Heating Buildings and Business Operations with Biomass Fuel:

A Planning Guide

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Abstract

Significant cost savings may be possible when locally produced biomass is used to heat large buildings, farm operations, and heat-intensive commercial ventures such as food processing, greenhouses, and fuel alcohol and biodiesel production. Biomass fuels in this context are solid plant-derived products, including grain, pelleted plant material and wood chips, which are alternatives to conventional fossil fuels. This guide introduces the steps involved in planning the installation of a biomass-fueled heating system that will safely and perhaps economically meet the needs of operators of larger scale heating systems in agricultural, institutional and commercial applications. Critical factors influencing heating system performance include fuel quality, furnace design and exhaust gas venting options to reduce airborne pollution.

Introduction

Common biomass heating fuels include cordwood, coal, corn kernels, cherry pits, wood chips and wood pellets made from compressed sawdust. Less common biomass fuels include switchgrass, salix (short-rotation forestry willow), sugar beet pulp, ethanol distiller's grain, oilseed meal from biodiesel processing, waste-paper, livestock manure and cropland residues such as corn stover.

Pros of biomass-fueled systems

- The processing and transportation of locally produced biomass fuel, and the installation, operation and servicing of biomass-fueled heating systems provide new employment opportunities.

- Use of locally produced biomass fuel reduces the need to import costly fossil fuel. Biomass fuel dollars remain at home, strengthening the local economy.

- Biomass fuel may be more economical than propane, electricity, fuel oil and, in some cases, natural gas. The cost benefit of biomass heating fuel may be significant in large-scale furnaces for commercial or institutional applications.

- Current fossil fuel prices are volatile. This makes it difficult for managers of large-scale heating systems to predict energy costs from one year to the next.

- Properly engineered and maintained furnaces burn biomass cleanly and safely with minimal airborne pollution.

- Ash produced from biomass-fueled furnaces can be used as a plant nutrient source for growing more biomass.

- The productivity potential of Michigan soils and climate creates great potential for the production of solid fuel feed-stocks within relatively short distances.

Cons of biomass-fueled systems

- Biomass-fueled heating systems tend to have higher capital and maintenance costs than fossil-fueled systems.

- To ensure safe furnace operation with minimal pollution, vigilance is needed to ensure that biomass producers provide clean, properly sized and contaminant-free fuel. The heating system operator must maintain a rigorous fuel quality control program.

Use of locally produced biomass fuel reduces the need to import costly fossil fuel. Biomass fuel dollars remain at home, strengthening the local economy.

Dangerous airborne emissions are possible without the proper furnace design. Some outdoor wood boilers have shown a need for exhaust cleaning and engineering improvements.

- Biomass-fueled heating systems occupy more floor space than fossil-fueled systems. Additional space is needed to store biomass fuel.

- Some biomass fuels may not be price-competitive with natural gas and other fossil fuels.

- Neighboring citizens and/or governmental units may have a negative perception of biomass-fueled furnaces, despite the fact that these furnaces, when properly maintained, are environmentally friendly. A strategy to inform the local public and build local support should be developed prior to furnace installation.

- Biomass pellet fuel is more expensive than raw, unprocessed biomass (e.g., chipped wood waste) because of the costs associated with pellet manufacturing. Some large-scale furnaces are capable of burning both pelleted and non-pelleted biomass fuel. Residential-scale furnaces are generally not equipped to burn raw, unprocessed biomass such as wood chips. Some residential furnaces can burn wood pellets only. Other residential units are capable of using several fuels, including wood pellets, corn kernels, cherry pits and other aggregated solid fuels.

- Because biomass fuels generate less heat per unit of volume than fossil fuels, transportation distances between producers and heating systems are critical for biomass systems to be economically viable.

- Dangerous airborne emissions are possible without the proper furnace design. Some outdoor wood boilers have shown a need for exhaust cleaning and engineering improvements.

- The Michigan Department of Environmental Quality (MDEQ) requires an air permit for all non-residential biomass-fueled heating systems. Air permits are not currently needed for residential installations. The cost of these permits may be substantial.

Operations Issues

Energy price comparison

Heating fuel prices are expressed in various and sometimes confusing units. The following example provides a convenient method of comparing energy prices from different sources. Let's say we wish to calculate the annual fuel cost for a 2,000-square-foot residence in Michigan. The residence will require, on average, a total of 85.3 million British thermal units (Btu) of heat energy throughout a typical Michigan winter. The annual heating bill, H, is calculated as such:

$$H = \frac{85.3\ A}{B\ C}$$

In this example, A = Michigan average retail energy price per pricing unit, B = heat content of fuel in million BTU per pricing unit and C = furnace efficiency factor. As shown in Table 1, the bill varies greatly, with coal as the least expensive option, followed by wood chips, natural gas, oak wood, corn kernels and wood pellets. Heating oil, propane and electricity are the most costly alternatives. Coal is not advised as a heating fuel unless the furnace is designed to eliminate hazardous airborne emissions (sulfur, mercury) that commonly result from burning coal.

Wood furnace efficiency varies from one furnace design to the next. In Table 1,

Table 1. The estimated annual heating bill for a 2,000-square-foot residence in Michigan with various energy sources.

Fuel	C	D	E	A
electricity	$0.1124 / kWh	0.00341 MBtu / kWh	1	$ 2,812
propane	$2.39 / gal	0.0915 MBtu / gal	0.85	$ 2,621
heating oil	$2.89 / gal	0.1399 MBtu / gal	0.8	$ 2,203
wood pellets	$200 / ton	15.3 MBtu / ton	0.8	$ 1,394
natural gas	$11.01 / Mcf *	1.0265 MBtu / kcf	0.85	$ 1,076
oak wood (dry)	$150 / cord	25 MBtu / cord	0.5	$ 1,066
corn kernels	$3.66 / bushel	0.3809 MBtu / bushel	0.8	$ 1,025
wood chips	$50 / ton	10.2 MBtu / ton	0.7	$ 597
coal	$75 / ton	29 MBtu / ton	0.8	$ 276

A 2,000-square-foot home in Michigan uses nearly 85.3 million Btu of heat (MBtu) per winter. The annual heating bill is calculated as such: A = annual heating bill in dollars ($A = BC \div DE$); B = Energy demand (MBtu / year) = 85.3; C = retail fuel price; D = heat content of fuel; E = furnace efficiency factor. * Mcf = thousand cubic feet.

a low efficiency of 0.5 is estimated for fireplaces and woodstoves that are not equipped with advanced heat recovery systems such as a catalytic converter or a dual-stage combustor. Without this equipment, much of the energy available in wood fuel is wasted in the form of heat and smoke exiting the chimney.

