IPRO 302

Impacts of Sulfur Capture on the Coal Power Market

Final Report

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Section 1 - Executive summary

Coal has been the fuel of choice for electricity generation in the United States over the last one hundred years, due to its abundance, low cost, and combustibility. However, a small percentage of an impurity in the coal can result in a large quantity of byproducts. Sulfur is a common impurity in coal and the concentrations vary geographically. Of the many factors that affect the cost of electricity produced in a coal fired power plant, one of is the amount of a power plant's operational income gained or lost in the transporting, disposal, storage, and/or selling of the power plant's byproducts. To gain a better understanding of the magnitude with which a sulfur byproduct can be an asset or a liability to a power plant, our project team has analyzed the two different methods that can be employed to utilize coal as fuel for the production of electricity. Our team has analyzed the two methods of sulfur removal in terms of the disposal, storage, and transportation costs, as well as commercial values of gypsum and elemental sulfur.

The pulverize coal (PC) plant uses the traditional method of combustion to remove the sulfur producing vast amounts of gypsum, calcium sulfate, as a byproduct. The next generation of coal processing, known as Integrated Gasification Combined Cycle (IGCC), ultimately produces elemental sulfur as a byproduct. IGCC is a proven technology that has several advantages over combustion. Although it has not yet been implemented on a nationwide basis, it produces much lower emissions of chemicals and particulate matter. It is 4-5% more thermally efficient and allows for fractionation of the gasified coal into pure hydrogen and carbon dioxide. This creates a concentrated stream of carbon dioxide, which will allow for easy implementation of carbon capture technologies pending the introduction of new carbon regulations.

Our sponsor, Sargent & Lundy, LLC, would like to perform an economic and environmental analysis of both traditional and IGCC power plants to determine which type of plant they want to recommend to their clients both now and in the future. Sargent & Lundy provides comprehensive engineering, energy, business, and project consulting for new and operating power plants. Sargent & Lundy has designed more than 884 power plants totaling over 122,149 MW for clients in the public and private sectors worldwide. This research is in the interest of our sponsor because it will offer an approach for them to account for the financial impact of the byproducts produced from their current combustion and future gasification client plants.

It was found that because gypsum is an inert compound and not harmful to the environment it could either be sent to a landfill or sold for use in commercial wallboard at rates so low as to be negligible. The demand for gypsum in the market was found to be somewhat affected by the housing market's demand or lack thereof for wallboard. Typically however, there is a large enough supply of gypsum in the market for giving it away to not be unreasonable.

Much less sulfur is produced in comparison to gypsum but, sulfur can form foul smelling hydrogen sulfide and corrosive chemicals like sulfuric acid. If the market value for sulfur is currently low, it can be stored in liquid pools or as giant solidifying blocks to be reheated and sold at a later date. However, a buildup of byproduct inventory could drive the price of sulfur low enough to make it unprofitable and potentially a liability.

Section 2 - Purpose and Objectives

Problem Statement

Because of the advantages of coal gasification in carbon dioxide sequestration, Sargent & Lundy LLC, is performing an economic and environmental analysis of pulverized coal combustion (traditional or PC) and coal gasification (IGCC) power plants. In each power plant, it is necessary to remove the sulfur from the gases created by the different processes. The sulfur is removed by flue gas desulfurization (FGD) in the traditional power plant, and by an amine scrubber process in coal gasification power plants. Each process produces a different sulfur byproduct. Our goal is to help our sponsor in their endeavor by analyzing the economic and environmental costs of sulfur byproduct removal in each process. Our focus is to find the amount of sulfur byproducts produced by each power plant, whether or not each byproduct can be sold on the market and the economic and environmental costs of disposal of the byproducts if they cannot be sold. We will not analyze the costs of the FGD and amine scrubber equipment, the carbon dioxide emissions of each power plant, or the cost of electricity, as that is beyond the scope of our problem.

Team Objectives

In order to reach our goal we needed to:

- Contact our sponsor to gain a greater understanding of the scope of our problem
- Develop a basic understanding of how PC and coal gasification power plants work, including the materials and processes necessary to run them
- Research the FGD and amine scrubber processes to gain a basic understanding of how they work and the sulfur byproducts they produce
- Calculate the amount of materials needed for each process and produced by each process
- Formulate different solutions for disposing of sulfur byproducts generated
- Determine the costs involved in each solution, as well as the money that can be recouped by selling the byproducts
- Determine the environmental impacts to each solution
- Extrapolate some of our results to the national scale, for a greater understanding of the scope of sulfur disposal
- Communicate our conclusions to Sargent & Lundy, LLC, as well as all background research involved.

Background

Almost all coal power plants today are pulverized coal (called PC or traditional) combustion plants. Sulfur is present in coal in small amounts, and during the combustion process, the sulfur is oxidized to produce Sulfur Dioxide (SO_2). Both combustion and gasification power plants require their fuel streams to be scrubbed of sulfur. If the sulfur is not scrubbed from the system, it can develop into sulfuric acid and corrode the plant turbines. When the sulfur finally makes its way into the atmosphere, it can acidify rain as well as cause respiratory problems. Because of this sulfur emissions have been regulated since the Clean Air Act of 1955.

According to the American Meteorological Society, in 1952, London, England experienced a smog event that killed over 4,000 people between December 1st and 15th. On the 7th and the 8th, approximately 900 people died each day. Approximately two and a half years later, the U.S. Congress enacted the first Clean Air Act of 1955. Congress amended the Clean Air Act again on December 17, 1963; October 25, 1965; November 21, 1967; and December 31, 1970. Additional amendments were made to the Clean Air Act on November 18, 1971; August7, 1977; and November 15, 1990.

During the early years of electricity generation, the sulfur gases (primarily SO_2) were passed on to the atmosphere along with the rest of the flue gas, but the increases in emissions regulations since 1955 have continually encouraged coal combustion power plants to increase the efficiency of their scrubber systems. These amendments encouraged the development of Flue Gas Desulfurization which became the technology used to remove the SO_2 from the stack, and is still used today for the traditional coal power plant. The sulfur removed from the flue gas is in the form of gypsum (Calcium Sulfate Di-hydrate).

Typically, coal combusts at temperatures between 1300 and 1700 degrees Celsius depending on what type of coal it is. In contrast to combustion, gasification typically occurs at lower temperatures and while oxygen is a necessary component for a combustion process, in gasification extremely high pressure with limited or controlled availability of oxygen is the case. Combustion plants produce sulfur oxides (SO_2, SO_3) which are subjected to limestone (calcium carbonate-$CaCO_3$) based Flue Gas Desulfurization (FGD) in order to remove sulfur from the stream, resulting in vast quantities of gypsum (calcium sulfate-$CaSO_4$). There are many small sub-reactions but, the generalized reaction equation appears as:

FGD: $$\mathbf{CaCO_3 + 2H_2O + SO_3 \rightarrow CaSO_4 \cdot 2H_2O + CO_2}$$

The steam may be sent back into the cycle or released, while the carbon dioxide may be scrubbed or sequestered, and the calcium sulfate (gypsum) is sold for a profit or transported to a landfill. Gypsum is naturally occurring in places like White Sands, New Mexico, where large bodies of water have evaporated to leave the gypsum behind. Gypsum is commercially used mostly for the production of wallboard. Aside from wallboard, it can be used as embankments for roads and adobe style, cast earth housing. Gypsum that has been dehydrated is called Plaster of Paris and is used for medical casts as well as plaster modeling. FGD produces much of this commercially used gypsum in order to remove sulfur from coal.

