

2a. Identification and Significance of the Problem, and Technical Approach

The Clean Air Act of 1990 listed 189 substances as hazardous air pollutants (HAP). Eleven of the 189 are trace metal species and mercury is one of greatest concern. During coal combustion, most of the mercury is transferred into the vapor phase due to its high volatility. Furthermore, the currently used pollution control technologies are not capable of controlling gas-phase mercury emissions. The Environmental Protection Agency recently issued a comprehensive 1,700 page technical report evaluating human and environmental impacts from air emissions of mercury. Major sources of the 159 tons of mercury emitted annually to air in the U.S. are coal fired utilities, municipal solid waste incinerators, medical waste incinerators, commercial and industrial boilers, and chlor-alkali plants.¹ Most human mercury exposure is due to consumption of contaminated fish. In fact, mercury is the largest cause of U.S. fishing advisories that eating fish from certain waters can be hazardous to health; it bioaccumulates easily in aquatic environments.

Mercury emissions from a typical 500 megawatt plant are about 500 pounds annually, which translates to about 1 ½ pounds per day. Mercury primarily consists of two species, Hg and HgCl₂, and most of the HgCl₂ will adsorb on the fly ash and be captured in electrostatic precipitators or flue gas desulfurization systems. Elemental mercury, however, is released to the atmosphere unless special pollution control technology is employed.

Studies at Argonne National Laboratory on mercury control technology by Livengood et al² have surveyed the use of dry sorbents and wet scrubbers. They concluded that elemental mercury removal is enhanced by the addition of activated carbon with chemical treatment of the carbon (sulfur or CaCl₂) greatly enhancing the removal capacity. In another mercury emission study by Hwang³, several techniques were considered for reducing mercury from flue gases such as metal amalgamation, liquid scrubbing, and sorbent adsorption. Adsorption was the most promising technique.

Injection of activated carbon into the flue gas, upstream of the particulate control system, has the potential of providing a low cost method for control of mercury. The low concentrations of mercury in the flue gas and short exposure time (<4 seconds) of the sorbent make large amounts of carbon relative to mercury necessary. More specifically, to achieve mercury removals in excess of 90%, the weight ratio of carbon to mercury (C/Hg) needed has been found to be 3000- 20,000, depending on the process conditions.⁴

Several recent studies on mercury control using carbon-based adsorbents^{5,6} have concentrated on increasing adsorption capacity, by impregnating with sulfur, chloride or

other chelating agents. The mercury capacity of sulfur-impregnated carbons (such as Calgon HGR) seems to be relatively high. Based on stoichiometry of HgS formation, the carbon could hold 0.6gram Hg per gram of carbon adsorbent. Chen et al⁴ has observed that the high carbon/Hg ratios required for the dry sorbent injection process could be the result of either low mercury capacity of the carbon or mass transfer limitations from the bulk flue gas to the external surface of the carbon sorbent. Their analysis concludes that mercury transfer plays a very important role in the process. For example, to achieve 90% mercury removal, the minimum carbon/mercury weight ratio is about 13,000 for 10nm particles, at 3 seconds residence time. The appears to be significant technical opportunity to improve this situation and is the motivation for the proposed research by Mega-Carbon Company.

Mixing and contacting of the mercury-containing flue gas is one area that can be improved upon. The fluid mixing pattern for the carbon sorbent injection process can be viewed as a perfectly mixed tank. As pointed out by Levenspiel⁷, this mixing situation does not lend itself to high removals when the rate process depends on concentration such as film mass transfer (first-order process); the vessel contents and exit stream are identical which reduces the overall driving potential for mass transfer. To achieve high mercury removal efficiencies, a plug situation is desirable. The fixed bed adsorber is a good example and is the opposite mixing situation from a perfectly mixed tank; it requires the flue gas to flow past a stationary carbon adsorbent rather than the powder flowing along with the fluid phase.

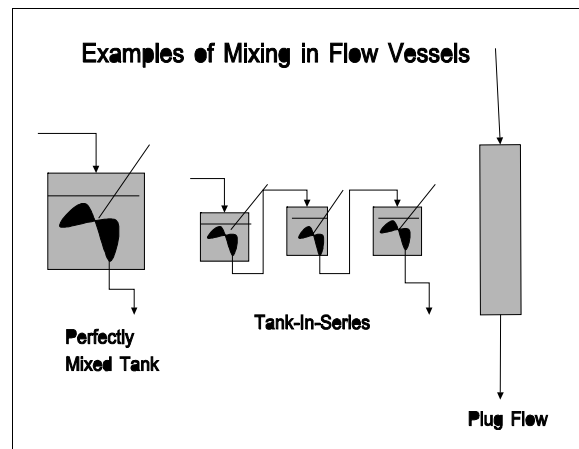


Figure 1

Somewhere between these two mixing extremes would be a tank-in-series process, which would be achieved by having multiple carbon injection ports staged along the flue. Although the carbon powder would still flow with the flue gas, the driving potential for mass transfer would be higher resulting in lower carbon/mercury ratios to achieve a specified mercury removal. Mega-Carbon thinks that a fixed bed adsorber would be highly preferred to achieve high mercury removals since a plug flow reactor is routinely used for situations requiring high conversion-per-pass. Also the removal of very low levels of mercury (10-50 $\mu\text{g}/\text{m}^3$) gas has similarities to the removal of trace contaminants in drinking water; a fixed bed carbon adsorber is used and a mass transfer zone moves along the column with essentially 100% removal of the trace chemicals until "break-through" occurs.