Prices for corn, fuel oil, propane, natural gas, electricity and wood pellets were obtained from the U.S. Department of Energy (**http://www.eia.doe.gov/neic/experts/heatcalc.xls**). The price of wood chips was obtained by a private communication with a Michigan supplier in November 2007.

Examples of biomass installations

Figure 1 illustrates the components of an institutional-scale solid-fuel combustion system designed to burn biomass. The system is made up of five primary components: the fuel storage bin, the fuel handling system, the combustion system, a computerized control system and a secondary fossil-fueled boiler. The facility is designed to accept semitrucks that deliver wood chips to the storage bin. The fuel handling system consists of belt conveyors, safety shutoff switches and covered troughs powered to move the chips from the storage bin into a metering bin. The metering bin is unloaded by an auger system that automatically regulates the flow of fuel into the combustion system. A computerized control system regulates the main components of the heating system, including the augers, belt conveyors, blowers, exhaust gas monitors, emergency shutdown system and fire suppression devices.

A secondary fossil-fueled boiler is located adjacent to a biomass-fueled boiler. As a general rule, biomass-fueled furnaces are capable of high thermal efficiencies only
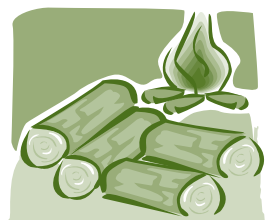
...institutional-scale biomass-fueled systems are often shut down during low heat demand periods, and the secondary fossil-fueled boiler automatically turns on.

Figure 1. Components of an institutional-scale solid-fuel combustion system designed to burn wood chips.
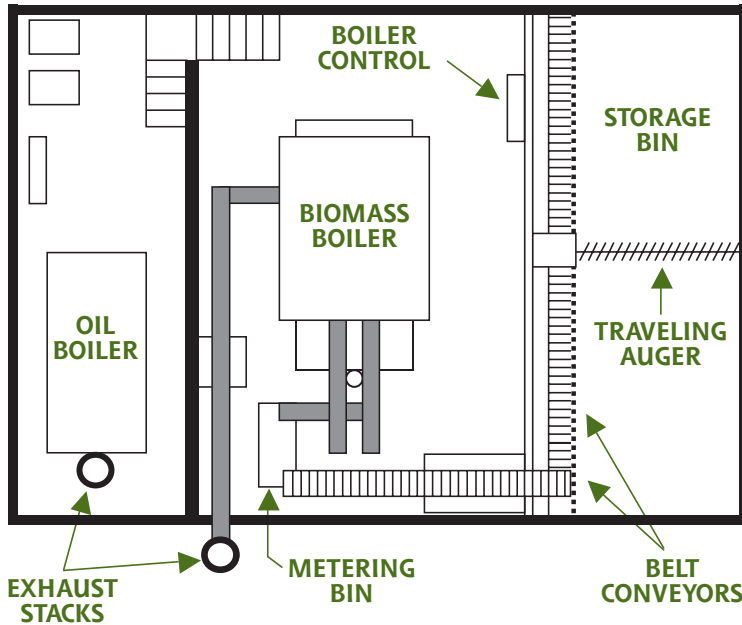
(Source: Messersmith Manufacturing, Bark River, Mich.; **www.burnchips.com***)*

when operated at maximum power. As a result, institutional-scale biomass-fueled systems are often shut down during low heat demand periods, and the secondary fossil-fueled boiler automatically turns on.

Maker (2004) published an extensive guide to help facility planners considering the installation of wood-chip-fueled heating systems for institutional or commercial applications. That reference contains an excellent discussion of financial strategies underlying the planning and construction of institutional-scale biomass heating units.

Another useful reference is the industry journal *Bioenergy International*, which provides engineering and economic details of the rapid growth of the European biomass heating fuel industry (**www.bioenergy-international.com**). Focusing mainly on the manufacture of fuel pellets from wood and other biomass materials, the journal

chronicles the growing number of European installations of large-scale boiler systems for electric power production, municipal district heating, institutional and commercial heating, and so on. When examining these and other information sources, be sure you have a clear understanding of any subsidy programs (e.g., government incentives), which may not be available for your system.

Definitions

The British thermal unit (Btu) is defined as the energy to raise the temperature of 1 pound of water by 1 degree Fahrenheit. As a rough approximation, one Btu is the energy produced by burning a single wooden match. Burning a single corn kernel (15.5 percent moisture) produces approximately 5.24 Btu of energy. Earlier it was mentioned that heating an average 2,000-square-foot residence throughout a typical Michigan winter requires 85.3 million Btu. To produce this much energy would require burning approximately 85.3 million matches or 85,300,000 / 5.24 = 16,278,626 corn kernels (12,540 pounds or 224 bushels).

Heat of combustion is defined as the amount of combustion energy available per pound of fuel. For example, the heat of combustion of 15.5 percent moisture corn kernels is 6,808 Btu per pound or 5.24 Btu per corn kernel (approximately 1,300 kernels per pound). Propane has roughly twice the heat of combustion: 15,000 Btu per pound of fuel.

An important consideration for operators of large-scale heating systems is the overall furnace efficiency. This is the percentage of available power that is transferred from the fuel to the surroundings as useful power. The two main components

of overall efficiency are thermal efficiency and combustion efficiency.

Low thermal efficiency occurs when too much hot flue gas exits a chimney into the atmosphere. As the exit gas temperature increases, the power loss increases and the thermal efficiency decreases. The higher the flow rate of the exit gas, the greater the power loss and the lower the thermal efficiency. Furnaces with high thermal efficiency are designed to transfer maximum power from the flue gas to the surroundings.

In contrast, combustion efficiency refers to how completely a furnace burns fuel. It is important to note that complete combustion fully transforms biomass fuel into the flue gases carbon dioxide (CO_2) and steam (H_2O), both of which are transparent to the naked eye. In other words, high combustion efficiency is indicated when a chimney emits colorless gas. Low combustion efficiency occurs under oxygen-depleted conditions, and the fuel does not fully transform into CO_2 and steam. Instead, the fuel decomposes into carbonaceous ash and organic gases, which are smoky looking. Such incomplete combustion fails to extract the maximum power available in the fuel. This problem is corrected by raising the oxygen concentration of the furnace supply air to so-called stoichiometric conditions so that the fuel fully combusts into CO_2 and steam. Such complete combustion produces maximum power per unit of weight of fuel consumed.