In recent years, a new form of coal-fired power plant called integrated gasification combined cycle (IGCC) has been developed. In this new process, the sulfur in the coal is converted to H_2S (Hydrogen Sulfide) instead of SO_2. The sulfur must still be removed because H_2S is highly toxic. In this case, the sulfur is removed by the Claus process, and the byproduct is elemental sulfur. All but a few coal power plants are currently of the traditional type, but there are advantages to this new plant. IGCC is 10-11% more thermally efficient than a traditional coal power plant but, the main reason that this new plant may become needed is because of potential CO_2 emissions regulations, in which carbon capture technology may be used to sequester potential CO_2 emissions. In contrast to PC plants, IGCC plants allow for the CO_2 gas to be removed and sequestered before combustion and at much lower temperatures.

IGCC plants utilize amines, such as methyldiethanolamine, to remove hydrogen sulfide from the gasified coal stream instead of the sulfur oxides that would have formed in the presence of more oxygen and higher temperatures. Amine scrubbing originated in the oil and natural gas industries and has been used to separate carbon dioxide (CO_2) from natural gas and hydrogen since 1930. There are a variety of amines, derivatives of ammonia, which may be used in an IGCC plant, but for the sake of maintaining project scope, this project research assumes that 100% of the hydrogen sulfide is removed by a generalized amine scrubber.

The hydrogen sulfide is then converted to elemental sulfur through the Claus process. The Claus process removes sulfur from hydrogen sulfide in two steps. The thermal step converts one third of the hydrogen sulfide into sulfur dioxide, elemental sulfur, and steam. In this thermal stage, H_2S burned in O_2 at temps above 850 degrees Celsius produces SO_2 for the catalytic stage. The catalytic stage, at 330 degrees Celsius for the first cycle and around 240 degrees Celsius if there is a second cycle, reacts the remaining hydrogen sulfide with the newly produced sulfur dioxide to produce more steam and gaseous sulfur. The steam is again recycled and the sulfur will condense into liquid at temps below 150 to degrees Celsius. The sulfur is then stored on-site as a liquid or solid, in pools or blocks respectively, to later be possibly sold for profit.

Thermal step: $10\ H_2S + 5\ O_2 \rightarrow 2\ H_2S + SO_2 + 7/2\ S_2 + 8\ H_2O$

Catalytic step: $2H_2S + SO_2 \rightarrow 3S + 2H_2O$

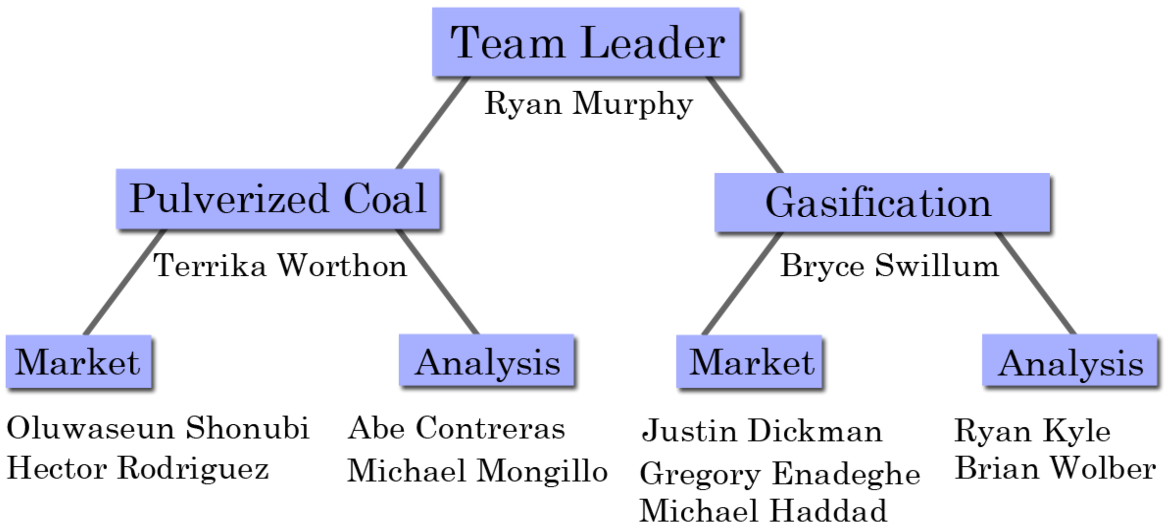
Most of the sulfur that is sold is sold for conversion to sulfuric acid. Sulfuric acid is the most frequently used industrial chemical in the world. Other portions of the sulfur are sold to fertilizer and cosmetic manufacturers. Recently, sulfur based asphalts and concretes have been developed as well.

Section 3 - Organization and Approach

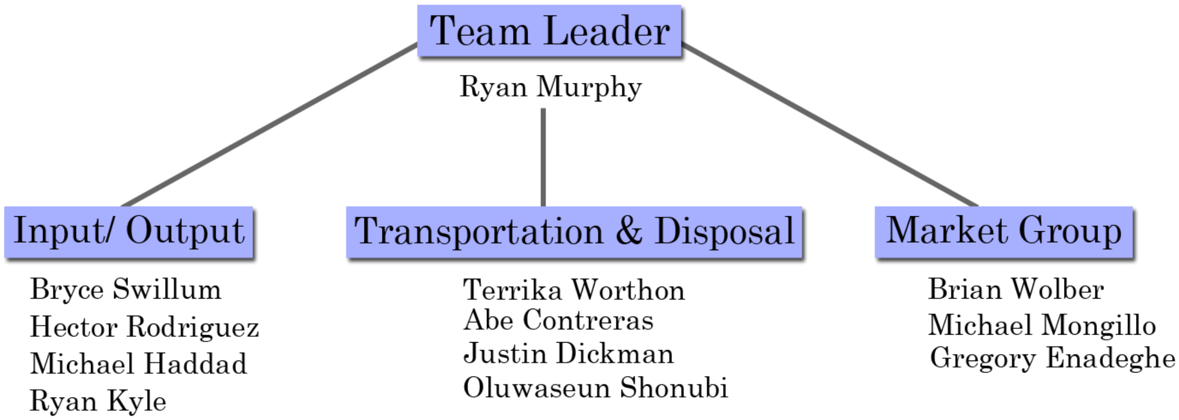
The presentations given at the beginning of the semester by professors Gottlieb and Chmielewski ensured that the team had a common base of terminology established as well as a clarified view of the overall project goal. Their presentation topics included coal combustion and gasification processes, the sulfur removing Claus process, and ethical considerations to keep in mind while researching these technologies. The ethics presentation gave us examples of ethics codes from the American Chemical Society and the Institute of Architects and gave us some viewpoints to consider while developing our code of ethics.

