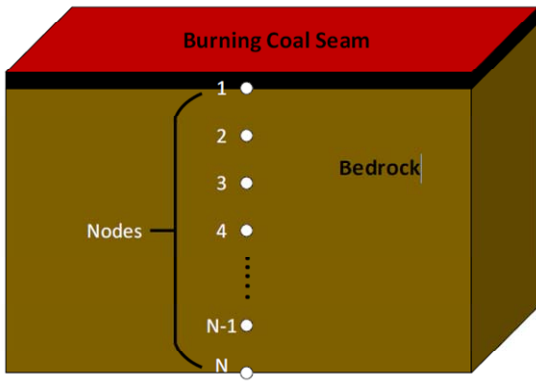


Figure 2. Diagram of the model setup.

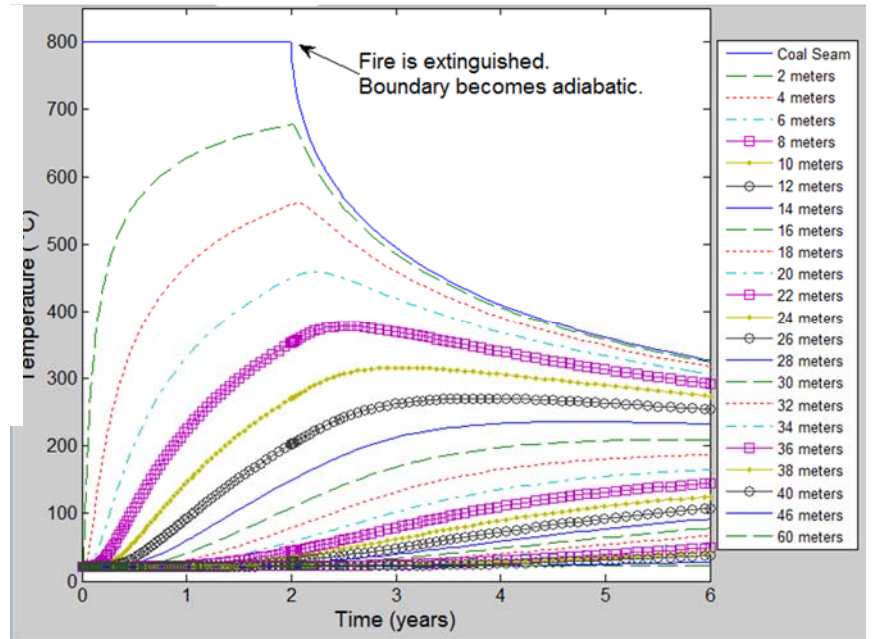


Figure 3. (Above) Example transient temperature distribution with a change from an isothermal to an adiabatic boundary condition. In this particular scenario, the fire burns at 800 °C two years before being extinguished. The temperatures at incremental depths are displayed.