Electric furnaces are typically 100 percent efficient. Each Btu of electric energy supplied to an electric furnace typically converts to a Btu of useful building heat energy. However, the initial generation of electricity at a commercial coal or natural gas-fueled electric power plant is only about 40 percent efficient. Therefore, using electricity for building heat is like burning coal or natural gas in a 40 percent efficient furnace.

Furnaces that are fueled with propane, natural gas or biomass are usually limited to 80 to 85 percent overall efficiency because a certain amount of latent heat is needed to ensure that steam in the flue gas is removed from the exhaust stack. The only way to overcome this is through the use of a moisture-condensing system to extract additional heat from the steam. This adds significant cost with only a small gain in efficiency (5 to 9 percent). A well-designed biomass furnace will extract the most heat possible from the flue gas without causing water condensation in the exhaust stack. Let us return to the hypothetical example above, where a 100 percent efficient furnace burns 636 corn kernels per minute, producing 200,000 Btu per hour of useful power. It turns out that a more realistic overall efficiency would be up to 85 percent for a typical corn-burning furnace. Such a furnace burning 636 corn kernels per minute would produce a total of 0.85 x 200,000 = 170,000 Btu per hour of useful power.

Currently, there is no reliable method of estimating the overall efficiency of a biomass-fueled furnace by simply visually inspecting the furnace design. Accurate determination of overall furnace efficiency requires a trained professional to perform calculations based on measurements of exhaust gas flow rate and temperature. Before purchasing a biomass-fueled furnace, it is important to ask the manufacturer to verify its overall efficiency.
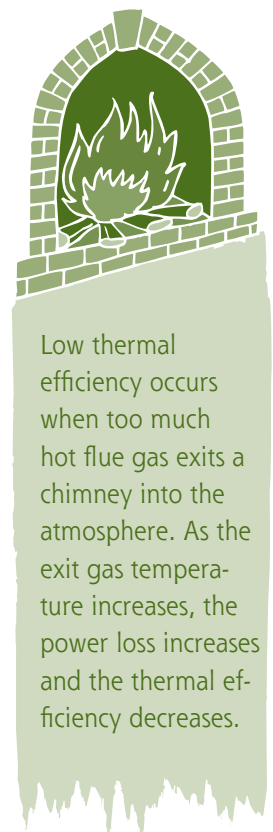
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Economics of Investment

How one approaches the economics of a decision to switch to biomass fuel sources depends on whether we are examining the installation of a new system or the replacement of a functional existing system.

Comparing new systems

In situations where we are comparing new systems with one alternative being a traditional system (e.g., a fossil fuel system) and the other a biomass system, one needs to evaluate the investment costs relative to the annual operation costs (e.g., fuel, repairs, labor for daily management, insurance). If one system has both lower investment cost and lower annual operation costs, then the economics of the decision are straightforward — choose the one with the lower costs. On the other hand, if the one system has a lower investment cost but higher annual operations costs than the alternative, then a more in-depth analysis is needed.

As a first step in this process, calculate how much more expensive the high investment cost system is than the lower cost system. Next, determine how much more expensive the annual costs of operation of the system with the lower investment cost are compared with the operating cost of the system with the higher investment costs. With these two figures, it is possible to calculate a payback period in years for the system with the higher investment cost[1]. This is done by dividing the difference in the investment by the difference in annual operating costs. If we assume the two systems

have a similar useful life of 15 years and you desire an 8 percent return on your investment, then you should be looking at a payback period of 8 years or less. For a return on investment of 10 percent, then the payback period would be 7 years or less.

EXAMPLE:
A farmer desires to heat a previously unheated small farm shop. He is considering a biomass stove that will burn either corn or wood pellets, or a propane stove. The cost of the installed biomass stove will be $2,600; the propane stove will be $1,300. He has a good source for wood pellets from the local sawmill, and he estimates the annual cost for the fuel, repairs and time to supply the stove with fuel to be $440. The annual cost for fuel and repairs for the propane stove will be $620. These figures indicate that the biomass stove's investment cost will be higher by $1,300 ($2,600 - $1,300) and its annual cost of operation will be lower by $180 ($620-$440). Dividing the savings in operating costs into the difference in investment cost gives a payback period for the biomass stove of 7.2 years — a reasonable return on investment.

Replacing an existing system with a new system

The decision to make an investment in a new heating system, either traditional or biomass, to replace an existing system uses basically the same method with slight modifications. In this situation, you are comparing the investment cost of the new system to the value of the existing system and the difference in operating

> Increases in moisture concentration significantly reduce the heat of combustion of all biomass materials.

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[1]The use of the payback period is a simple tool for evaluating investments. Because of its simplicity, it is not as powerful as more complex and precise tools such as internal rate of return (IRR) or net present value (NPV) methods. To illustrate the use of these tools is beyond the scope of this publication. Even with its limitation, the payback period is a good tool to examine this decision process.

costs. It is likely that the existing system would have a shorter life than the planned new system, so adjustments are needed when defining the investment cost. Several steps are involved in making this adjustment. First, estimate the value of the existing system if it could be removed and sold on the used market. Depending on the heating system and age, this value could range from scrap metal value to a high percentage of its original cost. It is also necessary to estimate how many years of useful life remain for the existing system. The next step is to determine the share of the investment cost of the new system to be compared with the remaining value of the existing system. First, specify the expected years of life of the new investment. Divide this value into the number of years that the existing system has remaining to determine the percentage of the useful life used as a replacement for the existing system. Then multiply this percentage by the total investment cost of the new system to establish the comparable cost of the new system in relationship to the existing system.

The next step involves comparing the annual operating costs of the existing system and the new system. It would be expected that the existing system would have higher annual operating costs because of increased repairs and lower efficiency. Also, it may have higher fuel costs because the new system might be using a lower cost fuel source.

The final step is to determine the payback period if the existing system is replaced with a new system. This is done by dividing the difference in the investment costs of the existing system and the new system by the difference in the annual operating costs of the two systems.