Two outside expert speakers gave presentations geared towards more specific aspects of combustion, gasification, and desulfurization. David Hasler from Sargent and Lundy addressed the processes of Pulverized Coal combustion plants with FGD, and IGCC with amine desulfurization in great detail. Ajay Jayaprakash, also from Sargent and Lundy, gave our team a very helpful critique regarding our presentation. Also, a representative from the Gas Technology Institute, Dennis Leppin, P.E., Senior Institute Engineer, offered invaluable insight into gasification and desulfurization processes. Mr. Leppin discussed various intricacies of removing sulfur based acid gas from the stream of gasified coal through the use of amines and chemical solvents.

The team chose Ryan Murphy as the team leader. Ryan created a project plan in the form of a Gantt chart and coordinated the development of an overall team project plan in order to layout expected dates for deliverables. He then divided the team into two subgroups distinguished by each of the competing coal processing technologies. Subsequently, each of the subgroups focused on the major byproduct of their respective technology in terms of market values, common uses, physical properties, chemical properties, storage methods, and disposability.



This work breakdown structure was effective in familiarizing each team member with either Pulverized Coal or IGCC power plants. The research provided questions that needed answering and thus tasks. The similar nature of some tasks inspired some members of the project team to recommend a shift towards a work breakdown structure of three subgroups that would be more task oriented than technology focused. The subgroup defining research tasks were mass balancing, byproduct transportation, and byproduct markets for the overall input and output of each plant.



Don Chmielewski, Professor
Myron Gottlieb, Professor

The scope of our analysis was further focused for the team by the project sponsor so that it pertained to two specific power plants, each exhibiting one of the competing technologies and byproducts. As beneficial as the added focus was, it was difficult to arrange the initial meeting with our Sponsor and so the first several weeks of the project were spent on defining the scope and becoming more familiar with the processes involved.

In hindsight, each of the structures made sense while they were in use, in that a thorough understanding of the competing processes and byproducts was initially paramount. However, once acclimated, it was necessary to begin analyzing the identified driving factors involved in a competitive cost-benefit analysis of traditional Pulverized Coal power plant technology and Integrated Gasification Combined Cycle power plant technology.

Each of the teams was headed by a subgroup team leader who was responsible for delegation of the relevant assignments to their team members, organization of subgroup meetings outside of class, and the compilation of all subgroup data. The three teams were composed in a manner that would make use of each team member’s skill set. In general, the market team was comprised of the team members with business backgrounds. While the transportation team was a mix of team members with engineering, design, and business backgrounds, and the input/output team included team members with chemical and physical science backgrounds.

The market research team analyzed the cost of limestone itself as well as its shipping. They also researched the profitability of commercial sulfur, the potential savings from storing the sulfur during unfavorable market conditions, the current profitability of gypsum versus the cost to landfill the gypsum, and historical market trends for both gypsum and sulfur.

The transportation team determined the byproduct shipping rates and gross transportation costs associated with byproduct amounts produced from the specific power plants. They also researched necessary shipping considerations such as heating (to keep the sulfur in liquid form), and maximum legally allowable shipping weights.

The input/output team calculated the total quantities of coal used and byproduct amounts produced according to the sponsor's data as well as through the analysis of the associated chemical reaction equations. This also included total amounts of interim products like hydrogen sulfide and sulfur dioxide.

Most research and analysis was accomplished outside of regular class time. Regularly scheduled classes were used primarily for the synthesis of results via presentations and coordination and planning for upcoming deadlines. Presentations were given by each of the subgroups to the rest of the team in order to maintain a current and cohesive team viewpoint throughout the semester. Once all of the data from each sub-team was shared through in class presentations, differences in the units used were discovered and corrected accordingly.

Overall there were no major problems with the team as a whole or within the subgroups. However, some obstacles were encountered during the semester. One obstacle was that many data sources were using metric tons and others, like our sponsor, were using U.S. tons. It was also then decided that data from each sub-team would be presented in annual terms as opposed to daily. Another obstacle was conflicting data from different sources. We overcame this obstacle by comparing multiple data sources. These sources included but were not limited to the Department of Energy, The Environmental Protection Agency, and various market research websites and publications.

Section 4 - Analysis and Findings

In order to jump start the analysis process, it was very important to determine the necessary input and output amounts of the different products associated with each power plant. In order to determine the input and output amounts, the mass balance sub-team carefully followed the constraints set aside by the sponsor. These constraints included net 600 MW power out put with an 85% efficiency located in Texas using Texas lignite coal. Utilizing the values for the net out put, the amount of coal per year to input into the PC and IGCC plants were determined to be 3.6 million and 3.4 million respectively.

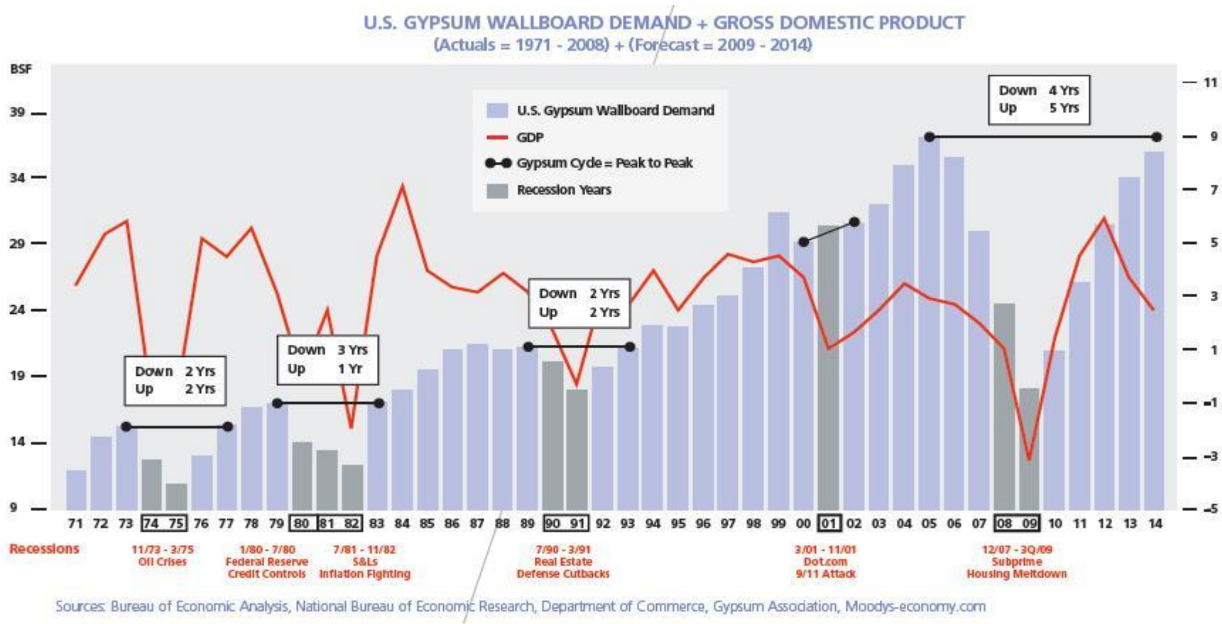
It was determined for a 600 MW PC power plant approximately 3.6 million tonnes of coal were needed per year to run this plant. With the above listed coal input approximately 46,000 tonnes of sulfur dioxide (SO_2) is produced and must undergo the desulfurization process. In order to undergo such a process, 73,000 tonnes of limestone was needed to react with the 46,000 tonnes of SO_2 and 125,000 tonnes of gypsum is produced. Investigating similar conditions for the IGCC power plant, it was determined that approximately 3.4 million tonnes were needed to run the plant for a year. This coal input then produced 22,000 tonnes of elemental Sulfur.