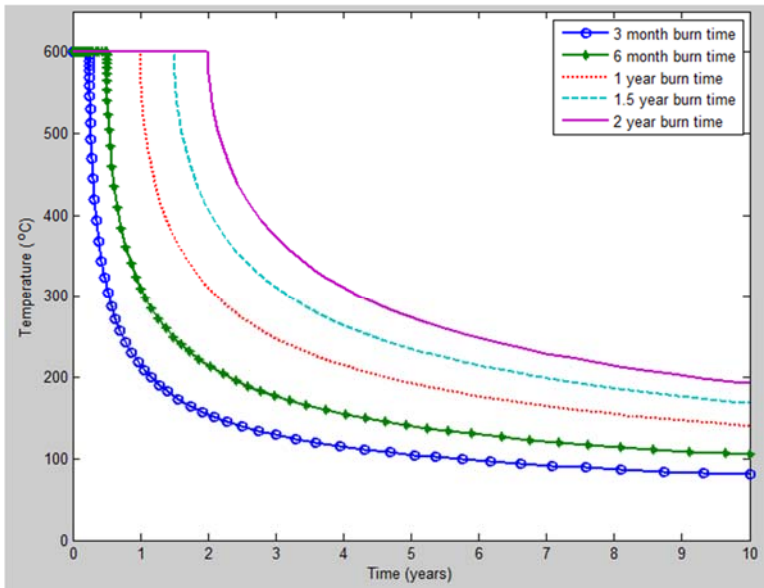
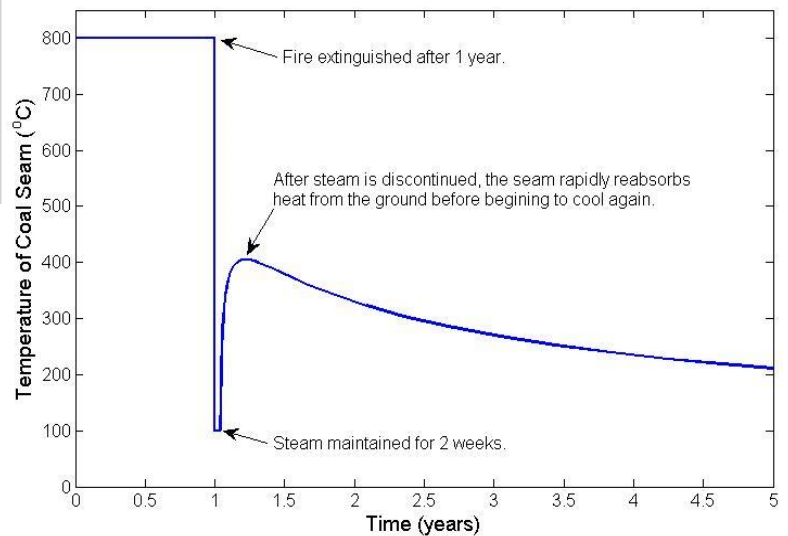


Figure 4. (Left) Plot displaying the cooling of a 600 °C fire allowed to burn for various lengths of time before being extinguished.

Figure 5. (Right) Example model behavior of a coal seam extinguished with saturated steam.



One scenario investigated with the model is a worst-case, where the burning coal is placed at the top of the temperature column and is allowed to heat the ground underneath (isothermal boundary condition at the first node, adiabatic at the Nth). After a specified amount of time, the fire is extinguished and the boundary condition at the first node is made adiabatic. The temperature of the coal seam is then modeled as its thermal energy dissipates into the already-heated ground below; the transient temperature distribution within the Earth simulating such a scenario is presented in Figure 3, for a fire temperature of 800 °C, a burn time of 2 years, and a soak time of 4 years. It can be noted that the cavity lower surface temperature is still above 300 °C 4 years after extinguishing the fire. Figure 4 presents surface temperature simulations for coal burn times of 3 and 6 months, and 1, 1½, and 2 years. Note that for the 3-month burn time, the time required to cool the cavity surface to 200 °C is about 1 year, whereas for a 1-year burn time, the time required is about 4½ years.

A key feature that this model scenario clearly shows is that the longer a coal fire is allowed to burn, the more heat is pumped into the ground and the longer it takes for the seam to cool to safe temperatures after the fire is extinguished. This showcases the extreme importance of extinguishing coal fires early after their ignition, before they become very large and hot.

Proposed Extinguishing Method

CFG's proposed extinguishing method is to fill the combustion gas exhaust cavities with sand and spray water over the sand. The heat of the coal fire, along with the heat that has been captured by the surrounding environment, will vaporize the water. The wet sand in the exit vents will block the flow of gases, forcing any combusted gases or steam to exit through the air inlets, minimizing oxygen flow to the fire. The energy removed by the steam will also increase initial cooling of the coal seam below the auto ignition temperature.

Using the transient heat transfer model developed by CFG, the proposed sand-water extinguishing method was modeled by maintaining a 100 °C isothermal top boundary after the fire is extinguished. After a short period of time, the steam supply is removed and the interface condition is changed to adiabatic. The results of this simulation are presented in Figure 5. After the steam is removed, the temperature of the coal bed rapidly rises as it reabsorbs leftover heat from the ground below, though it is evident that much of the thermal energy was absorbed by the

steam.