Enhancement of mass transfer is the second area that Mega-Carbon intends to study in the proposed program. Data suggest that transfer of mercury from the flue gas to the external surface of the carbon sorbent is slow, or possibly a rate-limiting step. The mass transfer rate equation is frequently written as:

$$N_A = k_g A \Delta C_A$$

where N_A = rate of mass transfer ,moles/time
 k_g = mass transfer coefficient
 A = transfer area of bed
 Δc = concentration gradient

The mass transfer coefficient, defined by the above equation, can be approximated by the diffusion coefficient divided by the boundary layer thickness($k_g = D_{A,B}/\delta$). Mercury has a very low diffusion coefficient since it is heavy, with low velocity; this helps to explain why the mass transfer rate is typically low. The carbon sorption injection process causes very little slip between flue gas and the small carbon particles which keeps the boundary layer thickness high. However, in a fixed bed adsorber, the carbon sorbent is held stationary with the flue gas passing around the surface. This leads to a thinner boundary layer and higher mass transfer rates. We recognize that the fixed bed adsorber produces higher pressure drop than the carbon sorbent injection process so the appropriate balance between mass transfer rate, sorption capacity, and pressure drop will be addressed this study. Mega-Carbon has developed bonding technology to make activated carbon blocks and monoliths, which we believe will improve mercury removal from flue gas. Furthermore, we have been actively working with a major automotive company on the development of gasoline vapor canisters using carbon block adsorbents, and we have developed strategies already for balancing adsorption performance with pressure drop constraints.

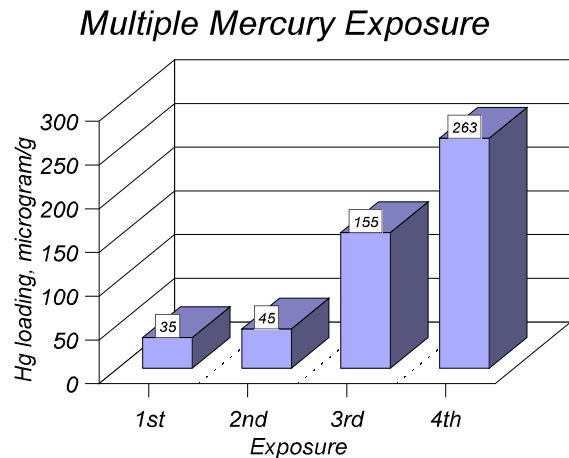
Technical Approach

The main purpose of this proposal is to develop a carbon-based adsorbent system that eliminates the deficiencies of the current technology, specifically injection of fine carbon sorbent into the flue gas. These deficiencies include:

- Elemental mercury removal is limited to around 50%
- Low mercury loadings on the solid sorbent
- High carbon to mercury ratios required (3,000-20,00 by weight)
- Capture and disposal of carbon sorbent following mercury adsorption

The technical approach will be to develop a higher capacity carbon sorbent along with a flue gas contacting device which will promote rapid transfer of mercury from the flue gas to the external surface of the sorbent. Vadic⁵ has demonstrated that sulfur-impregnated carbon is effective and may have much higher mercury loading capacity than it initially appears to have. The Calgon HGR carbon was subjected to multiple exposures of mercury containing gas over an eight day period. After breakthrough of mercury in the fixed bed of carbon, the flow was stopped and the adsorption bed held at 140°C. Four mercury loading steps were used and are shown in the bar graph.

Pore diffusion limitations, possibly due to diffusion of mercury in the molten sulfur, are probably responsible for this effect. This carbon sorbent behaves much like a “shrinking-core” model frequently used to model solid-gas reactions like burning coal or wood.



Since liquid diffusion is limiting the mercury holding capacity, we believe the pore structure of the carbon sorbent should be different from that currently used. Approaches include:

- Identify other carbons with a more open structure, particularly with macropore (diameter > 1000Å⁰) feeder pores in combination with smaller mesopores (20Å⁰ <diameter< 1000Å⁰)
- Modification of existing activated carbons via additional activation and pore enlargement.
- Better impregnation so that sulfur, etc is uniformly distributed in a monolayer on adsorbent surface.

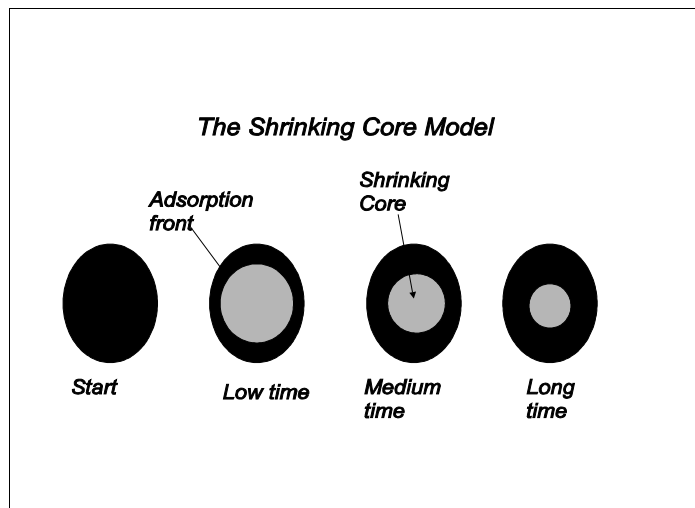


Figure 3

Potential candidates for new types of adsorbent carbons may be derived from those now used for capturing gasoline emissions from automobiles (Westvaco WV-A1100). The second way to do this is to modify existing

commercial carbons by further thermal activation with air and steam or chemical activation with reagents like phosphoric acid or potassium hydroxide. Furthermore, researchers at the ICCI have developed new activated carbons, based on Illinois coal, which will outperform commercial impregnated carbons, while these new carbons contain no adsorbent promoters. It appears that these improved mercury sorbents are based on better pore distribution, which is tailored for this application. Finally, the impregnation of carbon sorbents seems to offer many opportunities for improvement. Vidic⁵ showed that higher impregnation temperatures (600°C versus 250°C) would improve mercury holding capacity while maintaining most of the original surface area of the starting carbon. Young⁶ has investigated iodated active carbons and found them to be quite effective and exceeding sulfur-impregnated carbon.