EXAMPLE:
In this case, the farmer is already heating the small farm shop with a propane stove. He is considering replacing the still functional propane stove with a wood pellet stove. As in the earlier example, the cost of the installed biomass stove will be $2,600 with an expected annual cost of operation of $440. The existing propane stove is not old and should last another 10 years. If he were to remove it, the salvage value would be $100. The annual cost of operation will be slightly higher than with a new stove, amounting to $630 annually. Assuming a 15-year life for the biomass stove, 67 percent of its life will be depleted as a replacement for the propane stove (10 years of remaining life of the propane stove divided by 15 years of total life of the new biomass stove). This makes the net investment cost of the biomass stove to be $1,742 ($2,600 x .67) These figures indicate that the biomass stove has a higher investment cost of $1,642 ($1,742 - $100) and its annual cost of operation will be $190 ($630 - $440) lower. Dividing the savings in operating costs into the difference in investment cost indicates that the payback period for the biomass stove is 8.6 years — perhaps a more questionable investment.

Critical combustion factors

Biomass composition strongly controls heat of combustion. Concentrations of lignin, oil, fiber and moisture are critical. The heat of combustion of fully dry plant biomass can be estimated by considering that the majority of the dry weight of virtually all plant biomass consists of carbon (C), hydrogen (H) and oxygen (O) atoms in polysaccharide molecules (e.g., cellulose, hemicellulose, starch). As a result, nearly all types of plant biomass will tend
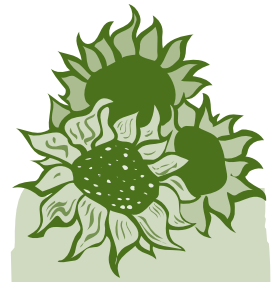
Most of the purchased biomass fuel for large, institutional-scale furnaces is green or undried wood chips, in which 30 to 55 percent of the delivered weight is water.

The right furnace design involves so-called oxidizing combustion, which is accomplished by injecting excess supply air into a furnace's combustion chamber.

to have roughly the same heat of combustion per unit of dry weight, regardless of the source of biomass. For example, consider two important features in Table 2: the majority of the dry weight of maple, spruce and corn consists of carbon, hydrogen and oxygen; and the concentrations of carbon, hydrogen and oxygen are approximately the same for each type of biomass indicated in that table. Furthermore, individual heats of combustion of maple, spruce and corn are within a narrow range of 8,120 to 8,720 Btu per dry pound, a difference of only 7.4 percent of the minimum value reported. In stark contrast, Table 2 illustrates the properties of fuel oil and natural gas: depleted in oxygen, these fossil fuels exhibit much greater heats of combustion than maple, spruce or corn.

Increases in moisture concentration significantly reduce the heat of combustion of all biomass materials. For example, Buffington (2006) reported that fully dry corn (0 percent moisture) has a heat of combustion that varies between 8,000 and 8,500 Btu per pound. This value depends on the variety of corn, storage conditions, the drying method, and weather conditions during the harvest

and growing seasons. Buffington (2006) also reported that the heat of combustion of a pound of 15.5 percent moisture corn is 6,808 Btu, a reduction of nearly 17.5 percent below the average value (8,250 Btu / lb) of fully dry corn.

Maker (2004) and Buffington (2006) provide a convenient formula to estimate the effect of moisture concentration on the heat of combustion of biomass:

$$G = G_1 (1 - m/100)$$

G is the heat of combustion of biomass containing a moisture concentration of m weight percent. G_1 is the heat of combustion of the same biomass material in a fully dried state. Ranges of heat of combustion (G_1) for several biomass materials are listed in Tables 3 and 4.

Most of the purchased biomass fuel for large, institutional-scale furnaces is green or undried wood chips, in which 30 to 55 percent of the delivered weight is water. For example, mill chips usually contain approximately 40 percent moisture; whole-tree chips are slightly higher in moisture concentration. Moisture levels vary significantly — 5 to 10 percent — by the season of the year and the species of wood.

Table 2. Composition analysis and heat of combustion data for maple, spruce, corn, fuel oil and natural gas. (SOURCE: MAKER 2004.)

	maple	spruce	corn	fuel oil	natural gas
Heat of combustion (Btu/dry pound)	8,350	8,720	8,120	19,590	22,080
% carbon	48.94	51.97	47.63	86.4	71.6
% hydrogen	5.6	5.59	6.7	12.7	23.2
% nitrogen	0.22	0.43	1.46	0	0
% sulfur	0.16	0.1	0.11	0.7	0
% oxygen	43.67	41.24	42.69	0.2	0.9
% ash	1.41	0.67	1.45	trace	0

Table 3. Heat of combustion (G_1) of dried wood *(Maker 2004)*.

Woodstoves	Low (Btu/lb)	High (Btu/lb)
ash, white	8,246	8,920
birch, white	8,019	8,650
elm	8,171	8,810
hickory	8,039	8,670
maple	7,995	8,580
oak, red	8,037	8,690
oak, white	8,169	8,810
poplar	8,311	8,920
cedar, white	7,780	8,400
pine, white	8,306	9,900

High fuel moisture levels decrease burning efficiency because the significant portion of the fuel that is water is not combustible. Efficiency is lost because a large part of the energy available in the biomass is used to heat up and evaporate this moisture. (It takes 1,050 Btu to evaporate 1 pound of water.) One way to increase efficiency is to dry the fuel on site. However, the costs of building and operating such a dryer are high. For this reason, biomass fuel driers are almost never found in facilities sized below 10 million Btu per hour.

When comparing the costs of two sources of biomass that have different moisture levels, two adjustments need to be considered to ensure that you are getting the best value. The first adjustment relates to paying for only actual biomass, and not the water. The second adjustment is needed to take into account the energy needed to evaporate the moisture. To standardize the cost, the following equation can be used:

$$HC = G_1 \times (PDM/100) \times (PM/100 \times 1050)\backslash$$

HC is actual heat in Btu from combustion, G_1 is the heat obtained from 1 pound of 100 percent dry biomass, PDM is the percent dry matter of the fuel source, and PM is the percent moisture of the fuel source.

Table 4. Heat of combustion of selected biomass materials. (Moisture concentrations of each material were not reported.)

Fuel source	Heat of combustion (Btu/lb)
pine needle[1]	9,157
sunflower husk[1]	8,598
switchgrass[1]	8,254
short-rotation forestry willow[1]	8,254
alfalfa stems[2]	8,025
wheat straw[2]	7,714
rice hulls[2]	6,811
rice straw[2]	6,486
switchgrass[2]	7,766
willow wood[2]	8,424
hybrid poplar[2]	8,178
demolition wood[2]	7,916
yard waste[2]	7,009
mixed paper[2]	8,934
corn[3]	7,016
corn stover[3]	7,188
corncobs[3]	7,429
corn silage[3]	7,080
soybean stover[3]	7,339
sunflower stover[3]	6,676
sugar beet tops[3]	6,208

[1]Samson et al., 2000; [2]Jenkins et al., 1998; [3]Helsel and Wedin, 1983.