Bench-scale Experimentation Apparatus

The experimental apparatus simulates an underground mine fire. An angle-iron steel frame was constructed as shown in Fig. 4. Into the angle-iron frame was placed Hardy-Board panels on the two sides, bottom, and both ends. Two-inch thick high-temperature insulation was placed on the sides and ends of the Hardy-Board box. In the bottom of the box, above the hardy-Board, about 6 inches of soil was placed. Above the soil, two layers of two-inch thick firebricks were placed. Cast-iron grates were placed over the fire bricks, and these grates were covered with one inch of sand. Kerosene was distributed into the sand layer, and pieces of wood were placed on the sand on the fire-side of the box. A metal grate held the coal above the firewood, below which the fire was ignited.

There will be a steel insert that fitted into the frame to produce a cavity between the bottom of the insert and the coal fire. This cavity simulated a cavity within the Earth which exhausted combustion gases out of one opening (the fire side) and received combustion air from a separate opening to the atmosphere (opposite fire-side).

Kerosene and wood were used to start the fire, because unrefined coal is difficult to ignite directly. The coal was placed onto the Kerosene-wetted sand. The discharge of a box fan was directed into the cavity opposite the fire-side, between the insert and the end of the box. This arrangement provided combustion air to the bed of coal and forced the combustion gases to exit at the opposite end of the box.

After the fire had burned for a sufficient amount of time to heat the brick, it was extinguished by adding sand and then spraying water, at a predetermined rate, onto the sand. The sand was poured into the cavity within 6 in of the top. The wetted sand then prevented the hot combustion gases from escaping to the atmosphere. When water was added, after migrating down to the hot bricks/coal, it was vaporized and forced out the opening opposite the fire side, which previously served to supply combustion air. The steam that exited extinguished the fire within the cavity by excluding air and oxygen from the cavity as long as water was added, and as long as the fire brick and coal supplied the heat required to vaporize the water. This prevented air from entering, ensuring the fire would remain extinguished.

Experimental Setup

Use the shovel to level the ground.

1. Arrange the cinder blocks to be used as the steel frame foundation.
2. Place the steel frame on the cinder blocks.
3. Cut and place the cement board in the sides of the steel frame so it is flush with the frame.
4. Place the soil in the steel frame and level it.
5. Place a 1” layer of sand over the soil and level it.
6. Cut and place the board insulation in the sides of the steel frame so it is flush with the cement board.
7. Use the steel wire to secure the top of the board insulation to the steel frame.
 - a. Use the drill to put holes in the cement board and loop the steel wire through the cement board and insulation and around the steel frame at the corners.
8. Place two layers of bricks over the sand.
9. Use sand to fill in the cracks between the bricks.
10. Place a layer of firebrick around the area where the fire-side inner-perimeter of the apparatus. (See Figure 6 for an example of the final coal-grate-wood-firebrick arrangement.
11. Place the grates cast-iron grates on top of the fire bricks so that there is an open pit below the grates.
12. Place wood below the grates in the pit.
13. Place a second layer of firebrick on the grates around the perimeter.
14. Load coal on top of the grates within the fire-brick pit formed in step 13.
15. Install the steel insert.
16. Tape the roll insulation around the handles of the steel tinsert.
17. Attach the ball valve to the pump outlet with the PVC pipe fittings.
18. Attach a garden hose to the inlet and outlet of the pump using the PVC pipe fittings.
19. Fill the trash can with water.
20. Use the funnel to pour water into the pump inlet hose until it is full.
21. Place the pump inlet hose in the trash can.
22. Connect the pump and the box fan to a power source.
23. Turn on the pump to ensure water will be discharged.
24. Adjust the ball valve until the pump runs at 0.5 gpm.



Figure 6 - coal-grate-wood-firebrick setup

Experiment

1. Place the metal pan in the end of the box with the firebrick lining.
2. Fill the pan with coal.
3. Fill the pan with about 0.25” of kerosene.
4. Place the steel top on the box allowing room for air egress over the pan and air ingress on the other end.
5. Use the roll insulation to fill any gaps between the steel top’s sides and the insulation.
6. Place the box fan over the air ingress hole so it will blow air into the box.
7. Use the propane torch to light the coal and kerosene.
8. Start the box fan.
9. When air flow has been established through the box, remove the fan and turn it off.
10. Allow the fire to burn for 30 min. to heat up the firebrick.
11. Pour sand into the air egress cavity until it covers the entire cavity.
12. Start the pump and move the pump outlet hose so that it wets the entire sand surface.
 - a. After a few minutes steam should be observed escaping through the air ingress cavity.
 - b. Continue this until steam is no longer observed.
 - c. When steam is no longer observed the cavity and coal temperature should be reduced to 100 C and the fire should be completely extinguished.
13. Turn off the pump.