The second major thrust of the technical program will be to develop a flue gas contacting device which promotes rapid mass transfer to the surface of the carbon sorbent. The basic approach is to use a solid carbon block with multiple flow channels in it. Mega-Carbon has been developing adsorbent carbon blocks to control gasoline vapor emissions with a major automotive company. The bases of this technology are two patents that will be granted to Mega-Carbon in a few months on a novel bonding technology.

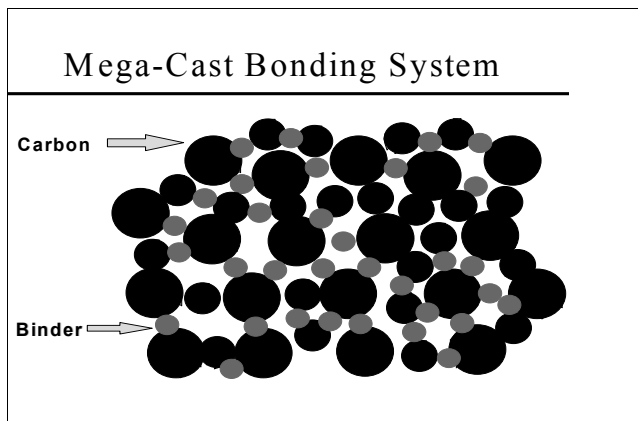


Figure 4

A bonding process called Mega-Cast has been developed to bond carbon powders and granules into adsorbent blocks. Two patents have been granted on this technology. What makes Mega-Cast bonding unique is that very little of the adsorption capacity is lost due to pore plugging. The illustration of the bonded carbon in Figure 4 is one way to view the process with the carbon particles bonded at various points by a polymer binder. Carbon particles are shown darker and are bonded by the polymer droplets shown in the lighter shade. Every carbon

is different and adjustments are always necessary in the formulation. Blocks can be cast routinely but extrusion is a special challenge and requires additives to impart desired rheological properties and stabilization of the slip.

To prepare a carbon adsorbent block, a carbon slip is first prepared with a polymer binder. There are two types of binders, one suitable for temperatures in the range of 200 °C and the other a higher temperature version which retains its strength at temperatures as high as 350 °C. The carbon slip can be prepared from either powder or granules and is then extruded, slip-cast, or compression molded to a variety of shapes(blocks, cubes, etc.). The binder cures at modest temperatures, eliminating the need for high temperature

calcination and most of the adsorption capacity is preserved. The use of compression during the forming process translates into higher bulk densities and will frequently lead to adsorption capacity per unit volume. Dynamic performance of the carbon blocks depends directly on how the block is formed, flow channels, and type/size of starting material. Most importantly, there are cases where the bonded carbon is noticeably better than a granular bed. Pressure drop of the carbon block depends on the form of the starting carbon and the incorporation of flow channels.

Mega-Carbon Company believes it has the capability to solve the present technical shortcomings which are impeding commercialization of mercury emission control on coal-fired power plants. Mega-Carbon believes it can use the following technical approach to successfully solve the problem:

- Mega-Carbon plans to develop improved activated carbon sorbents which have a pore size distribution that will facilitate diffusion from the external surface to the inside of the carbon sorbent.
- Mega-Carbon will develop a better flue gas contacting device so that external mass transfer limitations are reduced with a corresponding reduction in the extremely high C/Hg ratio required.
- Mega-Carbon will apply their proprietary bonding technology to developing the flue gas contacting device for producing carbon blocks.
- Mega-Carbon will apply their significant background in catalysis/adsorption to improving the impregnation procedure and surface modification of the carbon sorbents

In summary, Mega-Carbon has a unique mix of technologies and materials which will allow us to develop an improved carbon sorbent for capturing mercury emissions.

2b. Anticipated Benefits

The development of an improved technology to significantly reduce mercury vapors for the flue gas of power plants and municipal solid waste incinerators will have a major impact on the health of our US population, while sustaining an enhanced global environment.

The US has clearly made the commitment to generate electrical power from plants based on fossil energy, notably coal, rather than nuclear power. With this direction, it is important to mitigate the toxic effects associated with coal combustion, specifically mercury emissions. The electric power industry will benefit the most from the advances derived by

this study by retrofitting their coal-fired boilers with this novel adsorbent technology. The bioaccumulation of mercury in fish will be reduced, particularly in the Great Lakes, and make consumption of fish in these waters no longer a concern. The final commercial process will probably be a carbon block adsorption module that is either placed inside the flue of power plants or MSW incinerators as a post-treatment adsorption unit that the flue gas is directed into. The potential market for this technology is huge, since practically any coal-fired utility will be interested in installing. As mentioned earlier, about 159 tons of mercury are emitted to the air annually. Mega-Carbon believes they have the technical capability to apply their knowledge in catalysis, adsorption, and their proprietary bonding technology to make the proposed project become a commercial reality. The successful completion of the Phase I program will allow process demonstration in Phase II in a small flue gas test module. In Phase II, Mega-Carbon expects that we will collaborate with other DOE contractors who have access to larger flue gas test units. Furthermore, we would expect to perform tests on commercial units, both for coal-fired power plants and MSW incinerators, which have distinctly different levels of mercury emissions.

