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**Granular Activated Carbons from Agricultural By-products:  
Process Description and Estimated Cost of Production (Bulletin  
#881)**

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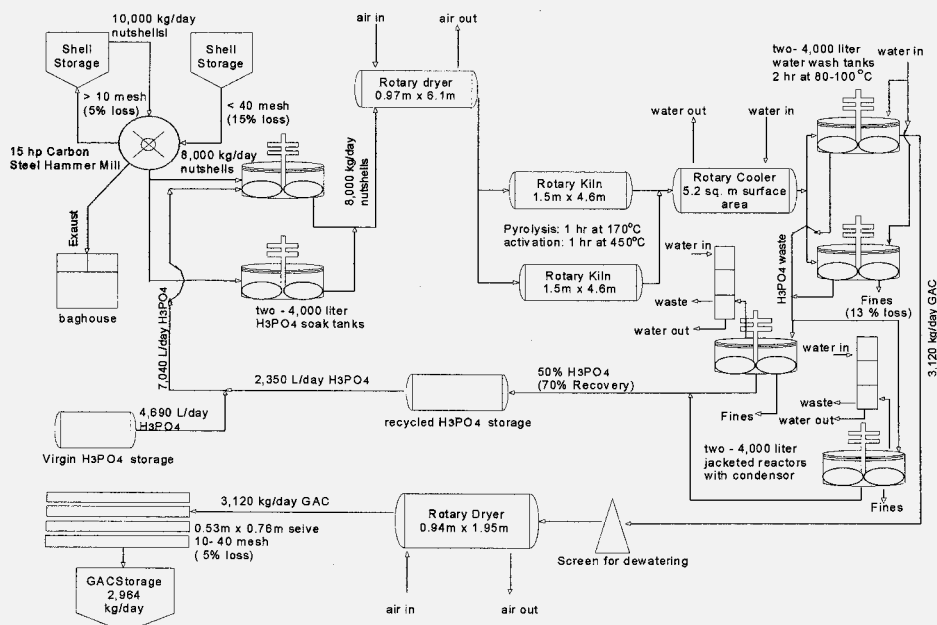
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# **Granular Activated Carbons from Agricultural By-products: Process Description and Estimated Cost of Production**

Chilton Ng, Wayne Marshall, Ramu M. Rao,  
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## **Introduction**

In crop year 2002, the United States produced 68.5 billion pounds of sugarcane and 178 million pounds of pecans (Agricultural Statistics, 2003). In Louisiana, 27.0 billion pounds of sugarcane and 2 million pounds of pecans were grown (Agricultural Statistics, 2003). This generated an estimated 9 billion pounds of sugarcane bagasse and 1 million pounds of pecan shells as by-products with little to no economic value for the Louisiana economy.

Chen (1985) reported that the greatest use of sugarcane bagasse (about 85 percent) is as fuel to produce steam used to manufacture sugar. Bagasse not used as fuel still accounts for about 1.4 billion pounds of excess bagasse in Louisiana alone. In Louisiana, bagasse has applications in the fiberboard, wallboard, insulating board, agricultural feed and bedding, and paper industries. Considerable quantities are available for additional use. Pecan shells find some use in landscape mulch, but most are discarded. Possible additional uses for Louisiana's bagasse and pecan shells could be the development of adsorbents such as activated carbon. Ahmedna et al. (2000a) demonstrated that granular activated carbon (GAC) could be made from Louisiana pecan shells and sugarcane bagasse.

Using Louisiana's pecan shells and sugarcane bagasse as feed-stock for carbon production would add value to the by-products, turning them into value-added commodities, as well as reducing waste disposal costs for the shelling plants and raw sugar factories. Using pecan shells and bagasse to produce GACs potentially pro-

vides a less expensive raw material than the coal now used, as well as producing a GAC manufactured from a renewable resource instead of a non-renewable one.

Activated carbon is a commonly used adsorbent in sugar refining, chemical and pharmaceutical industries, water treatment and wastewater treatment, and as an adsorbent in point-of-use (POU) and point-of-entry (POE) home water filtration systems. GACs are frequently used in water treatment plants to mitigate odors and tastes. Increasing requirements for cleaner and more polished effluent from many processes suggests that, barring the development of new technologies, industrial need for activated carbon will only increase in the future.

A number of different laboratories (see Review of Literature) have investigated the use of pecan shells and sugarcane bagasse as feedstocks for activated carbon production. These carbons have been used in a variety of applications, including metal ion remediation, sugar decolorization and adsorption of different organic pollutants. While uses for by-product-based activated carbons have been identified, few publications have addressed the manufacture of these carbons and the costs associated with their manufacture. Toles et al. (2000a, 2000b) developed cost estimates for the production of both steam-activated and phosphoric acid-activated almond shell carbons. Recently, Ng et al. (2002, 2003) gave process descriptions and manufacturing costs for the production of granular activated carbons from pecan shells and sugarcane bagasse. The Ng et al. publications were a joint effort between Louisiana State University (LSU) and the USDA-ARS, Southern Regional Research Center (SRRC) and form the basis for this LSU Agricultural Center bulletin.

The objectives of this investigation were to estimate the cost of production of these carbons through process descriptions and economic analyses. The depiction of process flow diagrams for the production of pecan shell-based and sugarcane bagasse-based carbons was determined from research conducted at LSU and SRRC. Estimated production costs were derived from equipment manufacturer's costs and capital and operating costs based on the process flow diagrams.

This bulletin is a follow-up, in part, of Bulletin #869, "Granular Activated Carbons from Agricultural By-products: Preparation, Properties and Application in Cane Sugar Refining." An estimation of production costs for these by-product-based carbons was considered

prudent at this time because of the potential interest from both bagasse and shell producers and activated carbon manufacturers based on the use of these carbons in various applications compared to commercial carbons.