Given that the plant was located in Texas the transportation methods that were best fitting for this analysis would be trucking. After investigation Texas loading regulations, it was determined that the trucks could carry a max load of 25 tonnes, approximately 55, 500 lbs. Due to limestone and gypsum being non hazardous material, these materials can be hauled via truck.

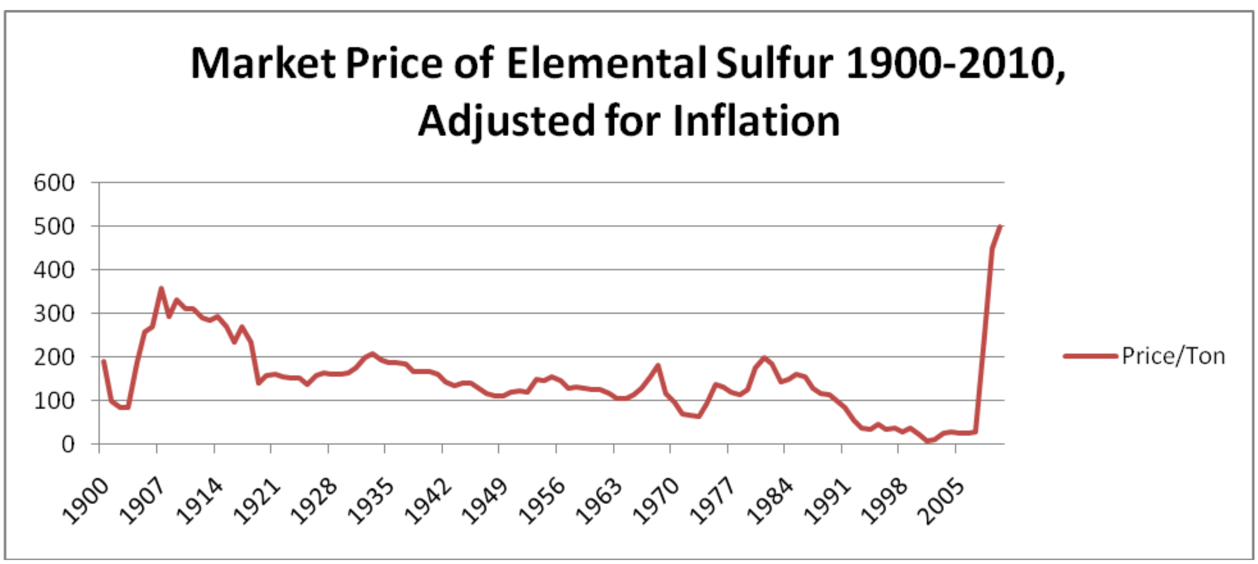
After researching trucking cost along with possible manufacturer site locations, it was determined the truck used to haul the limestone and gypsum would cost $1.25/mi. With the initial conditions of the limestone quarry being located 200miles roundtrip from the plant site with a load of 25 tonnes/truck, the transporting cost of limestone was found to be $730,000/yr. Using the same transportation cost along with the information of gypsum manufacturers being located 400 miles round trip from the plant site, the transporting cost for gypsum was determined to be $2,687,500/yr. Considering the scenario that the gypsum produced in the PC desulfurization process is not given to gypsum manufacturing companies and must be disposed of, it was determined that on-site disposal at a cost of $20/tonne would produce an annual cost for disposal of $2,500,000.

The same analysis is done for the transportation cost of the IGCC byproduct, elemental sulfur. However, a different truck is needed, tank truck, because the sulfur would be transported in liquid form. The sulfur is transported at a cost of $1.40/mile with a load of 25 tonnes/truck traveling 200 miles roundtrip, an annual transportation cost to manufacturers was determined to be $236,923. Categorizing elemental sulfur as “special waste”, disposal would be at a projected cost of $46/ton combined with transportation to obtain a total cost of $1,022,851 to dispose of the sulfur produced in the IGCC plant. Considering the scenario of the elemental sulfur not being sold to the market or disposed of, the storage options of sulfur pits or sulfur tanks would then be considered.

During our research of the gypsum market, we found a history of price variability over the past 100 years. There is a distinct correlation between the price of gypsum and drywall sales, which makes sense since gypsum is a key ingredient to the production of drywall. Those gypsum sales are in turn affected by the economy. Plainly, the demand for gypsum is rising at 6.8% annually with fluctuating prices. With our latest price data, the price per ton of gypsum is roughly $137 however we do not have a current number.



For 100 years, the price of elemental sulfur had been steadily declining. However within the past two years, that price has sky rocketed upwards. Normally, the majority of the elemental sulfur in the market came about as a byproduct from the refining of crude oil. However, the costs of extracting sulfur in crude refining have more than doubled and the demand for fertilizers has increased, causing the price of elemental sulfur to jump. In fact the price is ten times higher now than what it was two years ago in some parts of the world. In the West, a ton of elemental sulfur will cost $450-$500.



Section 5 - Conclusions and Recommendations

In our analysis, we have found that the sulfur disposal process will provide higher revenues than the gypsum disposal process. Even with elemental sulfur selling at its lowest prices and gypsum selling at its highest prices, the sulfur disposal process will have less negative revenue, and a majority of the time, the sulfur market should allow for positive revenue on this system. The reason for this is that the price of gypsum is so low that it cannot usually pay for its own transportation costs, let alone the operational and maintenance costs associated with the FGD process. Since gypsum is a major byproduct of one of the largest industries in the country, coal power, the price will not likely climb above fifteen dollars per tonne. Also, the production of gypsum in a conventional power plant far outstrips the production of elemental sulfur in a gasification plant of the same capacity. The hypothetical power plants that we studied produced 125,000 tonnes of gypsum and 22,000 tonnes of sulfur per year, respectively. This entails much higher transportation costs that cannot be recovered by a weak gypsum market. In addition, the cost of mining and transporting the limestone as well as the $6 million per year cost for operation and maintenance of the system factor in to the totals.