3. The Phase I Project

3a. Technical Objectives-Phase I

Phase I is critical in establishing the technical feasibility of a highly improved flue gas treatment technology for reducing mercury emissions. We will approach this problem by improving the carbon sorbent, i.e. mercury loading capacity, and how it should be used in a flue gas contacting device. The following questions will be addressed through this effort.

- How can the capacity of the carbon sorbent be increased through alteration of pore size distribution and impregnation of reagents such as sulfur, iodine, etc?
- What type of flue gas contacting device will allow high transfer rates of mercury with low pressure drop ?
- What is the preferred activated carbon sorbent system to use for mercury removal from flue gas ?
- What are the best process conditions to use for operation of this mercury control technology ?

Objectives

The following objectives for Phase I will address the questions listed above:

1. Characterize the carbon sorbents currently used for mercury control and identify key differences in pore size distribution and surface properties.
2. Modify pore structure of activated carbons through post treatment with thermal and chemical activation.
3. Increase the mercury holding capacity of the carbon sorbents by combining the best physical structure (i.e. pore size distribution) with reagent impregnation.
4. Develop flue gas contacting devices by binding carbon sorbent powders/granules into blocks with Mega-Carbon bonding technology, with subsequent introduction of flow channels.
5. Identify the best process conditions to remove mercury vapors using the flue gas contacting device, specifically the preferred temperature, geometric shape of the contacting device and flow channel configuration.

3b. Phase I Work Plan

The work to be performed consists of four tasks with collaboration by Dr. David Livengood at Argonne National Laboratory for a portion of the program in Task 1. The total project cost is \$75,247 (Line I of budget page) so Mega-Carbon will cost share \$461 to reduce the total requested (Line L of budget page) to \$74,786. Mega-Carbon will donate 8 hours (at \$55/hr rate) of the Principal Investigator's time which is equivalent to \$461. The four tasks include:

- Task 1- Characterization and Modification of Active Carbons (collaboration with Argonne National Laboratory)
- Task 2- Development of High Capacity Carbon Sorbent
- Task 3- Development of Flue Gas Contacting Device
- Task 4- Final Report Preparation

Details of the work to be performed are now given in the following tasks and subtasks:

Task 1. Characterization and Modification of Active Carbons

Subtask 1.1-Characterization of Active Carbons

A number of active carbons, both commercial and developmental, have been studied as potential sorbents for removing mercury from flue gas. It is our intention to obtain these and then establish their surface area and pore size distribution via BET nitrogen sorption and mercury porosimetry. Furthermore, we will obtain used samples of carbon sorbent to establish how the adsorbed mercury is distributed throughout the particle. Some of the samples that we plan to analyze include:

Carbon Samples for Surface Analysis

Sample	BET area	Pore distribution	Mercury profile
Calgon HGR	X	X	
Calgon HGR (used)	X	X	X
Norit FGD	X	X	
Calgon BPL	X	X	
Calgon BPL/S impreg	X	X	
Calgon BPL/S impreg (used)	X	X	X
Calgon FLUEPAC™	X	X	
Westvaco WV-A1100	X	X	

The first two carbons, Calgon HGR and Norit FGD, are currently used for controlling mercury emissions in the carbon sorbent injection process and fixed bed adsorption. Calgon BPL, impregnated with sulfur, has been studied in some detail by Vidic⁵ in a fixed bed adsorber in a DOE sponsored study. The last two carbons, Calgon FLUEPAC™ and Westvaco WV-A1100, have not been reported on widely, if at all, in the literature, but seem to have potential and are included. Most of the surface analysis will be subcontracted to Argonne National Laboratory, since they have extensive analytical capabilities.

Subtask 1.2 Modification of Active Carbons

The pore size distribution of active carbons can be modified significantly by post-treatment with various reagents and then chemical activation. Greinke⁸ and Jagtoyen⁹ describe the use of phosphoric acid impregnation to a cellulose precursor which will make a high surface area carbon. Baker¹⁰ describes a post-treatment of active carbon with potassium hydroxide to produce an extremely high surface area carbon. Research suggests that the carbon sorbent needs to be a more open pore structure. This will reduce pore diffusional limitations and utilize more of the carbon particle, rather than the “shrinking core” effect when the adsorption front moves slowly from the outside to the center. We plan to chemically activate carbons and the table summarizes the starting materials and reagents.

Post-Treatment of Carbons

Starting Materials	Activating Reagents
Wood-based carbons, Westvaco	zinc chloride
Coal-based carbons, Calgon	phosphoric acid
coconut shell char ¹	potassium hydroxide

Task 2. Development of High Capacity Carbon Sorbents

To achieve high mercury capacity, we believe that a careful balance between pore size distribution and mercury capture reagents must be maintained. Livengood² has pointed out that chemical treatment of active carbon with sulfur or CaCl₂ increases the capacity for mercury, while Young⁶ identified iodated carbon as an effective sorbent for mercury control. Based on these facts, Task 2 of the proposed project will consist of:

Subtask 2.1 Carbon Impregnation with Reagents

The information from Task 1 will help to identify which activated carbons are good candidates to impregnate. Specifically, we will be interested in carbons with a bimodal pore size distribution, containing both mesopores (20 Å < diam < 1000 Å) and macro feeder pores (diam > 1000 Å). The set of impregnating agents we will be using include sulfur, CaCl₂ and KI and we plan to vary impregnation temperature for sulfur and surface coverage (loading) for the other two.

Since the melting point of sulfur is 112.8 °C, it will be a thin liquid film on the pore walls at adsorption conditions; it is important to not allow sulfur to form larger globules since this situation prevents access to the entire pore. Consequently, extreme care must be taken in the sulfur impregnation when it is

vaporized and coated on the carbon surface. The other two reagents, CaCl_2 and KI , have high melting points and do not require the same consideration.