## **Review of Literature**

Activated carbon can be produced from a wide variety of plant materials, including nut shells, wood, peat, fruit pits, coffee grounds and sugar (Smisek and Cerny, 1970; Gergova et al., 1992; Girgis et al., 1994; Tam et al., 1999). Either physical activation with steam or carbon dioxide or chemical activation with a variety of activants, such as phosphoric acid or potassium hydroxide, can be used to produce activated carbon.

Several recent publications (Ahmedna et al., 1997; Toles et al., 1998; Johns et al., 1998, 1999; Ahmedna et al., 2000a, 2000b; Dastgheib and Rockstraw, 2001; Wartelle and Marshall, 2001; Ng, 2002a, 2002b) have demonstrated the use of pecan shell-based activated carbons toward both metal ions and organic species commonly found in a variety of water and wastewater sources, including ponds (including catfish ponds) and industrial sites (including “brownfield” sites). Ahmedna et al. (1997; 2000a; 2000b) have shown that pecan shell carbons have potential for use in the cane sugar refining industry. Some of these studies compared the physical, chemical and adsorptive properties of pecan shell-based carbons to commercial carbons and concluded there were little difference among the carbons in terms of physical and some chemical properties. Depending on the method of activation, pecan shell-based carbons were superior to commercial carbons in metals uptake and similar to commercial carbons in organics uptake and sugar decolorization.

Sugarcane bagasse-based activated carbons have been evaluated for their ability to act as adsorbents for sugar decoloration (Lavarack, 1997; Bernardo et al., 1997; Pendyal et al., 1999b; Ahmedna et al., 2000b). Additionally, other studies (Marshall et al., 2000; Tsai et al., 2001) have emphasized the physical, chemical and adsorptive properties of bagasse-based GACs, with emphasis on uptake of



organic compounds, such as dyes, and also on the adsorption of metal ions. Pendyal et al. (1999a, 1999b), Ahmedna et al. (2000b) and Marshall et al. (2000) have compared the properties of bagasse-based carbons to commercial carbons. These studies have demonstrated that bagasse-based carbons are similar to their coal-based counterparts in sugar decolorization and may be superior in metals uptake.

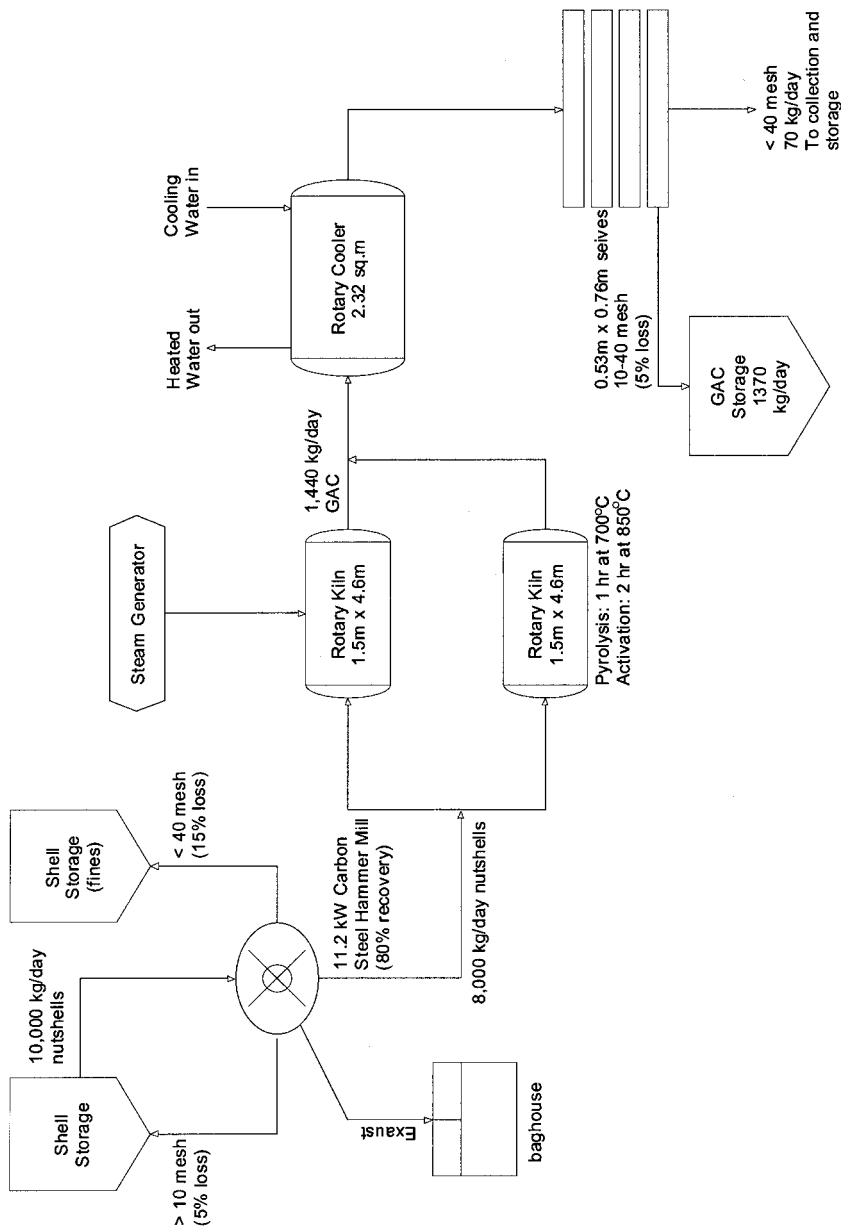
The low cost and high availability of sugarcane bagasse and pecan shells make them attractive feedstocks for carbon production and the subject of further research efforts to create carbons with properties that exceed those shown by commercial carbons.