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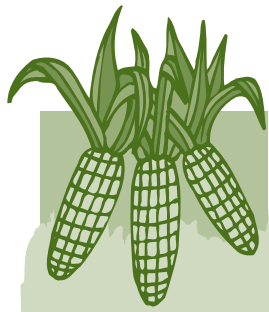
So-called slagging is the deposition of fly ash oxide coatings on metallic heat exchanger surfaces in furnaces...they act as thermal insulators.

For example, you might have the choice of two sources of corn, one at 14 percent moisture and the other at 30 percent moisture. To determine which is the better value, you would use the above equation. A pound of the 14 percent moisture corn would have a heat from combustion of 6,948 Btu [(8,250 Btu/pound corn x (86 percent dry matter/100)] - [(14 percent moisture/100) x 1,050 Btu]. A pound of 30 percent moisture corn would have a heat from combustion of only 5,460 Btu [8,250 Btu/pound corn x (70 percent dry matter/100)] - [(30 percent moisture/100) x 1,050 Btu]. Thus, the price per pound to be paid for the wetter corn should be only 78.6 percent (5,460/6,948) of that of the drier corn.

For institutional-scale furnaces, green biomass offers a major safety advantage. Green chips are almost unburnable outside the controlled conditions of the combustion chamber. Dry fuels, in contrast, combust readily. Systems that are intended to burn dry biomass fuel must have special fire suppression devices with sophisticated alarm signal systems.

Biomass combustion entails surface chemical reactions that occur on the outer surfaces of biomass. As a general rule, the smaller the average particle size of the biomass, the greater the surface area per unit weight of fuel and, in turn, the greater the combustibility. The risk of igniting a fire becomes most severe when biomass is in the form of small, dust-like particles. **It is important to prevent the buildup of excessive dust in the fuel storage and transportation equipment associated with a biomass-fueled combustion system**. Fire suppression systems are provided as standard equipment with large-scale biomass-fueled furnaces for institutional and commercial applications. It is important to regularly test and maintain these fire suppression systems.

Basics of biomass combustion

The majority of the dry weight of nearly all plant matter consists of carbon (C), oxygen (O) and hydrogen (H) atoms in the form of polysaccharide molecules. For example, wood consists of 40 to 50 percent cellulose, 15 to 25 percent hemicellulose and 15 to 30 percent lignin, depending on the wood variety. Table 5 shows that the primary constituent in

Table 5. Proximate analysis of yellow dent corn grain (Watson, 2003).

Characteristic	Range	Average
Starch (%, dry basis)	61 - 78	71.7
Fiber (neutral detergent residue) (%, dry basis)	8.3 - 11.9	9.5
Protein (%, dry basis)	6 - 12	9.5
Pentosans (as xylose) (%, dry basis)	5.8 - 6.6	6.2
Fat (%, dry basis)	3.1 - 5.7	4.3
Cellulose + lignin (acid detergent residue) (%, dry basis)	3.3 - 4.3	3.3
Sugars, total (as glucose) (%, dry basis)	1.0 - 3.0	2.6
Ash (oxide) (%, dry basis)	1.1 - 3.9	1.4

corn kernels is starch (71.7 percent), followed by smaller concentrations of cellulose, protein, xylose, fat, lignin and glucose.

With the right furnace design, plant biomass materials burn cleanly when carbon and hydrogen atoms in the fuel completely react with oxygen to form carbon dioxide (CO_2) and steam (H_2O). In this case, the right furnace design involves so-called oxidizing combustion, which is accomplished by injecting excess supply air into a furnace's combustion chamber. This design is standard in ordinary corn-burning stoves, wood pellet furnaces, and larger scale furnaces in institutional and commercial applications. Vital to this design is the so-called residence time: biomass in the combustion chamber is in residence with high-temperature oxygen gas for sufficient time to fully decompose into CO_2 and steam.

In contrast, fireplaces and woodstoves are not usually equipped with a fan to supply excess combustion air. As a result, they do not operate under sufficiently oxidizing conditions to fully decompose biomass into CO_2 and H_2O. Instead, biomass thermally decomposes into several intermediate gases, many of which are toxic and smoky-looking and have residual fuel value. In other words, given enough time within the burn chamber, these compounds would produce energy by reacting with oxygen and fully decomposing into CO_2 and steam. More than 40 airborne compounds are produced by wood combustion (EPA Report 453/R-93-036, 1993). Prevalent compounds are methane, carbon monoxide, alkanes, aldehydes, nitrogen oxides, acids and particulate carbon.

Nitrogen-containing biomass

Atmospheric air contains 78 percent nitrogen (N_2). At elevated temperatures, some N_2 molecules in air will react with oxygen to produce nitrogen oxide (NO_X), a source of acid rain and a pollutant regulated by the U.S. Environmental Protection Agency (EPA). This reaction typically occurs during the combustion of any fuel in air, even natural gas and gasoline. The extent of this reaction depends on temperature, oxygen concentration, airflow and the presence of nitrogen in the fuel. This reaction is pronounced during combustion of biomass that contains high concentrations of organic nitrogen. Examples include animal manure and high-protein biomass such as ethanol distiller's grain, seeds and beans. In contrast, it is less severe during combustion of the many types of plant biomass that are naturally low in organic nitrogen, including wood, corn kernels, cropland stover and grass.

Large-scale biomass combustors in agricultural, institutional and commercial applications are typically required by law to have the right equipment to reduce NO_X emissions. To accomplish this, sophisticated equipment is used: so-called dual-stage combustion and/or the injection of ammonia or urea into the combusting biomass. Smaller scale furnaces, such as residential corn or wood pellet furnaces, are not equipped in this manner. Measurements of NO_X emissions from such small-scale biomass-fueled furnaces are not yet reported in the public literature.

Ash chemistry, safety and utilization

The dry weight of nearly all types of plant biomass consists mainly of C, O and H atoms. Plant biomass also contains smaller

In single-stage combustion, high-velocity air is injected into a single combustion chamber to oxidize the biomass fuel into CO_2, steam and oxide ash.