Subtask 2.2 Mercury Adsorption Tests

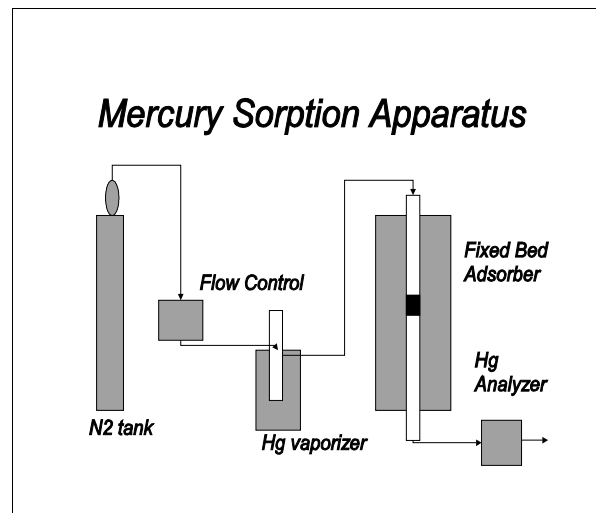
A fixed bed adsorption unit will be used to evaluate the carbon samples for mercury removal. Flue gas will be simulated by flowing nitrogen carrier gas through a mercury permeation cell submerged in a temperature controlled bath. This will allow us to simulate mercury levels in both a power plant flue gas ($50\mu\text{g}/\text{m}^3$) and MSW incinerator ($500\mu\text{g}/\text{m}^3$). A continuous mercury analyzer (atomic adsorption spectrophotometer) will be used to measure mercury concentration in the inlet and outlet of the adsorption unit; break through curves for mercury will be used to evaluate the performance of the carbon sorbents. A flow diagram is shown on the right for this small test apparatus. We expect that experiments will last as long as 3-4 days, but break through can occur as early as 3 hours on stream. This test will only use 100- 250 mg of carbon in a glass tube to be maintained at 140°C . Inlet and outlet lines will be comprised of Teflon to prevent mercury loss to the tube walls. The small sample size will be convenient and efficient for exploring numerous variations and their subsequent evaluation.

Task 3. Development of Flue Gas Contacting Unit

Subtask 3.1 Preparation of Flue Gas Contacting Unit

The flue gas contacting unit will be aimed at improving mass transfer of mercury to the adsorbent surface by having a stationary carbon sorbent with flue gas passing through and around it. A fixed bed adsorber is the most familiar unit to accomplish this, but sometimes introduces pressure drop limitations. Pressure drop in fixed beds, described by the Ergun equation, depends on particle dimensions (diameter and shape), bed properties (void fraction and length), and fluid velocity through the bed.

Another type of contacting device which has favorable mass transfer characteristics is a monolith, which in our particular case, could be a carbon



block with axial flow channels. Mega-Carbon has developed several variations of this concept for use in canister to control gasoline vapor emissions. The carbon monolithic block has a number of advantages over the conventional fixed bed unit. First, higher adsorption capacity per unit volume is usually realized when the carbon is compression cast during the forming process. Second, the pressure drop can be controlled by axial flow channels, varying size, hole density, and hole length. Finally, the carbon monolithic block is abrasion resistant with no grinding motion that the adsorbent granules will exhibit.

The final type of contacting device that shows potential is an activated carbon fiber composite described by Kimber¹¹. The composite is made by slurring chopped carbon fiber with phenolic resin, and then formed into a porous cylindrical mat. The pressure drop is not very high and the adsorption capacity is relatively high and can be enhanced by further activation with steam. These composites can also be impregnated with reagents, similar to granular carbon. Mega-Carbon will prepare specimens of the bonded carbon blocks and the activated carbon fiber (ACF) composites. Pressure drop will be controlled by introduction of axial flow channels in these two types of gas contacting devices. The experimental summary of samples that we will prepare is given below:

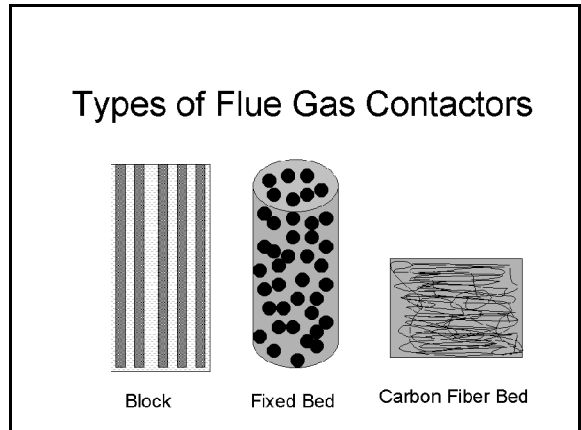


Figure 6

Parameter	Experimental Approach
Carbon Form	Carbons from Task 2 that exhibited high performance will be used for the carbon block specimens. Carbon fiber composites derived at low and high post activation will be used.
Flow Channels	Axial flow channels, varying diameter, hole density, and length.
Reagent Impregnation	Impregnated with sulfur and other reagents as well as no impregnation.