The sulfur disposal process is able to take advantage of a much stronger market. Although the supply of sulfur had been growing in the past few decades with steady demand, the price was still at around $40 per tonne in 2007. However, due to an increased demand for fertilizer, combined with market speculation, the price has skyrocketed in the last two years, to $500 per ton. There is no reason to believe that it will remain this high in the future, but it will most likely not return to the low prices of 2007 either. Even at low prices, however, the lower amounts of sulfur generated cut the losses from transportation.

With this information, we would recommend the gasification process over the conventional process from the limited scope provided by an analysis of the sulfur management systems in a single power plant. However, we must make clear the fact that the costs related to sulfur are only a small part of the costs incurred in generating electricity. According to our sponsor, Sargent and Lundy, a 600 megawatt gasification plant costs $600 million more to build than a conventional plant of the same capacity. Even using the highest sulfur prices and the lowest gypsum prices, the difference between sulfur management prices would only be $15 million per year. Assuming a thirty year lifespan, this difference in initial, capital cost could not be made up in sulfur revenues alone. The greatest chance for making the gasification system profitable lies in the implementation of carbon sequestration, combined with carbon taxes from the government. The costs of this system, as well as the possibility of carbon regulation, are being analyzed by Sargent and Lundy.

It is also worth noting that byproducts will never be able to supply a steady source of income for power plants. Both the sulfur and gypsum markets are dominated by byproduct sources. The vast majority of U.S. gypsum comes from coal power plants, and an increasing amount of the country's sulfur supply comes from oil refineries. Byproducts have a tendency to be unstable in markets, specifically because there is no easy way to set a low price. There is virtually no production cost associated with byproducts, and they are often sold simply to avoid the costs of land filling. Also, there is no way to regulate the supply of byproducts, so the market price for byproducts can easily swing with small changes in demand. We can honestly say that sulfur removal will always have higher net revenue than gypsum removal, but there is no way to guarantee any set revenue for either system.

For both byproducts, selling to the market was always more economical than disposal. Clearly this is also better from an environmental point of view. Sulfur is inert when poured into block form, but there is the possibility of powdered sulfur becoming airborne and entering the atmosphere from a landfill, which is exactly what the sulfur removal process is there to prevent. Gypsum is entirely inert, but the sheer quantity of byproduct to be land filled is startling. The 125,000 tonnes of gypsum produced per year would fill an acre to the height of 44 feet. These byproducts are often land filled, especially gypsum, but due to our power plant's location in central Texas, this would not be economical. Due to the relatively short distance to markets or manufacturers (between 100 to 200 miles), as well as relatively high land values and disposal costs, it will always be a better financial decision to sell the byproducts, even if the price for the commodity drops to zero. Closely related to this conclusion is the result that storage is not a feasible option. The cost for basically land filling and removing the large quantities of gypsum would not be covered by a possible $10 or $15 per tonne price increase. For sulfur, the option seemed more reasonable at first. The large swings seen in the sulfur market could make storage a good option. However, it seems as though sulfur is likely at its highest market value right now, and is likely to decrease. Also, if large amounts of sulfur were stockpiled and dumped on the market at a certain price, the market would likely be saturated and drop back down to low values. For either byproduct, the storage option is unlikely to generate more revenue than selling the byproduct at current prices.

We have also taken the opportunity to study the impacts of our research at a larger scale. First we wanted to look at what would happen to the results of our research if we were to use different coal. The lignite that our base case uses is one of two types of coal found in the Texas area where our power plant is located. Another type of coal found in the area is bituminous coal. This coal has a higher BTU value, but also has higher sulfur content. The results of this analysis showed that a switch from low-heat, low sulfur coal to high-heat, high sulfur coal had a large effect on the amount of sulfur produced. Although bituminous (and anthracite) coal is valued for its high heating value (about twice that of lignite), it contains four times as much sulfur per weight. Some power plants have shifted away from bituminous coal to lignite specifically to reduce the amount of sulfur that needs to be cleaned. A switch from Texas lignite to Texas bituminous for a single power plant would increase the sulfur produced by a gasification plant from 21893 tonnes per year to 44752 tonnes per year.

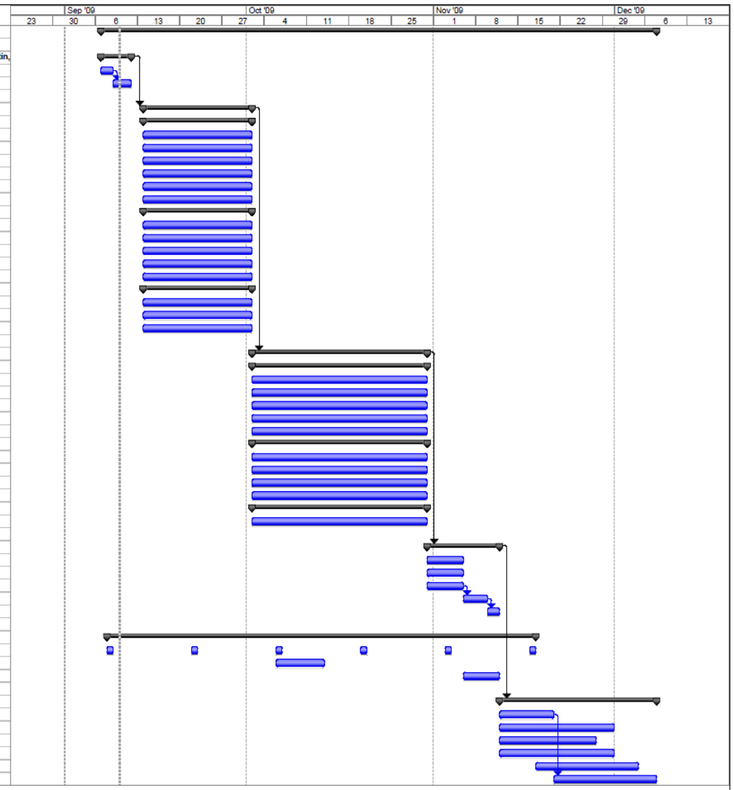
We also looked at the impact on the sulfur market of a large portion of U.S. coal power switching to gasification. Currently, there are very few coal gasification power plants in operation. Most of the sulfur in the market right now comes from oil refineries taking sulfur out of their products. The sulfur market is strong right now, at around 500 dollars per metric tonne. This market is stabilized at around 12 million metric tonnes per year, however, so the addition of elemental sulfur from coal power plants has the potential to drastically change this characteristic. If half of the nation's coal capacity were to switch to gasification, about 8 million metric tonnes would be added to the market. Likewise, if all pulverized coal plants were switched to gasification, there would be around 16 million metric tonnes of elemental sulfur added to the market, more than doubling the supply. Assuming that demand stays fairly level, this addition, even over the course of a decade, could easily bottom out the market for elemental sulfur. When produced as a byproduct, in both oil refineries and gasification power plants, it is cheaper to give away the sulfur than it is to landfill it, which could lead to the market settling out at a value near zero. Another unintended consequence of this would be the rising price of gypsum. Right now, very little gypsum is mined in the US, as the demand can, for the most part, be met by coal byproducts. However, if gypsum were no longer produced by the power industry, there is a possibility that gypsum would once again have to be mined on a large scale in order for the demand in the housing industry to be met. This would be a surprising consequence, as gypsum has always been a relatively cheap commodity. There is even a chance that the elemental sulfur produced by the amine process would be converted to gypsum, if the price of sulfur were lower than the price of gypsum.