Bench-scale Results and Conclusions

The CFG method of extinguishing successfully extinguished the coal fire and cooled the surrounding environment. Before sand was added the air egress temperature was measured at 560 C. This is consistent with observed exit gas temperatures at underground mine fires. Covering the air egress with sand greatly reduced the amount of combustion gases that could escape through that cavity, but did not completely cut off the flow. Adding water to the sand filled the voids in the sand and prevented combustion gases from escaping through the air egress cavity, stopping the chimney effect. Steam was observed escaping through the air ingress cavity. This greatly reduced the amount of oxygen that could reach the fire as the only means for its entry was through back-mixing. The steam temperature was measured to be 250 C. This superheated steam carried about 1242 Btu/lb of energy out of the cavity. This significantly reduced two points of the fire triangle, heat and oxygen. When steam was no longer observed exiting the air ingress cavity the temperature of the coal and surrounding environment was measured to be 100 C. Only 2 gallons of water were used.

This proved the concept that underground coal fires could be effectively and economically extinguished using this method. The principal materials needed are both cheap and readily available in most circumstances, sand and water. Water's use, being the more valuable of the two, could be limited. Still, extinguishing an underground fire fully, without the threat of it reigniting, requires significant dedication of steady effort over longer times than were tested here. Even after openings are filled with sand and the fire is cooled with water, the fire must be monitored and any new ingress openings must be treated in the same measure or otherwise sealed.

This is a very simple process and can certainly be implemented on a large scale. The combustion gas exit points would need to be identified either visually or by measurement of exhaust gas characteristics, e.g., temperature and/or composition. These cavities would then be filled with sand and water would be sprayed over the sand at a rate sufficient to keep the sand's surface wet. Steam will be observed exiting at prior ingress points not covered in sand and water. When the steam is no longer observed the water can be shut off and the points where steam was observed exiting can be filled with sand to help mitigate chances of reigniting. This method requires minimal rather inexpensive materials and modest man-hours.

Conclusions

1. Coal fires produce greenhouse gases, consume valuable resources, and emit pollution which is quite harmful to humans and the environment in general.
2. It is estimated that the CO₂ equivalent emissions from worldwide coal fires is about 1% of all manmade emissions, and 2% of the yearly CO₂ growth within the atmosphere.
3. From The Coal Fire Team's investigation, there is evidence that extinguishing coal fires is truly the "low-hanging fruit" for immediate short-term reduction in CO₂ emissions.
4. There are many methods for extinguishing coal fires. Many have been attempted. Some have been successful, and some have been unsuccessful. The successful methods involve adding solids like sand or fly ash in combination with water. The Coal Fire Gang has demonstrated that a relatively novel method is very effective for certain, if not many, underground coal fires. The CFG method injects dry sand into the combustion gas exit vents, followed by spraying water onto the sand which migrates down through the sand onto the heated Earth below, vaporizes, and flows back out the air inlet openings. The cavity fills with steam and the escaping steam velocity, leaving the previous air inlets, prevents air from entering the cavity. The steam within the cavity extinguishes the fire and keeps it extinguished as long as the hot earth beneath the cavity supplies sufficient heat to vaporize sufficient steam. The water vaporization will cool the surrounding soil as long as water is supplied and as long as there is stored heat in the soil to vaporize the water.
5. This novel technique has been demonstrated by small-scale test using an apparatus which simulates a coal fire in a cavity underground. The apparatus was operated in a manner such that there was a chimney effect for the hot gases exiting the vent opening which induced airflow for combustion in an inlet opening. When the sand was added, the exhaust gases ceased almost totally, and when water was added, exhaust gases not only ceased, but were forced out the air inlet opening.