Subtask 3.2 Performance of Flue Gas Contactor

Performance of the flue gas contactor will be evaluated by modifying the sorption apparatus described in Subtask 2.2. Because the samples will be about 100 times larger, (i.e. 25 grams), a higher range flow controller and equipment housing the carbon sorbents will be scaled up appropriately. Additionally a differential pressure gauge will be installed across the flue gas contactor to monitor pressure drop. Since mercury has a tendency to react with metal surfaces, we plan to use either quartz or Teflon lined stainless steel for the heated flue gas contactor. All other inlet and outlet lines will employ Teflon tubing. The two most important performance indices are:

- Mercury adsorption capacity
- Pressure drop across the flue gas contactor

Three types of contacting devices will be evaluated and include the conventional fixed bed of granules (as a base case), carbon block monolith, and the carbon fiber composite. The experiment will be performed by first bypassing the mercury vaporizer and only flowing nitrogen through the adsorption unit at low, medium, and high flow rates; this part of the experiment will provide a relationship between pressure drop and flow rate. Then the flow will be adjusted to a mid-range value and passed through the mercury vaporizer to start the adsorption test. Mercury concentration in the outlet will be monitored and recorded to develop breakthrough curves. In addition to testing all of the flue gas contacting devices (fixed bed + specimens from Subtask 3.1), we plan to vary adsorption temperature and identify the preferred conditions to operate the unit for maximum mercury removal. A base temperature of 150 °C will be used for the standard test with variations around that value.

Task 4. Final Report Preparation

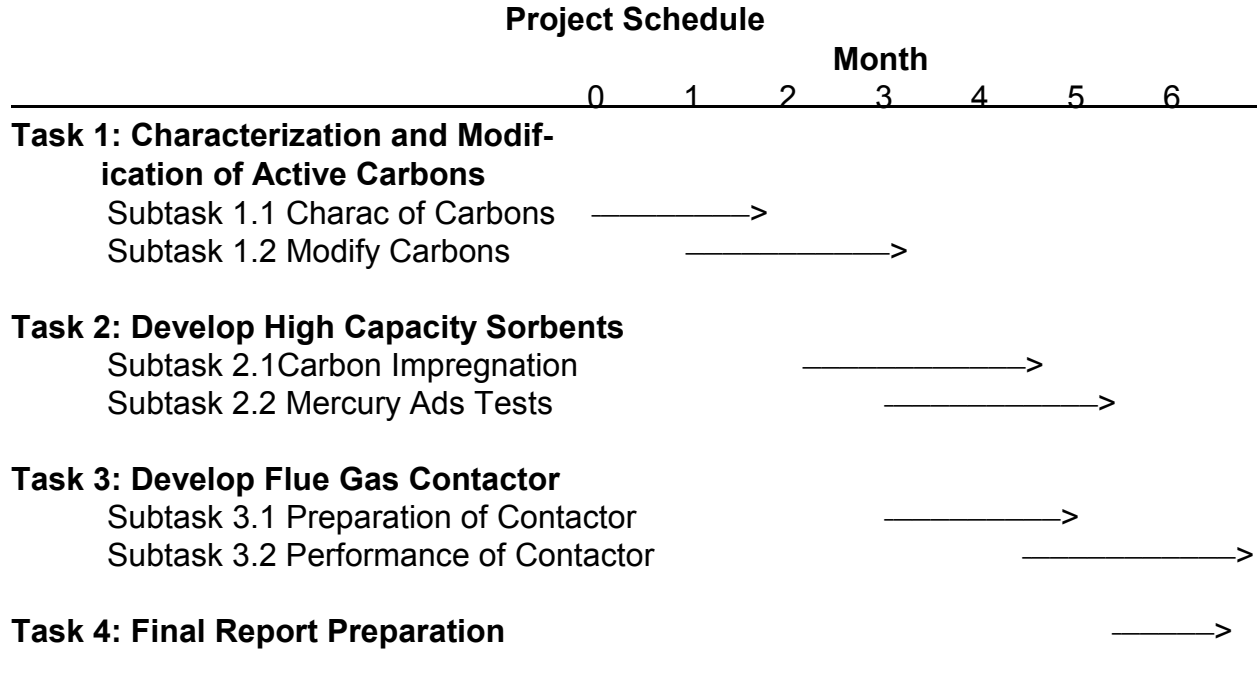
A final report will be prepared summarizing and analyzing the data for the carbon forming and natural gas adsorption tests. We plan to keep the analysis and monthly reporting very current so that this task will not involve excessive time.

3b. Phase I Performance Schedule

Task 1 to be completed 2 ½ months after start of work.

Task 2 to be completed 4 ½ months after start of work.

Task 3 to be completed 5 ½ months after start of work.
Task 4 to be completed six months after start of work.



3c. Related Research and Development

ADA Technologies is working on a DOE project¹² entitled “ Novel process for removal and recovery of vapor-phase mercury” which is based on supported noble metals such as gold and platinum. It is tailored for municipal waste incinerators which have higher levels of mercury than coal-fired power plants and the substrate materials are not carbon-based and include ceramic and metallic monoliths. The proposed work by Mega-Carbon is related in some ways but still significantly different and needed to develop a viable means to control mercury emissions from coal-fired power plants.

3d. Principal Investigator and other Key Personnel

Dr. David F. Tatterson (Principle Investigator)

1969 BS Chemical Engineering - Carnegie-Mellon University, Pittsburgh, Pennsylvania

1972 MS Chemical Engineering - University of Illinois, Urbana, Illinois
1974 Ph.D. Chemical Engineering - University of Illinois, Urbana, Illinois

EXPERIENCE

Business Development

1996 to *Marketing Business Unit*
present *Amoco Petroleum Products Sector*
Manager Business Development

Develop external business for Amoco's Automotive Research Laboratory in Naperville, IL. Responsibilities include business plan development, establish business processes and customer base development. Revenues for 1997 totaled \$3.0 million.

1994 to *International Business Development*
1996 *Amoco Petroleum Products Sector*
Marketing Consultant

Provide leadership to Amoco's efforts to enter the China petroleum product market. Co-leader of a team to develop a marketing joint venture with a Chinese Provincial Oil Company. Supported gasoline, motor oil and convenience store market entry efforts in Mexico, Turkey, Russia and Brazil with marketing research and assessment.