## **Methods**

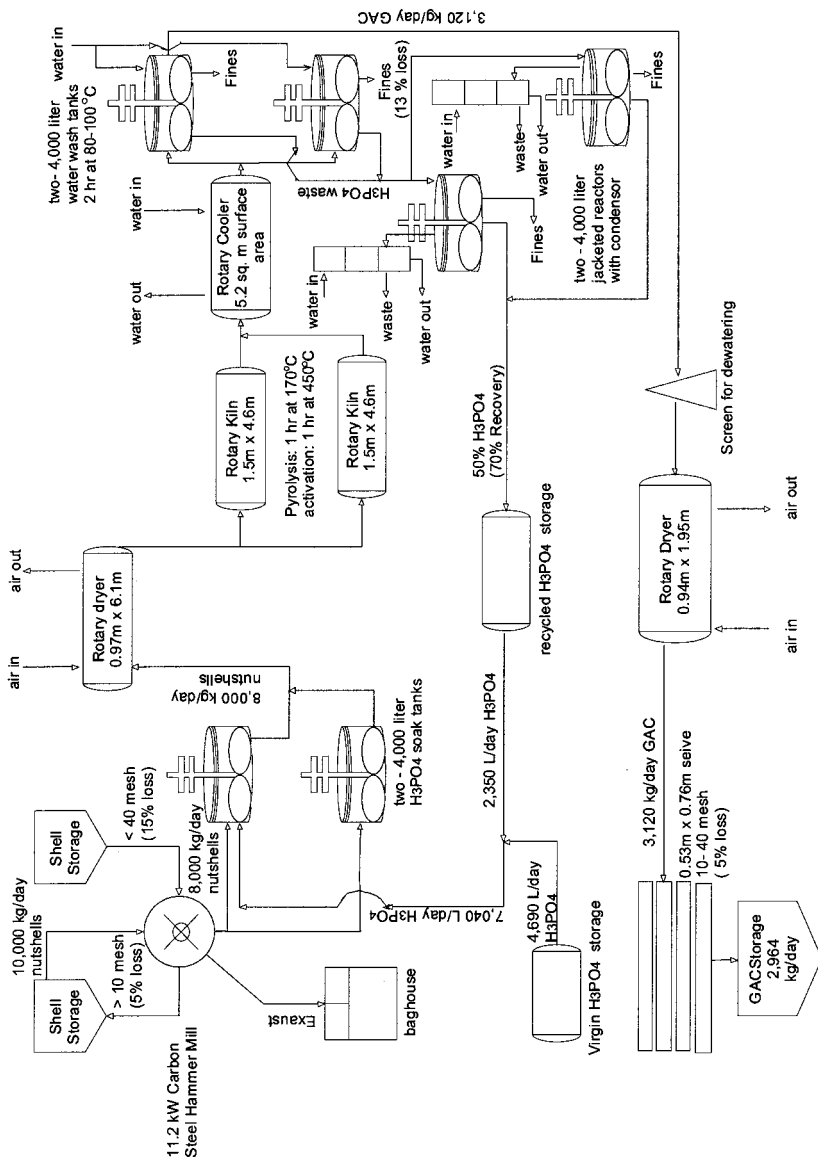
### **Process Flow Diagrams for Granular Activated Carbon Production**

Process flow diagrams were based on process descriptions used in this study, which are the culmination of research carried out by Pendyal et al. (1999a) and Johns et al. (1998) for the steam activation of sugarcane bagasse, Johns et al. (1999) for the steam and carbon dioxide activation of pecan shells and Toles et al. (1998) for the phosphoric acid activation of pecan shells. Process flow diagrams were developed to identify yield values at various steps in the process and to determine the basic process equipment necessary for constructing a manufacturing facility. Process flow diagrams were constructed using the Amazing Flow Charts and Diagrams computer software (COSMI Corporation, Rancho Dominguez, Calif). Development of process flow diagrams for large-scale production of GACs makes the manufacturing process easy to understand, easy to follow and helps highlight costly errors that could be made during large-scale commercial production of the carbons. Process flow diagrams also simplify material and energy balance calculations. Data obtained from these calculations will be used to make a preliminary estimate of the fixed capital investment required to construct a manufacturing facility.

Diagrams for three processes will be discussed, namely, steam and phosphoric acid activation of pecan shells, shown in Figures 1



**Figure I. Process Flow Diagram for the Production of Steam-activated, Granular Carbon from Pecan Shells.**



**Figure 2. Process Flow Diagram for the Production of Phosphoric-acid Activated, Granular Carbon from Pecan Shells.**



and 2, and steam activation of sugarcane bagasse, shown in Figure 3. Each process was divided into several unit operations, depending on the process. Each unit operation will be discussed in detail under Results and Discussion.

### **Estimation of Equipment and Capital Cost**

Once the process flow diagrams were constructed, equipment and capital costs were estimated from a combination of vendor quotes and printed literature. Equipment costs represent actual purchase costs and not investment costs. This capital cost estimate was then used in a procedure to estimate fixed capital investment using ranges of process-plant component costs. Procedures from Peters and Timmerhaus (1991) were followed for a high degree of automatic control and outdoor operation.

Most equipment was designed using procedures from Green (1984), McCabe et al. (1985), Peters and Timmerhaus (1991), Ertas and Jones (1993) or Biegler et al. (1997). Rotary kilns were sized based on recommendations by HiTemp Technology Corporation (Flemington, N.J.).

All equipment costs, unless otherwise noted, are based on carbon steel rather than stainless steel. Material transport between equipment, using augers or vibrating beds, was included as a component of the fixed capital investment costs. Likewise, boilers for steam generation are considered utilities and are also a fixed capital investment cost.

## **Results and Discussion**

### **Process Descriptions**

Two activation processes will be considered, namely, steam activation of pecan shells and sugarcane bagasse and phosphoric acid activation of pecan shells. Diagrams for the three processes are shown in Figures 1-3. The steam activation process for sugarcane bagasse (Figure 3) differs from steam activation of pecan shells (Figure 1), in that the former requires a binder and pelletization to increase particle density while the latter does not require either a binder or pelletization.