The sponsor for our IPRO, Sargent and Lundy, has put a great deal of effort into researching the viability of building coal power plants utilizing gasification technology. Our IPRO has been a small but significant part of this research. However, our IPRO cannot suggest an answer to the final problem, whether or not to start building gasification power plants. The technology behind gasification is proven; however, the economics are not. Our numbers on the cost and environmental impact of sulfur byproducts will help Sargent and Lundy determine what their course of action will be, and potentially whether gasification will be implemented in the future.

Section 6 – Appendices

Original/Projected Team Schedule

ID	Task Name	Duration	Start	Finish	Resource Names
1	**IPRO 302**	**68 days?**	**Mon 9/7/09**	**Mon 12/7/09**	
2					
3	**Project Plan**	**5 days**	**Mon 9/7/09**	**Fri 9/11/09**	**Ryan K,Abe,Brian,Bryce,Greg,Hector,Justin,**
4	Clarify IPRO purpose and goals	2 days	Mon 9/7/09	Tue 9/8/09	
5	Split into subgroups for project plan sections	3 days	Wed 9/9/09	Fri 9/11/09	
6					
7	**Research - Existing Conditions**	**14 days**	**Mon 9/14/09**	**Thu 10/1/09**	
8	**Current coal power and sulfur conditions**	**14 days**	**Mon 9/14/09**	**Thu 10/1/09**	**Bryce,Ryan K,Mike H,Abe,Hector,Justin**
9	Current coal power technology	14 days	Mon 9/14/09	Thu 10/1/09	
10	Conventional powerplant operation	14 days	Mon 9/14/09	Thu 10/1/09	
11	Flue scrubbers/ sulfur removal tech	14 days	Mon 9/14/09	Thu 10/1/09	
12	Form of sulfur generated	14 days	Mon 9/14/09	Thu 10/1/09	
13	Amount of sulfur generated	14 days	Mon 9/14/09	Thu 10/1/09	
14	Profitability of sulfur products vs. cost of removal	14 days	Mon 9/14/09	Thu 10/1/09	
15	**Current markets for sulfur**	**14 days**	**Mon 9/14/09**	**Thu 10/1/09**	**Terrika,Brian,Mike M,Greg,Seun**
16	Cost of sulfur in various forms	14 days	Mon 9/14/09	Thu 10/1/09	
17	Uses of sulfur in various forms	14 days	Mon 9/14/09	Thu 10/1/09	
18	Point of origin for commercial sulfur	14 days	Mon 9/14/09	Thu 10/1/09	
19	Import/Export to United States	14 days	Mon 9/14/09	Thu 10/1/09	
20	Disposal of sulfur	14 days	Mon 9/14/09	Thu 10/1/09	
21	**Current environmental regulation**	**14 days**	**Mon 9/14/09**	**Thu 10/1/09**	
22	Allowable release into atmosphere	14 days	Mon 9/14/09	Thu 10/1/09	
23	Allowable disposal techniques	14 days	Mon 9/14/09	Thu 10/1/09	
24	Fines for pollution	14 days	Mon 9/14/09	Thu 10/1/09	
25					
26	**Research - Future Conditions**	**21 days**	**Fri 10/2/09**	**Fri 10/30/09**	
27	**New Technology**	**21 days**	**Fri 10/2/09**	**Fri 10/30/09**	**Bryce,Ryan K,Mike H,Abe,Hector,Justin**
28	IGCC power plant operation	21 days	Fri 10/2/09	Fri 10/30/09	
29	Amine scrubbers	21 days	Fri 10/2/09	Fri 10/30/09	
30	Other powerplant sulfur removal techniques	21 days	Fri 10/2/09	Fri 10/30/09	
31	Form and amount of sulfur generated	21 days	Fri 10/2/09	Fri 10/30/09	
32	Technology for converting form of sulfur	21 days	Fri 10/2/09	Fri 10/30/09	
33	**Projected Market**	**21 days**	**Fri 10/2/09**	**Fri 10/30/09**	**Terrika,Brian,Mike M,Greg,Seun**
34	New/Growing Uses	21 days	Fri 10/2/09	Fri 10/30/09	
35	New/Growing Sources	21 days	Fri 10/2/09	Fri 10/30/09	
36	Benign Disposal techniques	21 days	Fri 10/2/09	Fri 10/30/09	
37	Possible growth in exports	21 days	Fri 10/2/09	Fri 10/30/09	
38	**Projected regulations**	**21 days**	**Fri 10/2/09**	**Fri 10/30/09**	
39	Allowable disposal/pollution/fines	21 days	Fri 10/2/09	Fri 10/30/09	
40					
41	**Solution**	**9 days**	**Sat 10/31/09**	**Wed 11/11/09**	
42	Estimate market prices for forms of sulfur	5 days	Sat 10/31/09	Thu 11/5/09	
43	Estimate size of markets	5 days	Sat 10/31/09	Thu 11/5/09	
44	Estimate capacity/costs of all sulfur sources	5 days	Sat 10/31/09	Thu 11/5/09	
45	Determine if sulfur will be commodity or waste	2 days	Fri 11/6/09	Mon 11/9/09	
46	Determine most profitable way of dealing with sulfur	2 days	Tue 11/10/09	Wed 11/11/09	
47					
48	**IPRO communications**	**52 days**	**Tue 9/8/09**	**Tue 11/17/09**	
49	**Internal Presentations**	**52 days**	**Tue 9/8/09**	**Tue 11/17/09**	
56	Mid-Term Reviews (10-minute project updates by team	6 days	Tue 10/6/09	Tue 10/13/09	
57	Individual Ethics Reflection Paper	4 days	Fri 11/6/09	Wed 11/11/09	
58					
59	**Final Reports/Presentations**	**19 days?**	**Thu 11/12/09**	**Mon 12/7/09**	**Subgroups TBD**
60	Draft Final Report	7 days	Thu 11/12/09	Fri 11/20/09	
61	Exhibit/Poster	14 days	Thu 11/12/09	Mon 11/30/09	
62	Abstract/Brochure	13 days?	Thu 11/12/09	Fri 11/27/09	
63	Presentation	14 days?	Thu 11/12/09	Mon 11/30/09	
64	IPRO Projects Day	14 days	Wed 11/18/09	Fri 12/4/09	
65	Final Report	12 days	Sat 11/21/09	Mon 12/7/09	