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2014 WERC Competition

University of Arkansas – Coal Fire Gang

Draft 1 Paper Audits

Auditor 1:

L. H. (Hop) Boyd, Jr., P.E.

Chief Manager

Process Engineering Associates, LLC

“

I have reviewed your paper and found it on whole to be informative, well-researched, and well-written. I have one major problem with the thesis involving the reduction of CO₂ emissions by extinguishing coal fires - and that is this: If the coal burned in coal fires was instead mined and consumed by industry, wouldn't the total amount of coal burned be the same, ergo the total CO₂ emissions the same? Whether or not coal is burned accidentally or is purposed for coal-fired power plants, etc. should really make no difference as to the total CO₂ produced. The fact is that the coal is burned and CO₂ is emitted.

The theses regarding lost economics and health effects to me are more valid. Having spent some time growing up in coal mining country in southwestern Virginia, I know that coal fires are a problem to mining companies in terms of lost revenue from the actual burned coal as well as the inability to extract other coal in the vicinity of the fire. The development of a method to economically extinguish coal fires would be greatly valued by private industry based on rational economic self-interest alone, and would prove to be a much greater method of solving the problem of coal fires than any government regulation ever could. I would tend to emphasize this benefit rather than the CO₂ reduction angle. I do agree with the health benefits analysis from this standpoint - controlled burning of coal (e.g., via power plant) offers the significant advantage of proper venting of gases as well as removal of many of the harmful byproducts via scrubber systems etc.

In summary, I think you are on solid ground regarding economic and health benefits, but I believe you are on very shaky ground with regard to your CO2 emissions theory.

Other than this, please review the paper carefully for typos and to make sure you have defined acronyms as soon as you introduce them.

I enjoyed the opportunity to review your project, and I wish you and your team the best of luck with your competition, as well as in the future.

”

Auditor 2:

Dr. Robert B. Finkelman

Research Professor

Finkelman, R, 2004, Potential human health impacts of burning coal beds and waste piles International Journal of Coal Geology, Vol. 59, nos. 1-2, p. 19-24.

Pone, J. D., Hein, K. A. A., Stracher, G. B., Annegarn, H. J., Finkelman, R. B., Blake, D. R., McCormack, J. K., and Schroeder, 2007, The spontaneous combustion of coal and its by-products in the Witbank and Sasolburg coalfields of South Africa. International Journal of Coal Geology. Vol. 72, p. 124-140.

“

First, I commend you on selecting the important but often overlooked issue of uncontrolled coal fires. Second, your review of the issue and background is well written and generally well documented. There are, however, many missing relevant references. If you have time I urge you to read my 2004 and 2007 papers that are supportive of your proposal and would add much useful information. There are quite a few additional references in the geoscience literature that I could recommend as well. The formatting of your references in the text needs to be improved.

On Table 1 you need to emphasize that there are many hundreds of known coal fires in China and that China is where your proposal would see the most benefit. I believe that Dr. Prakash has a relevant map on her web site.

The Morwell coal mine fire in Australia has been in the news recently and should be noted.

On page 10 you confuse coal rank with coal quality. Lignites are the lowest rank but do not necessarily have the lowest quality. Quality is an amalgam of a number of parameters such as heat content, moisture, ash yield, sulfur content, etc. Lignites commonly have low quality but some can have exceedingly high quality. Similarly anthracites can have very poor quality.

I can not comment on the thermodynamics which is outside my field of expertise.

On page 24 you say that 'coal is difficult to ignite directly.' This seems to be a contradiction to your basic contention that coal fires are a common worldwide hazard.

You present an interesting and innovative way to simulate coal fires. However, I am concerned that your approach did not adequately reflect real life situations where there are generally multiple points of entrance to and exit from the fires. Blocking one path may have virtually no effect on the fire. Using steel pans and inserts, bricks, wood, and kerosene takes this experiment further from a real-life situation.

To convince anyone that your proposed method of extinguishing the fires is practical you need to compare the of cost of your approach to the costs of existing methods of putting out the fires. How does your approach stack up to just pouring water down a shaft; using nitrogen foam such as is done by CAFSCO.com, or using other inert gas such as carbon dioxide, or any of the other methods? What does it cost to transport sand to a coal fire site, drill the necessary bore holes and force the sand and water down?

A diagram would have helped me to visualize what you describe on page 24.