## **Steam Activation of Pecan Shells**

The production of pecan shell carbons by steam activation as outlined by Johns et al. (1999) was used in the development of Figure 1. The unit operations are sample preparation, pyrolysis/activation and screening/collecting (Figure1). A yield value of 18 percent for pyrolysis/activation of pecan shells results in an activated carbon with a surface area of 750-800 m<sup>2</sup>/g (Johns et al., 1999). Since these values fall within the range of surface areas for commercial carbons, we chose this particular yield. A yield of 18 percent of kiln input (8,000 kg) produces 1,440 kg of pyrolyzed/activated product. The 5 percent loss of carbon during the sieving operation is based on our laboratory's experience. The final product yield for all unit operations was 13.7 percent, based on the initial input of 10,000 kg. This gave 1,370 kg of final product.

### **Sample preparation**

Clean and dry pecan shells with moisture content of less than 13 percent are required for carbon production. These shells should have less than 10 percent nutmeat and hull contaminants by weight. Specifications regarding moisture content and percentage contaminants in the shells will have to be followed by the pecan sheller before the delivery of the shells to the carbon manufacturing facility, and these specifications are included in the cost of the shells. Long-term shell storage was not provided because we anticipated that the 10,000 kg/day of shells would be delivered each day to the production facility and all shells would be processed the same day. For production, a 10,000 kg/day feed of shells was defined, and all scaling based on that amount.

Clean and dry pecan shells are fed into an 11.2 kW carbon steel hammer mill and milled to a 10- to 40-mesh (2.00 to 0.425 mm) particle size. Coarse particles (larger than 2.00 mm) were recycled back to the mill to produce more feedstock. Fine particles (smaller than 0.425 mm) generated by the hammer mill can be directed for disposal or other use, such as to a boiler to provide the steam required for activation by burning the fines. The process stream, with an 80 percent or 8,000 kg/day recovery, was directed into a rotary kiln.

## **Pyrolysis/activation**

In this design, a dual kiln system made from carbon steel with a chamber size of 4.6 m x 1.5 m and a 0.15 m refractory liner in each kiln is described. A dual kiln system was used because of shipping considerations with larger kilns. A built-in-place kiln may not need the dual kiln system, thus lowering expense.

The process stream was split to feed each kiln. The shells were fed to the rotary kiln where pyrolysis can occur by maintaining the shells at 700 degrees C for one hour under an inert atmosphere comprised of off-gases generated by pyrolysis. Considerable waste heat is available from this process, as well as off-gases generated during pyrolysis that are capable of further combustion. Equipment was not designed for any heat recovery or off-gas recycling and combustion. Any cost associated with air pollution control of the off-gases also has not been included in this study. Pyrolytic gases are reported to have a net heating value ranging from 11,100-18,500 kJ/m<sup>3</sup> and may be burned for heating. In comparison, natural gas has a heating value of 37,100 kJ/m<sup>3</sup>.

After pyrolysis, the char was heated to 850 degrees C for 2 hours in the presence of steam to achieve activation. After activation, the carbons were conveyed to an indirect rotary cooler, one of the few types of coolers that can operate at high temperatures.

Assuming a process stream (mass flow rate) of 1,440 kg/day, a rotary cooler with a surface area of 2.32 m<sup>2</sup> will be necessary to reduce temperature from 850 degrees C to less than 100 degrees C in less than 1 hour. The equations of McCabe et al. (1985) were followed in establishing the rotary cooler surface area required.

## **Screening/Collecting**

After being cooled to less than 100 degrees C, the carbon was sieved to retain the 0.425- to 2.00-mm particles. A 0.53 m x 0.76 m sifter should be adequate. A carbon loss of 5 percent is anticipated. The fines can be separated and bagged separately as powdered carbon. The 0.425- to 2.00-mm activated carbon can then be taken for bagging and storage. The bagging station was not included in the process flow sheet.

Final yield for steam-activated pecan shell-based GAC is an estimated 13.7 percent, or 1,370 kg/day of product generated based on a 10,000 kg/day feed.

## Cost Analysis

Costs were developed assuming a 14 percent yield of pecan shell-based activated carbon (1,400 kg/day output), 320 days per year of production and two men per shift (three shifts) for 24 hours a day at \$18 an hour. Production of 448,000 kg/year of steam-activated pecan shell carbon requires a fixed capital investment of \$2.12 million (Table 1) and an annual operating cost of \$1.22 million (Table 2). The estimated product cost is \$2.72/kg (Table 3).

### Steam Activation of Sugarcane Bagasse

The production of a GAC from sugarcane bagasse by steam activation is the second process discussed. The basis for the process presented in Figure 3 is an evolution of a process originally described by Pendyal et al. (1999a), who used bagasse mixed with one

**Table 1. Estimated capital costs for steam activation of pecan shells**

<b>Equipment</b>	<b>Cost (\$)</b>
Hammer mill	9,000
2 Rotary kilns	205,000 each
Rotary cooler	65,000
Sieve	3,000
<b>Total equipment cost</b>	<b>487,000</b>
Equipment installation	175,000
Instrumentation	136,000
Piping and material transport (augers)	155,000
Electrical installation	97,000
Buildings	97,000
Yard improvements	38,000
Service facilities	292,000
Land	19,000
Engineering and supervision	195,000
Construction expense	233,000
Contractor's fee	38,000
Contingency	155,000
<b>Total capital costs</b>	<b>2,117,000</b>

Capital costs based on different percentages of the total equipment cost according to Peters and Timmerhaus (1991).