Project: IPRO302
Date: Thu 9/10/09

Task | Progress | Summary | External Tasks | Deadline

Split | Milestone | Project Summary | External Milestone

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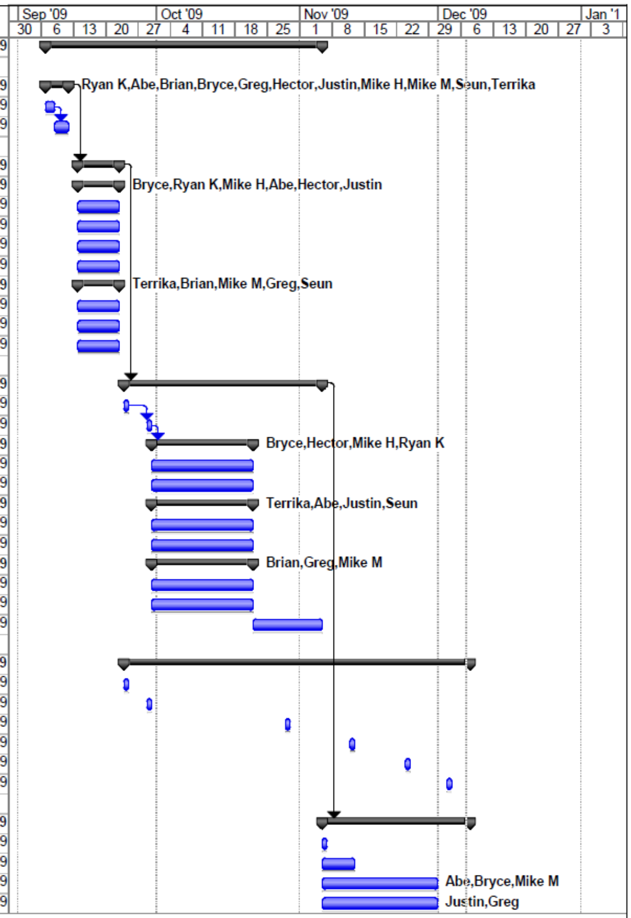
Actual/Final Team Schedule

ID	Task Name	Duration	Start	Finish
1	**IPRO 302**	**45 days?**	**Mon 9/7/09**	**Thu 11/5/09**
2				
3	**Project Plan**	**5 days**	**Mon 9/7/09**	**Fri 9/11/09**
4	Clarify IPRO purpose and goals	2 days	Mon 9/7/09	Tue 9/8/09
5	Split into subgroups for project plan sections	3 days	Wed 9/9/09	Fri 9/11/09
6				
7	**Research - Existing Conditions**	**7 days**	**Mon 9/14/09**	**Tue 9/22/09**
8	**Current coal power and sulfur conditions**	**7 days**	**Mon 9/14/09**	**Tue 9/22/09**
9	Current coal power technology	7 days	Mon 9/14/09	Tue 9/22/09
10	Conventional powerplant operation	7 days	Mon 9/14/09	Tue 9/22/09
11	Flue scrubbers/ sulfur removal tech	7 days	Mon 9/14/09	Tue 9/22/09
12	Amount of sulfur generated	7 days	Mon 9/14/09	Tue 9/22/09
13	**Current markets for sulfur**	**7 days**	**Mon 9/14/09**	**Tue 9/22/09**
14	Cost of sulfur in various forms	7 days	Mon 9/14/09	Tue 9/22/09
15	Uses of sulfur in various forms	7 days	Mon 9/14/09	Tue 9/22/09
16	Disposal of sulfur	7 days	Mon 9/14/09	Tue 9/22/09
17				
18	**New Research Subgroups**	**32 days?**	**Thu 9/24/09**	**Thu 11/5/09**
19	Clarify Purpose/Organization	1 day?	Thu 9/24/09	Thu 9/24/09
20	Split into new research subgroups	1 day	Tue 9/29/09	Tue 9/29/09
21	**Mass Balances**	**16 days**	**Wed 9/30/09**	**Wed 10/21/09**
22	Masses of byproducts in base case	16 days	Wed 9/30/09	Wed 10/21/09
23	Mass of byproducts in implications	16 days	Wed 9/30/09	Wed 10/21/09
24	**Transportation and Disposal**	**16 days**	**Wed 9/30/09**	**Wed 10/21/09**
25	Transportation Costs	16 days	Wed 9/30/09	Wed 10/21/09
26	Disposal costs and regulations	16 days	Wed 9/30/09	Wed 10/21/09
27	**Market**	**16 days**	**Wed 9/30/09**	**Wed 10/21/09**
28	Current market conditions	16 days	Wed 9/30/09	Wed 10/21/09
29	Final revenues	16 days	Wed 9/30/09	Wed 10/21/09
30	In class subgroup presentations	12 days	Thu 10/22/09	Thu 11/5/09
31				
32	**Meetings/Presentations**	**56 days?**	**Thu 9/24/09**	**Mon 12/7/09**
33	First sponsor meeting - clarifying purpose	1 day	Thu 9/24/09	Thu 9/24/09
34	Meeting with GTI representative	1 day	Tue 9/29/09	Tue 9/29/09
35	Proposed meeting date with sponsor	1 day	Thu 10/29/09	Thu 10/29/09
36	Second sponsor meeting - finalizing research	1 day	Thu 11/12/09	Thu 11/12/09
37	Presentation review with Bob Anderson	1 day	Tue 11/24/09	Tue 11/24/09
38	Final meeting with Sargent and Lundy	1 day	Thu 12/3/09	Thu 12/3/09
39				
40	**Deliverables**	**24 days?**	**Fri 11/6/09**	**Mon 12/7/09**
41	Split into deliverables teams	1 day	Fri 11/6/09	Fri 11/6/09
42	Work on presentation for Sargent and Lundy	5 days?	Fri 11/6/09	Thu 11/12/09
43	Poster	19 days?	Fri 11/6/09	Mon 11/30/09
44	Brochure	19 days?	Fri 11/6/09	Mon 11/30/09



Project: IPRO302_final
Date: Mon 12/7/09

Task		Milestone	◆	External Tasks	
Split		Summary		External Milestone	◆
Progress		Project Summary		Deadline	⇩

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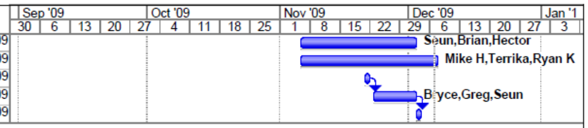
Final Team Schedule Continued

ID	Task Name	Duration	Start	Finish
45	Presentation	21 days?	Fri 11/6/09	Wed 12/2/09
46	Report	24 days?	Fri 11/6/09	Mon 12/7/09
47	Assign presenters	1 day	Sat 11/21/09	Sat 11/21/09
48	Practice Presentation	9 days	Mon 11/23/09	Wed 12/2/09
49	IPRO day	1 day	Thu 12/3/09	Thu 12/3/09