> The amount of ash produced during biomass combustion depends on the type of biomass fuel and ranges from 1 to 5 percent of the dry weight of the initial biomass material.

quantities of nitrogen (N) and trace amounts of silicon (Si), sodium (Na), potassium (K), phosphorus (P), calcium (Ca), iron (Fe), zinc (Zn), manganese (Mn), copper (Cu) and magnesium (Mg). These trace elements enter the roots of living plants as dissolved ions, acids or salts in water. These elements deposit in the cells of a plant, and their concentrations in the plant depend on the soil nutrient concentration and the plant variety. During biomass combustion, these trace elements react with oxygen to form oxides (SiO_2, Na_2O, K_2O, P_2O_5, CaO, FeO, MgO), which react with one another to form solid crystals or viscous liquids at elevated temperatures. Upon cooling, these oxides form "bottom ash" (ash that is collected at the bottom of the combustion sector in a furnace) or fly ash particulates (microscopic airborne particles that are carried into the chimney).

As shown in Table 6, chemical analysis was performed on corn kernels obtained from a local Michigan grain elevator. Results indicate the main constituents are P and K, with smaller amounts of Mg and S, and much smaller amounts of Ca, Na, Fe, Zn, Mn and Cu. After burning a sample of the same corn in a residential corn-burning furnace, x-ray diffraction analysis revealed that the bottom ash consisted of potassium phosphate, sodium metaphosphate and oxide glass. In Table 6, the composition of the bottom ash follows the same trend as the corn kernel (rich in P and K), although the Fe concentration was much higher (1700 ppm in ash versus 21 ppm in kernel). Further analysis revealed that these oxides slowly dissolve steel surfaces lining the furnace combustion chamber. In turn, this is likely a source of the high Fe concentration in

the bottom ash in Table 6. The amount of ash produced during biomass combustion depends on the type of biomass fuel and ranges from 1 to 5 percent of the dry weight of the initial biomass material. For example, Table 5 indicates that the amount of ash formed during corn kernel burning ranges between 1.1 and 3.9 percent of the original dry weight.

As a general rule, biomass fuel containing high concentrations of silica or clay tends to produce higher amounts of ash during combustion. For example, soil particles can be embedded in wood logs that have been dragged across the forest floor during harvesting. Another example is switchgrass that is grown in the summer, which contains higher silica concentrations than winter switchgrass.

So-called *slagging* is the deposition of fly ash oxide coatings on metallic heat

Table 6. Chemical analysis of corn kernels and bottom ash from a corn-burning furnace.

Components	Corn kernel	Bottom ash
P (%)	0.25	21.80
K (%)	0.28	24.3
Mg (%)	0.09	8.9
S (%)	0.08	0.0065
Ca (%)	<.01	0.36
Na (%)	<.01	0.016
Fe (%)		0.17
Zn (ppm)	19	922
Fe (ppm)	21	
Mn (ppm)	6	377
Cu (ppm)	2	115
B (ppm)		66
Al (ppm)		92

(Source: Corn Marketing Program of Michigan.)

exchanger surfaces in furnaces. The main problem with these oxide coatings is that they act as thermal insulators. Over time, oxide coating buildup significantly reduces furnace thermal efficiency. Removing these coatings is an important part of routine furnace maintenance. Some boiler systems are equipped with pneumatic nozzles that automatically cycle on and off, directing high-pressure air at heat exchanger surfaces to dislodge slag. Smaller furnaces are not designed with this equipment and typically have manually operated steel scrapers to remove slag deposits on heat exchanger surfaces. Routine manual operation of the scrapers is a critical part of furnace maintenance.

Ash is an inhalation hazard and should be stored in securely covered, noncombustible containers. Ash should also be stored under dry conditions because it tends to be water-soluble. It is important to avoid spilling aqueous solutions of ash into storm drains or municipal sewers. Because of its water solubility, ash can be used as a plant fertilizer.

Single- versus dual-stage combustion

It is important to distinguish between the two main types of biomass-fueled combustion equipment: single-stage and dual-stage combustors. The simplest design is a single-stage combustor, which is typical in ordinary corn-burning furnaces and wood pellet furnaces, and in some large-scale furnaces that are used in municipal and commercial applications. In single-stage combustion, high-velocity air is injected into a single combustion chamber to oxidize the biomass fuel into CO_2, steam and oxide ash. A concern with injecting high-velocity air is that it can violently stir biomass fuel in the combus-

tion chamber, causing tiny fly ash particles to be carried into the exhaust gas and polluting the atmosphere. In large-scale institutional or commercial applications, an exhaust gas cleaning system such as a cyclone or a bag filter may be required before an air permit can be approved by the MDEQ. Measurements of fly ash emissions from residential-scale corn-burning furnaces are not yet publicly available. The Corn Marketing Program of Michigan is currently conducting scientific tests to evaluate airborne emissions from corn-burning furnaces.

Dual-stage combustors emit smaller concentrations of airborne particulates than single-stage combustors and are based on a more complex design. Although not yet available in residential-scale biomass-fueled furnaces, dual-stage combustors are commonly used in large-scale biomass furnaces for institutional and commercial applications. In dual-stage combustion, biomass is consumed in two consecutive stages: gasification and pyrolysis. In the first stage, biomass fuel is injected with oxygen-depleted air at elevated temperatures. This air is injected at low velocity to avoid violent stirring of the biomass, which would otherwise make too much particulate matter enter the exhaust gas stream.

In stage one, the injection of oxygen-depleted air prevents complete oxidation of biomass into CO_2, steam and ash; instead a solid, carbonaceous residue (charcoal) forms along with the gases CO, H_2O and others. All gases produced in stage one are subsequently injected into a pyrolyzer, which operates at high temperatures under oxygen-rich conditions. Oxygen-rich gas injected into the pyrolyzer explosively reacts with the gases injected from the stage one gasifier. Gases

emitted from the pyrolyzer are low in particulate matter because the pyrolyzer is supplied with low-particulate matter gases from stage one.

Design to reduce air pollution

Basic guidelines

In designing a biomass combustion system for any location, careful consideration must be given to reduce health risks from the inhalation of airborne pollutants. An air permit from the MDEQ is required prior to installing a biomass-burning unit at an agricultural, commercial or institutional establishment. An air permit is not currently required if the unit is installed at a residence, but all units must comply with the Michigan Air Pollution Control Rules, which include limits on visible emissions and particulate matter. If you are required to obtain an air permit, you may need to submit emissions data as part of the permit application. Emission data may be required for each type of fuel that will be burned in the burning unit. If you must conduct the test, it may be an expensive process. Be sure that the emissions from the unit have been tested by the manufacturer to ensure that it meets all state requirements. Biomass-burning units installed at commercial or institutional establishments may be required to be equipped with an air pollution control device such as a cyclone or an exhaust gas scrubber.