**Table 2. Annual operating costs for steam activation of pecan shells**

Item	Annual cost (\$)
Raw materials	
Pecan shells	35,000
Utilities	
Steam	4,000
Water	1,000
Natural gas	10,000
Electricity	38,000
Labor	
Operating labor	316,000
Maintenance labor	42,000
Supervision	47,000
Fringe benefits	126,000
Supplies	
Operating supplies	32,000
Maintenance supplies	21,000
General Works	
General and administrative	319,000
Property insurance and tax	17,000
Depreciation <sup>a</sup>	212,000
<b>Total cost</b>	<b>1,220,000</b>

Annual operating costs for labor, supplies and general works are based on percentages given in Peters and Timmerhaus (1991).

<sup>a</sup>Capital costs (Table 1) divided by an economic life of 10 years, rounded off.

**Table 3. Summary of costs for steam activation of pecan shells**

Purchased equipment cost <sup>a</sup>	\$487,000
Capital cost <sup>a</sup>	\$1,630,000
Total fixed capital investment <sup>b</sup>	\$2,117,000
Total annual operating cost <sup>c</sup>	\$1,220,000
Estimated annual production of carbon <sup>d</sup>	448,000 kg
Estimated cost for activated carbon	\$2.72 kg

<sup>a</sup>See Table 1.

<sup>b</sup>Purchased equipment cost plus capital cost.

<sup>c</sup>See Table 2.

<sup>d</sup>Based on a 1,400 kg/day output and a 320 day/year production schedule.

of several binders, including sugarcane molasses. The authors then pyrolyzed the samples and activated them with a mixture of carbon dioxide and nitrogen gas. The Pendyal et al. process was modified by Johns et al. (1998). They activated a bagasse/cane molasses mixture with steam after using the pyrolysis method of Pendyal et al. (1999a). Steam was chosen as the activant for the current process rather than carbon dioxide because it is less expensive than carbon dioxide (Toles et al., 2000a), and surface areas are similar for the two activation methods under most burn-off conditions (Johns et al., 1999).

This process has many steps in common with the steam activation of pecan shells, but the process is sufficiently different because of the need for a binder, which necessitates a pellet mill and a binder feed tank for the pelletization step, and acid wash tanks and acid storage for the acid wash step (Figure 3).

### **Sample Preparation**

Clean and dry bagasse, with moisture content at or below 13 percent, is required for carbon production. In cost calculations, it was assumed that specifications regarding cleaning and ensuring the proper moisture content of the bagasse would be adhered to by the raw sugar factory before delivery of the bagasse to the carbon manufacturing facility. For our calculations, we assumed the cost of this material to be \$10/metric ton.

### **Milling**

Ten thousand kg/day of clean and dry bagasse is fed into an 11.2 kW carbon steel hammer mill and milled to a particle size of 30 to 40 mesh (0.60 to 0.425 mm). This equipment should be able to process the desired daily amount in 8 hours, but specific product testing would have to be done to confirm equipment compatibility with the process stream. Screens are an integral part of the hammer mills, and separate screening equipment should not be necessary. The goal is to have 80 percent by weight of the initial feed as 0.425- to 0.60-mm particles. The small particle size of the bagasse is necessary for effective interaction between bagasse and binder. Material larger than 0.60 mm is redirected back to the feed hopper and is passed again through the mill. Fines of less than 0.425 mm can be directed for disposal or other use, such as to a boiler to provide the activation steam by burning the bagasse. The 0.425- to 0.60-mm particles, with an 80 percent or 8,000 kg/day recovery, are directed to a pelletizer.

## **Pelletization**

Bagasse is mixed with sugarcane molasses binder (estimated cost of \$77/metric ton) in a 2:1 (bagasse:binder) ratio and compressed at 34,500 kPa at the die plate to form approximately 5 x 10 mm pellets. Because pellet mills run at a capacity of 46-182 kg/(kWhr)(Green, 1984), a 33 kW pellet mill will be required to pelletize the daily feed of bagasse and binder. Because of the high viscosity of sugarcane molasses at ambient temperature, a heated 4,000 L storage tank will be used to supply the pelletizer. Depending on the physical distance between the pelletizer and storage tank, insulated or heated transfer lines may be necessary. Once the pellets are formed, they are delivered to a feed hopper and then the rotary kiln.

## **Pyrolysis/activation**

In this design, a dual kiln system with a chamber size of 1.5 m x 4.6 m for each kiln is described. In this process design, a dual kiln system is used because of shipping considerations with larger kilns. A built-in-place kiln may not need the dual kiln system and may save on equipment costs.

The process stream is split to feed each kiln. The bagasse/binder pellets are fed to the rotary kiln where pyrolysis occurs by holding the pellets at 700 degrees C for one hour under an inert atmosphere comprised of off-gases generated by pyrolysis. As with the previous process described, considerable waste heat is available from this process, as well as off-gases generated during pyrolysis that are capable of further combustion. Waste heat is used to maintain the pyrolysis temperature at 700 degrees C and conserve natural gas used to generate this temperature initially.

After pyrolysis, activation occurs by heating the char to 850 degrees C for one hour in the presence of steam. These pyrolysis/activation conditions are expected to achieve a 20 percent yield based on a target surface area of 700 to 800 m<sup>2</sup>/g. Earlier results of Pendyal et al. (1999a) and Ahmedna et al. (2000a) indicated yields of 25 percent to 30 percent using carbon dioxide activation of bagasse with a sugarcane molasses binder, but surface areas were only 200 to 400 m<sup>2</sup>/g. Johns et al. (1999) have noted that decreased yields during activation result in increased surface area.

After activation, the carbon is conveyed to an indirect rotary cooler. With a process stream of 2,400 kg/day, a rotary cooler with a surface area of 3.5 m<sup>2</sup> will be required to achieve a reduction in

temperature from 850 degrees C to less than 100 degrees C in less than one hour. The equations of McCabe et al. (1985) were followed in establishing the rotary cooler surface area required.