Marketing

1990 - 1994 *Amoco Oil Company, Chicago, IL*
Director of Marketing Research

Responsible for managing the development and execution of all marketing research in support of Amoco Oil's marketing efforts. Provided consulting services to Amoco Oil management on customer opinions and perceptions of Amoco and competitors.

1988 - 1990 *Amoco Oil Company, Chicago, IL*
Senior Specialist - Marketing Research

Responsible for developing and executing market research projects aimed at developing gasoline product strategies and promotions.

R&D and Technical Experience

1980 - 1988 *Amoco Oil Company, Naperville, IL*
Research Supervisor

Supervised research and development groups in the areas of synthetic fuels process development, remote natural gas utilization and economic evaluations.

1974 - 1980 *Amoco Oil Company, Naperville, IL*

Research Engineer

Responsible for specific projects aimed at refining process improvement, catalyst development and synthetic fuels development.

Published numerous articles in refereed professional journals and professional meetings, see attached list. Received eight US Patents, see attached list.

AFFILIATIONS

American Institute of Chemical Engineers
Marketing Research Conference Board
Industrial Advisory Board, Marketing Department, DePaul University
Society of Automotive Engineers

Patents Awarded

1. Catalyzed Vapor Phase Process for Making Alcohols, US Patent 5,364,979, Nov. 1994. (C. A. Radlowski, G. P. Hagen, L. E. Grimes)
2. Oil Stabilization, US Patent 5,059,303, Oct. 1991 (with J. L. Taylor, A. L. Hensley and J. M. Forgac)
3. Oxidative Coupling Process for Converting Methane and/or Natural Gas to More Transportable Products, US Patent 5,015,799, May, 1991. (with R. H. Walker, P. A. Willem, G. A. Huff, L. E. Grimes, and R. L. Melberg)
4. Shale Oil Stabilization with a Hydrogen Donor Quench and a Hydrogenation Transfer Catalyst, US Patent 4,536,277, Aug. 1985. (with T. M. O'Grady and R. Coates)
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7. Fluid Catalytic Cracking of Heavy Petroleum Fractions, US Patent 4,298,459, Nov. 1981. (with W. D. Ford)
8. Fluid Catalytic Cracking of Heavy Petroleum Fractions, US Patent 4,280,898,

July 1981.(with I. A. Vasalos)

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2. Feedstock Effects in Coal Flash Pyrolysis, I&EC Research, Vol. 29, P. 2154, 1990. (with K. K. Robinson, R. Guercio and T. L. Marker)
3. Preliminary Analysis of Upgrading Alternatives for the Great Plains Liquid By-Product Streams, Presented at the AIChE Summer National Meeting, Denver Col., Paper 52e, August 1988. (with L. Sault, J. Fox, M. W. Furlong, and J. Masin)
4. Nickel and Vanadium Interactions on Cracking Catalyst, I&EC Research, Vol. 27, P. 1595, 1988. (with R.L. Mieville)
5. Coal Flash Pyrolysis in a Free Jet Reactor, I&EC Research, Vol. 27, P. 1606, 1988. (with K. K. Robinson, T. L. Marker and R.Guercio)
6. Comparative Economic of Methanol and Gasoline, SAE Technical Paper, Presented at the International Fuels and Lubricants Meeting and Exposition, Toronto, Ontario, Nov. 1987. (with T. O. Wagner)
7. Particle Effects on Free Jet Entrainment, Canadian Journal of Chem Engineering, Vol. 65, June 1987. (with T. L. Marker and J. M. Forgac)
8. Application of a Bhatia-Epstein Model to the H-Coal Fluidized Bed Reactor, Presented at the AIChE Annual Meeting, Chicago II, Nov. 1980. (with I. A. Vasalos, D. N. Rundell and E. M. Bild)
9. Experimental Techniques for Studying the Fluid Dynamics of the H-Coal Reactor, Coal Processing Technology, Vol VI, AIChE Publication, 1980. (with I. A. Vasalos and E. M. Bild)
10. Drop Sizes in Annular Gas-Liquid Flows, AIChE Journal, Vol. 23, No. 1, P. 68,

January 1977. (with J. C. Dallman and T. J. Hanratty)

11. Rates of Atomization and Drop Size in Annular Two-Phase Flow, PhD Thesis, University of Illinois, Dec. 1974.
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Dr. Ken Robinson

D.Sc. Ch.E. 1970, Washington University-St. Louis

M.S. Ch.E. 1964, University of Michigan

B.S. Ch.E. 1963, University of Michigan

Experience-

10/93-present: Mega-Carbon Company, President

10/93-present: Northwestern University, Lecturer

10/93-10/96: California Institute of Technology, Ass Director-Corporate Relations

04/93-10/93: Argonne National Laboratory, Ass Director-Technology Transfer

11/89 -04/93: Amoco Corporation Manager, Technical University Relations

11/84-01/89: Amoco Oil Company, Res and Devel , Research Associate

01/80-11/84: Standard Oil (Indiana), Director, Coal Utilization

01/73-01/80: Amoco Oil Company, Research and Development Project Manager

01/65-01/73: Monsanto Company, Senior Development Engineer

Member of AIChE, ACS, Chicago Catalysis Society

Professional Engineer in Illinois

5 Patents, 14 Publications

Selected Publications:

1. J. A. Mahoney, K. K. Robinson, and E. C. Myers, "*Catalyst Evaluation with the Gradientless Reactor*," CHEMTECH, 758 (December 1978).