Biomass burners should be operated only using the fuels specified by the manufacturer. For corn-burning units, it is important to burn only clean corn kernels. Blends of corn kernels with dusty, fine particulate material included will produce greater amounts of exhaust stack

particulates upon combustion. It is also important not to burn seed corn -- this material is treated with chemicals, and burning it can release toxic pollutants. It is also important not to burn trash, chemicals, treated wood or other hazardous materials in your unit. Burning these items releases toxic chemicals and is a health and safety hazard. Commercial and institutional establishments are prohibited from burning waste except in an approved incinerator that has been permitted by the MDEQ.

The exhaust stack should, at a minimum, be taller than the rooflines of all nearby structures. Stacks that are too short do not allow the emissions to adequately disperse into the atmosphere. This is often the cause of nuisance complaints and can adversely affect your and your neighbors' health. The following procedure illustrates how to reduce airborne pollutants by controlling two main design factors: the height and the location of the exhaust stack. (For additional information, please refer to *Michigan Department of Environmental Quality Report: Air Pollution Control Rules, Part 2. Air Use Approval As Amended July 1, 2003*. You can also contact the MDEQ Environmental Assistance Center at 800-662-9278 or **www. deq-ead-env-assist@michigan.gov**.)

Exposure limits

All biomass-fueled furnaces emit airborne pollution at a rate proportional to the furnace power. The emission rate of each pollutant listed in Table 7 should be calculated for the type of fuel you plan on burning before you apply for an MDEQ permit. The procedure starts with looking up EPA emission factors, which are unique to various types of fuels. For example, let us consider a wood-fueled

furnace rated at 200,000 Btu per hour. Table 7 indicates that the emission factor for particulate matter is 0.4 pound per hour per million Btu of furnace power. Multiplying this factor by the furnace power of 0.2 million Btu per hour yields an emission rate of 0.08 pound of particulate per hour. Increasing the furnace power increases the rate of emission proportionately. For example, if the size of the furnace is raised to 1 million Btu per hour, the same emission factor is multiplied by 1 million Btu per hour, yielding an emission rate of 0.4 pound of particulate matter per hour.

The next step is to repeat this procedure for the remaining pollutants in Table 7. Keep in mind that Table 7 pertains to wood-fueled furnaces only. It is important to ask your furnace manufacturer to provide EPA-approved emission factors for other types of biomass fuel that you might consider burning in your furnace. Emission factors for corn-burning furnaces are not currently publicly available. The Michigan Corn Growers Association

is conducting scientific tests to provide these data.

Two main factors control whether the emission rates calculated above are harmful to human health: the pollutant concentration and the exposure time. In Table 8, the EPA specifies maximum permissible concentrations of airborne pollutants that are of most interest to operators of biomass combustors. For example, consider the case of particulates less than 10 microns in size (PM_{10}). If a human is exposed to PM_{10} for one year, Table 8 indicates that 50 micrograms (µg) per cubic meter is the maximum safe concentration of airborne PM_{10}. Notice in Table 8 that the maximum safe concentration of PM_{10} triples if a human is exposed for a shorter time of 24 hours. Notice also in Table 8 that smaller safe concentrations are stipulated when the particle size is below 2.5 microns ($PM_{2.5}$).

Table 7. Airborne pollutant emission factors for wood-fired boilers.

Pollutant	Emission factor*
particulate matter	0.4
oxides of nitrogen (NO_x)	0.49
sulfur dioxide (SO_2)	0.025
carbon monoxide (CO)	0.6
volatile organic carbon (VOC)	0.017

*Emission factors are expressed in units of pounds of pollutant emitted per hour divided by furnace power in millions of Btu per hour.

(Source: U.S. Environmental Protection Agency, Section 1.6 of AP-42.)

Table 8. The EPA provides the following National Ambient Air Quality Standards (maximum permissible concentrations) for criteria pollutants.

Criteria pollutant	Maximum permissible concentration
PM_{10} (annual)	50 µg/m^3
PM_{10} (24 hr)	150 µg/m^3
$PM_{2.5}$ (annual)	15 µg/m^3
$PM_{2.5}$ (24 hr)	65 µg/m^3
NO_2 (annual)	100 µg/m^3
SO_2 (annual)	80 µg/m^3
SO_2 (24 hr)	365 µg/m^3
CO (8 hr)	10 µg/m^3
CO (1 hr)	40 µg/m^3

(Source: Michigan's 2005 Annual Air Quality Report, August 2006.)

Stack height and location

Two design factors determine whether an exhaust stack poses an inhalation risk: the exhaust stack height, H_S, and the ground-level horizontal distance from the exhaust stack, Z (Figure 2). Increasing both factors improves dispersion of pollutants into the atmosphere. The following procedure helps the designer select both H_S and Z to achieve safe air quality.

The first step is to calculate the so-called *ambient impact*, which is the ground-level concentration of an airborne pollutant at a horizontal distance (Z) from the exhaust stack. If the ambient impact exceeds any permissible concentration in Table 8, the stack is unsafe. For example, let us assume H_S = 12.5 feet, H_B = 10 feet, and Z = 100 feet. Referring to Table 9, select the column with H_S = 12.5 feet and H_B = 10 feet. Then select the row with Z = 100 feet to identify the value of R = 0.011 in that table. R is the *annual ambient impact ratio* or the *annual AIR*. It is the ratio of the annual averaged hourly emission rate divided by the maximum annual ambient impact, in units of pounds per hour per $\mu g/m^3$. Recall our example of a 200,000-Btu-per-hour wood furnace emitting 0.08 pound per $\mu g/m^3$ of particulates per hour. For this case, the ambient impact at the property line is (0.08 / R) = 7.3 $\mu g/m^3$, which is well below the permissible PM_{10} concentration averaged over a year (50 $\mu g/m^3$) in Table 8. It is also below the permissible $PM_{2.5}$ concentration averaged over a year (15 $\mu g/m^3$). The next step is to repeat the above procedure for the remaining pollutants in Table 8.

It is instructive to modify this example by raising the size of the wood furnace to 1 million Btu per hour. Earlier we showed that such a furnace emits particulate matter at a rate of 0.4 pound per hour. Repeating the above procedure, set H_S at 12.5 feet, H_B at 10 feet and Z at 100 feet, and identify R = 0.011 from Table 9. The ambient impact is 0.4 / R = 36.4 $\mu g/m^3$, which is below 50 $\mu g/m^3$, the permissible PM_{10} concentration averaged over a year (Table 8). However, the same ambient impact is above 15 $\mu g/m^3$, the permissible $PM_{2.5}$ concentration averaged over a year in Table 8. The stack is, therefore, unsafe.