### **Acid and Water Wash**

The activated carbon is acid washed with 0.1 N HCl (cost of \$12/metric ton) to remove any ash that has formed from pyrolysis of the binder and to a lesser extent from pyrolysis of the bagasse. The process stream is then water washed to remove the residual acid until the pH is 5-6. A dual wash tank system is used, with one tank filling while the other is acid or water washing. Two 4,000 L glass-lined wash tanks are included. The tanks would require 90 minutes to fill and 90 minutes to wash the carbon in alternating tanks. It is assumed that 10 kg of 0.1 M HCl are required for every kg of product. Neutralization of the acid wash and removal of suspended carbon particles from the washing procedure would be handled by an effluent treatment system before the water is transported to the municipal sewer system. A 4,000 L tank is provided for acid storage. The tank will be filled six times per day as needed from a tanker truck parked outside the plant. The activated carbon is removed from the wash tanks and dried for two hours at 60 degrees C in a rotary dryer.

### **Drying**

To calculate the size of dryer needed for a throughput of approximately 2,500 kg/day of wet activated carbon, the equations of McCabe et al. (1985) were used.

With the above assumptions, a 1.1-m x 7.2-m rotary dryer will be required. To avoid the possibility of rust, a stainless steel dryer will be used. The next step is for the GAC to be sieved to a 0.425- to 2.00-mm particle size.

### **Sieving/Collecting**

After drying, the activated carbon is sieved to retain the 0.425- to 2.00-mm particles. A 0.76-m x 0.53-m sifter is required. A carbon loss of 5 percent is anticipated. The fines can be separated and bagged separately as powdered carbon. The finished product can then be taken for bagging and storage. A bagging station was not included in the flow diagram.

Final yield for steam activated, bagasse-based carbon is estimated to be 19.4 percent based on an input of 10,000 kg/day of

bagasse. If 4,000 kg/day of sugarcane molasses binder is also included as input, then the final yield is 13.8 percent.

## Product cost

Costs were developed assuming a 19.4 percent yield or 1,940 kg/day output of bagasse-based granular activated carbon, 320 days a year of production and three men per shift (three shifts) for 24 hours a day at \$18 an hour. For this process, a fixed capital investment of \$4.32 million is required (Table 4). An annual production

**Table 4. Estimated capital costs for steam activation of sugarcane bagasse**

<b>Equipment</b>	<b>Cost (\$)</b>
Hammer mill	9,000
Pellet mill	81,000
Binder feed tank	10,000
2 Rotary kilns	205,000 each
Rotary cooler	100,000
2 Acid/Water wash tanks	80,000 each
Acid Storage tank	70,000
Dryer	150,000
Sieves and collector	3,000
<b>Total equipment cost</b>	<b>993,000</b>
Equipment installation	358,000
Instrumentation	276,000
Piping and material transport (augers)	315,000
Electrical installation	199,000
Buildings	199,000
Yard improvements	78,000
Service facilities	596,000
Land	39,000
Engineering and supervision	397,000
Construction expense	475,000
Contractor's fee	78,000
Contingency	315,000
<b>Total capital costs</b>	<b>4,318,000</b>

Capital costs based on different percentages of the total equipment cost according to Peters and Timmerhaus (1991).

cost was estimated at \$1.94 million for an annual output of 621,000 kg/year (Table 5). Therefore, the estimated cost to produce steam-activated, bagasse-based carbon would be \$3.12/kg (Table 6).

### Phosphoric Acid Activation of Pecan Shells

The production of GAC from pecan shells using phosphoric acid activation is the third and final process discussed (Figure 3). Four unit operations were considered and consisted of sample preparation

**Table 5. Annual operating costs for steam activation of sugarcane bagasse**

Item	Annual cost (\$)
Raw materials	
Sugarcane bagasse	32,000
Sugarcane molasses	98,000
Hydrochloric acid	242,000
Utilities	
Steam	4,000
Water	5,000
Natural gas	23,000
Electricity	77,000
Labor	
Operating labor	315,000
Maintenance labor	86,000
Supervision	47,000
Fringe benefits	126,000
Supplies	
Operating supplies	32,000
Maintenance supplies	43,000
General Works	
General and administrative	345,000
Property insurance and tax	34,000
Depreciation <sup>a</sup>	432,000
<b>Total cost</b>	<b>1,941,000</b>

Annual operating costs for labor, supplies and general works are based on percentages given in Peters and Timmerhaus (1991).

<sup>a</sup>Capital costs (Table 1) divided by an economic life of 10 years, rounded off.

(milling, soaking with acid, drying), pyrolysis/activation, sample washing and acid recovery, and finally drying/screening and collecting. Based on results from Toles et al. (1998), the yield of carbon after pyrolysis/activation was 45 percent (3,600 kg) of kiln input (8,000 kg) and the carbon yield after washing and drying was 39 percent (3,120 kg) of kiln input. Finally, we estimated a 5 percent loss of carbon during the final sieving operation. Therefore, total yield was 37 percent of kiln input or about 30 percent (2,964 kg) of the initial input of 10,000 kg.

### Sample preparation

The milling operation is the same as for the steam activation of pecan shells (Figure 1). After milling, the shells are given an overnight (about 16 hours) soak at ambient temperature in a 30 percent phosphoric acid solution at a ratio of one kg shells to one L of acid.

A dual tank system was incorporated for the acid-soaking operation, with one tank used for soaking while the other tank was emptied of acid-treated pecan shells for the drying operation. Phosphoric acid will be stored in two glass-lined 4,000 L storage tanks — one tank to store virgin phosphoric acid to replace acid lost in the process and one to store recycled phosphoric acid from the wash step.

The 1:1 ratio of shells to acid for the soak step will result in very little free acid. Any free acid could be added to the recycle acid from the acid wash step. The wet shells were transferred to the hopper of the rotary dryer.