Project: IPRO302_final
Date: Mon 12/7/09

Task		Milestone		External Tasks	
Split		Summary		External Milestone	
Progress		Project Summary		Deadline	

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Stochiometric Calculations

PC Power Plant

Coal Input:
(9,449Btu/Kwh) x (680,000Kw) / (5,968btu/lb) = 1,080,000 lbs Coal/hr

Sulfur Content:
(1,080,000 lbs Coal/hr) * (.0064 lb S/ lb Coal) = 6,900 lbs/hr
(6,900lbs/hr)*(1tonne/2,205/lbs)*(24hr/day)*(365day/hr)*(85%) = 23,000 tonnes 'S'/year

The limestone then reacts with the sulfur dioxide to produce gypsum:

(23,000 tonne S/year) / (32.065 tonne S/tonne mol S) * (1 tonne mol $CaSO_4$*$2H_2O$/ tonne mol S) * (172.2 tonne $CaSO_4$*$2H_2O$ /tonne mol $CaSO_4$*$2H_2O$) = 124,000 tonnes of Gypsum/year

IGCC Power Plant

Coal Input:
(8,515Btu/Kwh) x (710,000Kw) / (5968btu/lb) = 1,010,000 lbs Coal/hr

The Coal is partially burned in an IGCC plant and H_2S is released. This H2S must then be converted through the Claus process to elemental sulfur:

Sulfur Content:
(1,010,000 lbs Coal/hr) * (.0064 lb S/ lb Coal) = 6,500 lbs/hr
(6,500lbs/hr)*(1tonne/2,205/lbs)*(24hr/day)*(365day/hr)*(85%) = 22,000 tonnes 'S'/year

Financial Calculations and Total Revenue

Revenues (in dollars per year)						
				O and M		
		input costs	**input transportation**	**low**	**high**	**output transportation**
PC	**market**	**146,000**	**730,000 (limestone)**	**6,000,000**		**2,688,000**
	disposal					**0 (onsite)**
IGCC	**market**	**0**	**0**	**1,500,000**	**2,000,000**	**237,000**
	disposal					**237,000**
	market revenue			**total revenue**		
disposal costs	**low**	**high**	**swing**	**low**	**high**	
0	**600,000**	**1,900,000**	**1,300,000**	**-8,964,000**	**-7,664,000**	
2,500,00	**0**			**-9376000**		
0	**0**	**10,900,000**	**10,900,000**	**-2237000**	**9163000**	
1,200,000	**0**			**-3437000**	**-2937000**	

		Total Revenue	
		low	**high**
PC	**market**	**-8,964,000**	**-7,664,000**
	disposal	**-9376000**	
IGCC	**market**	**-2237000**	**9163000**
	disposal	**-3437000**	**-2937000**

Team Member Biographies

Abraham Contreras

Abe is in his last semester at IIT, soon to receive a professional bachelor's in architecture. Abe is Chicago born and raised, with two brothers and one sister and being the eldest of the bunch. What he plans to learn from this IPRO is a better understanding of other people's majors and how they go about solving a problem. I expect that this IPRO will involve extensive research and data analysis, as for anything else he couldn't say but he's sure it will be surprise.

Justin Dickman

Justin Dickman is a fourth year Aerospace and Mechanical Engineering student. He possesses good leadership skills and communication skills. He hopes to gain some knowledge of how sulfur is captured from coal processed by power plants and its impacts on the environment. He hopes to also gain a perspective into how a group project works in the engineering industry.

Gregory Enadeghe

Gregory Enadeghe is a 4th year chemical engineering student with a strong interest in a business minor. He is learning advanced knowledge of chemical processes and marketing strategies. He hopes to get a deeper understanding of the day-to-day of industries like coal plants. Gregory is a quick learner and unafraid to take on leadership responsibilities. He thinks unconventionally and is always a good analytic board to bounce ideas off of.

Hector Garza Rodriguez

Dedication and hard work will be the two most important things that can be contributed to the project. The one thing that I want to develop is communication with all team members in order for me to learn new things about them and they learn some things about me. Economic, environmental, and industrial impacts will be learned during the development of this project. I think that this project has a lot of potential because it analyzes future technologies that can improve our environment.

Michael Haddad

Michael's bachelor's degree is in physics and he is currently in his last semester of graduate studies in the Industrial Technology and Manufacturing Operations program. He has prior professional experience working in laboratories (semiconductor and materials science) but much of the time between his two degrees was spent in sales. He prefers to work in a creative capacity geared towards innovation. He expects that this project will produce useful information for Sargent and Lundy, as well as, invaluable interdisciplinary experience for himself.

Ryan Kyle

Ryan's strengths are his hard work and dedication to tasks that need to be done and his knowledge of chemical engineering.

Ryan hopes to gain knowledge of sulfur capture technologies as well as building his teamwork skills by participating in IPRO 302.

Michael Mongillo
Michael Mongillo is a third year Applied Mathematics major. He has strong research and analytic skills. Over the course of this IPRO he will learn to effectively report and present research to a group of fellow researchers. He expects to research an interesting question of how to effectively make use of a new technology.

Ryan Murphy
Ryan Murphy is a fifth year architecture major and electrical engineering minor. Because of his experience in the Architecture and ECE departments, he is able to see problems from multiple viewpoints. He is also skilled in presenting and preparing graphics. Over the course of this IPRO, he will learn how to effectively manage a group of people from different backgrounds for a single purpose. He expects this to be a challenging but rewarding experience for real world situations.

Bryce Swillum
Bryce is a 4th year chemical engineer already possesses a basic knowledge of the unit operations involved in sulfur capture and coal plant operation. Bryce looks to expand this knowledge and to identify the economic impacts involved in sulfur production from its extraction in the plant. Bryce expects to gain this knowledge and hopes this project will provide Sargent and Lundy with the necessary information to make a well advised decision on the future of the coal-fired/gasification power plants.

Oluwaseun Shonubi
Strengths: working in a team, affinity to learn new things, power system analysis
Needs: knowledge of a better understanding of how power systems work.
Expectations: to better understand the different technologies of sulfur capture in coal based power plants and to understands the markets for sulfur. He's from Nigeria, loves IIT and has interests in soccer, facebook, the economy (stocks and all), Power systems and electricity markets I intend to go ahead and do a Masters and PhD in the field Electrical Engineering with concentration in Power system optimization and specialization in Electricity markets.

Brian Wolber
4th year business major, specializing in Entrepreneurship.
Plan to pursue a career in the energy industry.

Terrika Worthon
Terrika Worthon is a fifth year Mechanical Engineering student. She possesses good communication skills and a non bias approach when tackling different problems. She hopes to gain knowledge about the different Sulfur capture technologies available along with investigating the beneficial usage of sulfur by-products in society.

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