You may be on to a worthwhile approach to extinguishing these nasty fires. I hope that my comments are helpful and do not extinguish the fire of your enthusiasm to tackle this worthwhile task.

”

Auditor 3:

Hayden Dwyer

Facilities Engineer

Southwestern Energy company

“

- Title Page – Dates on cover do not match. Top line list *WERC 2013 Open Task* while the team is the *2014 UofA WERC Team*. This may be correct but it just looked odd to have a 2014 Team competing in a 2013 event.
- Page 2, second paragraph – The use of the word fruitless in regards to the greenhouse gas emissions makes me think that the emissions themselves are fruitless and carries the connotation that they have little to no effect. I would change the wording to better state that these emissions are occurring as an unnecessary evil since there is no societal benefit.
- Page 3, first paragraph – In the last sentence of this paragraph it I would use prolonged exposure in the near proximity of coal fires or something along those lines. The phrase “prolonged proximity” just sounds a bit odd to me.
- Page 4, middle of page – Where you talk about the volatile elements present in coal. Just a question I had was how are certain elements more prevalent in coal ash than in the solid, unburnt coal? If they were not present to the same prevalent degree in the solid coal how did they get there once it was burned? Does the heat/fire cause a reaction that generates more volatile elements?
- Page 5 – Just a curiosity question that you may be able to clarify. I was a little confused how the Centralia Mine Fire, which occurred in a mine that had been near abandoned due to coal depletion, so assumingly there was little coal, would have cost \$663 million to extinguish; while the next section discusses the Xinjiang province in China which “contains some of the largest untapped coal reserves in the world” is burning yet this would only cost \$10 million to extinguish. There was just a logic jump I could not make on how a small depleted coal mine burning could cost 6000% more to extinguish than a huge reserve that has plenty of coal/fuel and long existing fires.

- Page 7 – I am going to go ahead and assume that in finalizing this paper to meet length all of the page break issues, such as the header for this table being on a different page, will be resolved. Also applies to all section headers such as the Classification section.
- Page 8, second to last paragraph – Says coal *fries* instead of coal *fires*
- Page 10 – This may not need to be added because I am not sure how much value it would add to the paper and you are already pressed on the length, but the top paragraph discusses lignite and anthracite and then the list throws in Bituminous. Is bituminous metamorphic or sedimentary. Or as the list said is it just a sub classification of lignite. May just mention it somewhere in the preceding paragraph.
- Page 12 – Do these fires fuel themselves by creating a flue type situation where the off-gas goes out one channel while the air is pulled in through a separate opening. I would think that if a fire was burning and the only access to it was through a mine shaft, the fire would generate hot air that would push air/off-gas outward through the shaft and prevent air from entering into the shaft, especially as it got nearer the flames to heat it up making it want to rise. This would starve the fire of oxygen. This would make sense if there were multiple opening where the gas left one through one channel creating a vacuum on the backside from another shaft that would pull in new oxygen. This question only pertains to the deeper fires, I understand the near surface fires will have easy access to air.
- Page 14 - Glad to see some Nodal Analysis, you can solve any heat problem with that tried and true technique!
- Page 17 – On this page as well as some of the pages later in the paper, there is a lot of repeated information that I have already read through in the beginning sections. Some of it may be good to repeat if trying to stress a point but I feel like in this area as well as others you can cut out a lot of the fat in the paper to shorten it down when needed by finding the information you have already discussed, such as the background on the Jharia region, etc..
- Page 21 – Remove the “with by injections” statement. Just a typo. There is also more repeated information here about the extinguishing efforts and the size. Also “extenguishing” is spelt wrong.
- Throughout the Experiment sections you may want to throw in a little bit about safety, such as stating that fire proof gloves were worn while handling hot stones or things like that. Just little

things in the Setup and Procedure regarding safety precautions that you followed will not take up much space but will add a lot to show that you considered safety a high priority.

- Page 32 – Bullet point 7, “manner such hat” just add a t- so the “hat” is “that”

Overall I think the paper is very well done and well written. You made all of the arguments clearly so that I had no real problems understanding what you were trying to get across. The issue with coal fires was presented well so that I know why they are bad and the call to action about what we should do about them. Sounds like you guys have a good idea that works well! I think you stand a great shot in the competition.

”