2. R. J. Bertolacini, L. C. Gutberlet, D. K. Kim and K. K. Robinson, "*Catalyst Development for Coal Liquefaction*," EPRI, AF-574 (1977).
3. R. J. Bertolacini, L. C. Gutberlet, D. K. Kim, and K. K. Robinson, "*Catalyst Development for Coal Liquefaction*," EPRI AF-1084 (1979).
4. D. K. Kim, R. J. Bertolacini, J. M. Forgac, R. J. Pellet, and K. K. Robinson, "*Catalyst Development for Coal Liquefaction*," EPRI AF-1233 (1979).
5. D. F. Tatterson, K. K. Robinson, T. L. Marker, and R. Guercio, "*Coal Flash Pyrolysis in a Free-Jet Reactor*," I&EC RESEARCH, 27 1606 (1988).
6. K. K. Robinson "*Molecular Structure of Heavy Coal Liquids*," EPRI ER-6099-SR (1988).
7. R. J. Bertolacini, J. M. Forgac, D. K. Kim, R. J. Pellet, and K. K. Robinson "*Catalytic Functionality for Cool Hydroliquefaction*," Third International Conference--The Chemistry and Uses of Molybdenum (1979).
8. D. F. Tatterson, K. K. Robinson, R. Guercio, and T. L. Marker, "*Feedstock Effects in Coal Flash Pyrolysis*," Communication, I&EC, Vol 29, No. 10, (1990).

Patents:

- 1 .F. E. Paulik, K. K. Robinson, and J. F. Roth.
"*Vapor Phase Hydroformylation Process*," US 3,487,112--British Patent 1,228,201.
2. D. K. Kim, R. J. Bertolacini, L. C. Gutberlet, and K. K. Robinson, "*Process for Coal Liquefaction and Catalyst*," US 4,257,922.
3. D. K. Kim, R. J. Bertolacini, L. C. Gutberlet, and K. K. Robinson, "*Process for Coal Liquefaction and Catalyst*," US 4,294,685.
4. J. S. Meyer, K. K. Robinson, J. M. Forgac, and D. F. Tatterson, "*Rapid Hydroxyrolysis of Carbonaceous Solids*," US 4,326,944.
5. K. K. Robinson, "*Granulated Activated Carbon for Water Treatment*," US 4,954,469.

3e. Facilities/Equipment

Mega-Carbon has their laboratory and corporate offices in St. Charles, IL. The research facilities provide a full service organization in which all resources are under one roof: chemical engineering, computer technology, process assembly, and maintenance. Additionally Mega-Carbon has a full complement of chemical research equipment including UV spectrometers, gas chromatographs, analytical balances, temperature controllers, furnaces, and test rigs. Presently Mega-Carbon is conducting research on an improved evaporative loss control device to capture gasoline vapors in automobiles. Additionally Mega-Carbon is located near both Northwestern University, in Evanston IL and Argonne National Laboratory in Argonne, IL where it is possible to have analyses run on the adsorbents to determine surface area, examine its microstructure via scanning microscopy, and measure its adsorption capacity.

3f. Consultants and Subcontractors

C. David Livengood (Argonne Subcontractor)

EDUCATION: Ph.D., Nuclear Engineering, Purdue University, 1970
M.S., Nuclear Engineering, Purdue University, 1967
B.A., Physics (Cum Laude), Wabash College, 1964

EXPERIENCE:

Since 1979 **Environmental Systems Engineer**, Argonne National Laboratory
Leads research activities focused on flue-gas cleanup technologies for SO₂, NO_x, and air toxics, site-remediation technologies for soils and groundwater, development of advanced sensors, reduction of greenhouse-gas emissions, and energy systems studies.

1984 - 1993 **Section Manager**, Environmental Technology Section, Argonne National Laboratory.

1981 - 1984 **Deputy Section Manager**, Environmental Control Technology Section, Argonne National Laboratory

1975 - 1979 **Assistant Nuclear Engineer**, Argonne National Laboratory

1975 - 1976 **Visiting Professor**, Nuclear Engineering Program, Northwestern University

1970 - 1975 **Assistant Professor**, Nuclear Engineering Program, Northwestern University.

PROFESSIONAL: Air and Waste Management Association

Vice-Chairman of the Particulate and Associated Acid Gases
Committee
American Association for the Advancement of Science

PUBLICATIONS: Author/coauthor of 1 book, 10 journal articles, 20 topical reports, 87 conference papers, and numerous presentations.

Dr. David Livingood has met with Mega-Carbon and agreed to serve as a consultant for the work performed at Argonne, as well as work in Mega-Carbon's laboratories. His letter confirming this understanding is shown on page 24 of this proposal.

Dr. John B. Butt (Consultant)

D.Eng. Ch.E. 1960, Yale University
M.Eng. Ch.E. 1958, Yale University
B.S. Ch.E. 1963, Clemson University

Academic Experience-

1969 to Present: **Northwestern University**, Department of Chemical Engineering,
Professor. Walter P. Murphy Professor
1964-1969: **Yale University**, Department of Engineering and Applied
Science, Associate Professor
1963-1964: **Yale University**, Department of Engineering and Applied
Science, Assistant Professor
1961: **University of Texas**, Visiting Professor of Chemical Engineering

Member of AIChE, ACS, Chicago Catalysis Society
New York Academy of Sciences
American Association for the Advancement of Science
Associate Editor, "Catalysis Reviews-Science and Engineering"
168 technical publications, 1 patent and 2 textbooks

John Butt has met with Mega-Carbon and agreed to serve as a consultant on the Phase I proposal described, herein. He has agreed to the salary indicated in the budget sheet and also the number of hours listed. A letter confirming his involvement is included as page 23.

4. Similar Grant Applications, Proposals, or Awards

No prior, current, or pending support for proposed work.

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Carbon Sorbents for Control of Mercury Emissions