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**Table 6. Summary of costs for steam activation of sugarcane bagasse**

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Purchased equipment cost <sup>a</sup>	\$993,000
Capital cost <sup>a</sup>	\$3,325,000
Total fixed capital investment <sup>b</sup>	\$4,318,000
Total annual operating cost <sup>c</sup>	\$1,941,000
Estimated annual production of carbon <sup>d</sup>	621,000 kg
Estimated cost for activated carbon	\$3.12/kg

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<sup>a</sup>See Table 6.

<sup>b</sup>Purchased equipment cost plus capital cost.

<sup>c</sup>See Table 7.

<sup>d</sup>Based on a 1,940 kg/day output and a 320 day/year production schedule.

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The acid-soaked shells were dried before being fed to the kiln. Assuming a process load of 16,000 kg and using the parameters defined by McCabe et al. (1985), a 0.97-m x 6.1-m rotary dryer will be required. To avoid the possibility of rust and reaction with phosphoric acid, a stainless steel dryer must be used.

### **Pyrolysis/activation**

From the dryer, the acid-coated pecan shells were conveyed to a feed hopper of a rotary kiln. A dual kiln design was used, the same design as used for the steam activation process (Figure 1). In the kiln, the feedstock was pyrolyzed by heating to 170 degrees C for 1 hour under an atmosphere of breathing air. Following pyrolysis, the char was heated to 450 degrees C and activated under an oxidizing atmosphere of breathing air for 1 hour. As in the steam activation processes described earlier, waste heat and off-gases are generated and are available from this process for recovery and reuse. The activated carbon was conveyed directly from the rotary kiln to a rotary cooler.

Based on the same calculations and assumptions for rotary cooler size as in the production of steam-activated pecan shells, and assuming a process stream of 3,600 kg/day at this point, a rotary cooler with a surface area of 5.2 m<sup>2</sup> will be necessary.

### **Water wash/acid recovery**

The cooled carbon must be water washed to remove any residual phosphoric acid. This was done by washing the carbon with 80-90 degrees C water for 2 hours at a ratio of 40 L water per kg carbon. This will be done in one of two 4,000 L glass-lined reactors.

The dilute phosphoric acid must be concentrated before being mixed with virgin phosphoric acid for use in the acid soak tanks. This will be done in two 4,000 L glass-lined reactors with condensers. Any costs associated with waste disposal for acid wastes are not included in this analysis.



## **Drying/screening and collecting**

The activated carbon was collected on a dewatering screen and taken to a rotary dryer before it is ready for packaging or storage. Assuming a process load of 3,500 kg of wet carbon and using the parameters defined by McCabe et al. (1985), a 0.97-m x 1.95-m rotary dryer will be required. A stainless steel dryer must be used to avoid rusting.

Screening and collecting processes were carried out as described previously for steam activation. We estimated a loss of 5 percent of the dryer mass by screening the carbons. Therefore, the final yield for phosphoric acid activated carbons was 29.6 percent or a final output of 2,964 kg/day.

## **Cost**

Costs were developed assuming a 30 percent yield or 3,000 kg/day output of acid-activated carbon, 320 days a year of production and three men per shift (three shifts) for 24 hours a day at \$18 an hour. For the phosphoric acid activation process, a fixed capital investment of \$6.32 million (Table 7) is required. An annual production cost was estimated at \$2.78 million (Table 8) for an annual output of 960,000 kg. Therefore, the estimated cost for acid-activated carbon would be \$2.89/kg (Table 9). Equipment for energy recovery was not included in this design.

**Table 7. Estimated capital costs for phosphoric acid activation of pecan shells**

<b>Equipment</b>	<b>Cost (\$)</b>
Hammer mill	9,000
2 Glass-lined, acid soak tanks	80,000 each
Rotary dryer	150,000
2 Rotary kilns	205,000 each
Rotary cooler	100,000
2 Glass-lined, acid wash tanks	80,000 each
2 Glass-lined, acid recovery tanks	83,000 each
2 Glass-lined, acid storage tanks	70,000 each
Rotary dryer	150,000
Sieve	3,000
<b>Total equipment cost</b>	<b>1,448,000</b>
Equipment installation	526,000
Instrumentation	405,000
Piping and material transport (augers)	462,000
Electrical installation	291,000
Buildings	291,000
Yard improvements	114,000
Service facilities	874,000
Land	57,000
Engineering and supervision	583,000
Construction expense	697,000
Contractor's fee	114,000
Contingency	462,000
<b>Total capital costs</b>	<b>6,324,000</b>
Capital costs based on different percentages of the total equipment cost according to Peters and Timmerhaus (1991).	

**Table 8. Annual operating costs for phosphoric acid activation of pecan shells**

Item	Annual cost (\$)
Raw materials	
Pecan shells	35,000
Phosphoric acid	217,000
Utilities	
Steam	4,000
Water	14,000
Natural gas	268,000
Electricity	77,000
Labor	
Operating labor	473,000
Maintenance labor	127,000
Supervision	71,000
Fringe benefits	189,000
Supplies	
Operating supplies	47,000
Maintenance supplies	63,000
General Works	
General and administrative	516,000
Property insurance and tax	51,000
Depreciation <sup>a</sup>	632,000
<b>Total cost</b>	<b>2,784,000</b>

Annual operating costs for labor, supplies and general works are based on percentages given in Peters and Timmerhaus (1991).

<sup>a</sup>Capital costs (Table 4) divided by an economic life of 10 years, rounded off.

**Table 9. Summary of costs for phosphoric acid activation of pecan shells**

Purchased equipment cost <sup>a</sup>	\$1,448,000
Capital cost <sup>a</sup>	\$4,876,000
Total fixed capital investment <sup>b</sup>	\$6,324,000
Total annual operating cost <sup>c</sup>	\$2,784,000
Estimated annual production of carbon <sup>d</sup>	960,000 kg
Estimated cost for activated carbon	\$2.89/kg

<sup>a</sup>See Table 9.

<sup>b</sup>Purchased equipment cost plus capital cost.

<sup>c</sup>See Table 10.

<sup>d</sup>Based on a 3,000 kg/day output and a 320 day/year production schedule.

## Summary and Conclusions

Three different process flow diagrams were developed for processing pecan shells by steam activation and phosphoric acid activation and sugarcane bagasse by steam activation. Process flow diagrams, besides simplifying material and energy balance calculations, offer a systematic approach in determining purchased equipment costs and total fixed capital investment. Costs can be estimated from a combination of vendor quotes and printed literature as carried out in the current study. Capital cost estimation may be used to calculate capital investment using information available in the published literature on ranges of process-plant component costs. Design of most process equipment follows accepted standard formulae and methodology used in engineering practice.

From these process flow diagrams, an estimated fixed capital investment was developed and an estimated product cost for each different feedstock and activation condition. Many specific details could be changed without significantly affecting the designs, such as using coal tar as a binder instead of molasses, or changes in pyrolysis or activation conditions. For example, one of the diagrams was used to describe steam activation of the bagasse/binder pellets.

The same diagram can be used to describe other methods of physical activation besides steam, such as carbon dioxide and combinations, such as steam and air or carbon dioxide and air, with little change in process design. Activation of agricultural by-products involving concurrent use of phosphoric acid and air imparts negative charge on the carbon, and the resulting carbon appears useful in removal of metal ions from solution (Toles et al., 1998). The potential for improved metal ion adsorption with concurrent steam activation and air oxidation would add to the range of pollutants that could be adsorbed by bagasse-based carbons to include not only organics but also metal ions.

Steam-activated pecan shell carbon manufacture required less equipment in the process flow sheet and fewer steps, but had a lower yield compared with acid activation. Phosphoric acid activation required more steps and more equipment, but the product costs only a little more to manufacture, because of the higher yield of final product in the acid activation process. The least efficient process was the steam activation of sugarcane bagasse that required a high fixed

capital investment and high annual operating cost, but had a relatively low product yield. Therefore, this process generated the highest product cost.

Our estimated product cost for steam-activated pecan shell carbon was \$2.78/kg. High quality, high surface area, granular activated carbons made from steam activation of coal or coconut shell sell for \$3.30/kg and more, depending on their particular use. If the pecan shell-based carbons are used effectively in a particular niche market, they could sell for \$4.00 to 5.00/kg. In this case, the difference in product manufacturing cost and product sales cost could be sufficient to realize a profit for the manufacturer. In the case of phosphoric acid-activated pecan shell carbons, our estimated product cost was \$2.89/kg. Acid-activated, pecan shell-based carbons have been shown to possess superior metal ion adsorption compared to peat-based and coconut shell-based commercial carbons (Johns et al., 1999). Therefore, these carbons could be sold in a niche market for metal ion-adsorbing carbons. Effective, metal ion-sequestering carbons made from coal sell for about \$20/kg. Therefore, there is a considerable cost differential between our manufacturing cost and a potential selling price for this carbon in the commercial marketplace.

Toles et al. (2000a; 2000b) developed estimated costs of production for both steam-activated and phosphoric acid-activated almond shell carbons. They determined a production cost of \$1.54/kg for steam activation of almond shells (Toles et al. 2000a) compared to \$2.78/kg for steam activation of pecan shells given in this study. Their inputs were different from the inputs used here. They used a shell input of 14,000 kg/day and a carbon output of 2,180 kg/day versus our input of 10,000 kg/day and carbon output of 1,370 kg/day. Toles et al. (2000b) calculated production costs of \$2.45/kg for phosphoric acid-activated almond shell carbon compared with our value of \$2.89/kg for pecan shell acid-activated carbon. Again, as with the steam-activated carbon comparison, their shell input and shell output values were higher. They based their production costs on a 14,000 kg/day shell input and a 4,900 kg/day shell output compared with our 10,000 kg/day shell input and 2,964 kg/day output.

Our estimated cost for steam-activated bagasse carbon was \$3.12/kg. This is a relatively high cost of production if bagasse-

based carbon is to be used for general use in such applications as treatment of municipal or industrial wastewater. Carbons used in these applications normally sell in bulk for about \$1.00/kg, well below the production cost in this study. Additional value can be added by addressing niche markets, such as metals adsorption or potable water treatment, either in point-of-use (POU) or point-of-entry (POE) water filtration systems. In these selected niche markets, commercial carbons sell for \$4.00/kg and up. Moreover, the difference in manufacturing cost (\$3.12/kg) and product sales cost, as determined by the manufacturer, could be sufficient to realize a profit for the seller.

The possibility of manufacturing bagasse-based carbons at less cost than \$3.12/kg should be considered, since the sale of activated carbons takes place in a competitive market. Carbons can be manufactured more economically in plants with a larger throughput than the 10,000 kg/day throughput considered here. Doubling or tripling the throughput will result in a higher total fixed capital investment, but the higher yearly output of product should result in lower product costs. The estimates given for total fixed capital investment in our study reflect a turnkey operation built with modern engineering technology and all new equipment. Substantial savings in equipment and infrastructure could be realized by renovating existing structures and retrofitting existing manufacturing facilities and equipment. In one example, a carbon manufacture could modify an existing process with little or no equipment change and a substantial cost savings could be realized. In another example, a carbon manufacturing facility could be constructed as part of or adjacent to a raw sugar factory. The sugar mill could supply power and activation steam to the carbon plant from burning bagasse, use any spare power generated from the carbon plant and provide an existing wastewater treatment facility. Additionally, transportation and raw materials costs would be minimized and construction costs would be reduced. The same scenario could involve pecan shellers, as well.

Based strictly on the production costs presented, further research on uses for bagasse-based granular activated carbon should focus on developing a high quality carbon for niche markets, such as metals remediation. Few effective metals adsorbing carbons are commercially available, and the addition of a new product in this particular niche market could justify relatively high production and sales costs.

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