Figure 2. The ambient impact (ground-level concentration of airborne pollutants) at the property line is a strong function of the exhaust stack height (H_S) , the height of the neighbor's building (H_B) , and the distance between the stack and the property line (Z).
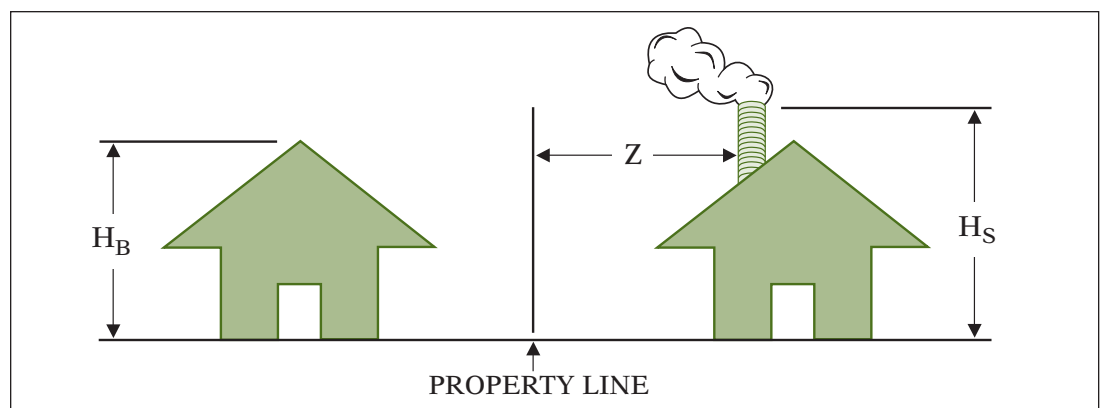
At this point, the designer has two options: increase the stack height or the distance to the property line, Z. In Figure 3, the ambient impact is calculated from the above procedure for two scenarios: a short stack (H_S = 12.5 feet) and a tall stack (H_S = 17.5 feet). As shown in Figure 3, the ambient impact significantly decreases as the distance (Z) increases. At all distances, the ambient impact is below the allowable PM_{10} concentration (50 µg/m³) averaged over a year. However, at short distances, the allowable $PM_{2.5}$ concentration of 15 µg/m³ is exceeded using both stack heights in this example. When H_S = 12.5 feet, Z must exceed 260 feet to reduce the ambient impact below 15 µg/m³ and achieve safe air quality. When H_S = 17.5 feet, Z must exceed 125 feet to achieve the same goal.

The preceding examples refer to exposure times averaged over one year. It is important to examine whether the ambient impact exceeds safe exposure limits over shorter durations. In this case, R is adjusted accordingly:

24-hour AIR (pounds/hour)/(µg/m³) = annual AIR x 0.091

8-hour AIR (pounds/hour)/(µg/m³) = annual AIR x 0.046

1-hour AIR (pounds/hour)/(µg/m³) = annual AIR x 0.02

Let us return to the first example above, where the furnace power is 200,000 Btu per hour, the particulate emission rate is 0.08 pound per hour, and R = 0.011. Let us calculate the ambient impact assuming that the exposure time is 24 hours instead of a year. In this case, the ambient impact is 0.08 / [(0.091)(0.011)] = 79 µg/m³, which is less than 150 µg/m³, the permissible PM_{10} concentration averaged over 24 hours in Table 8. However, the same ambient impact is above 65 µg/m³, the permissible $PM_{2.5}$ concentration averaged over 24 hours in Table 8. The stack in this example is, therefore, unsafe.

Figure 3. The ground-level concentration of airborne particulates (impact) emitted by a 1 million-Btu-per-hour wood-fueled furnace is modeled as a function of the distance Z from the exhaust stack.
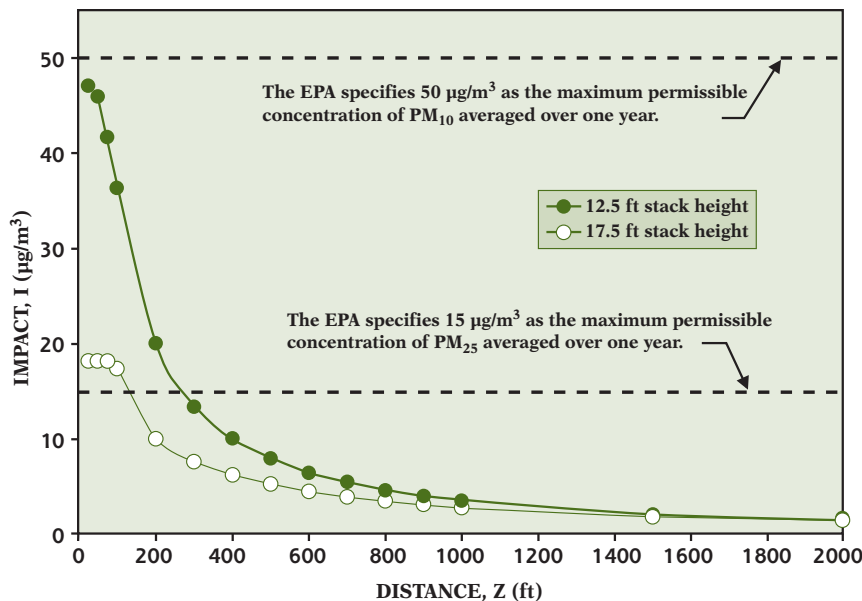
The next step in the design is to repeat the above procedure and increase the stack height and/or the distance to the property line.

The previous examples pertain to conditions where H_S, H_B and Z are easily identified in Table 9. The procedure is modified for special conditions where H_B is between values in the column headings in Table 9, H_S is less than H_B, and Z is between the values shown in the row headings in Table 9. The procedure is detailed in the Michigan Department of Environmental Quality Report: Air Pollution Control Rules, Part 2. Air Use Approval As Amended July 1, 2003. The procedure is briefly outlined below.

If HB is between values in the column headings in Table 9, then use the lower value or interpolate between values in the column headings. If H_S is less than H_B, then set $H_S = H_B$ and use the 1.25 H_S/H_B column. If H_S/H_B is between 1 and 1.25, then select the 1.25 column. If H_S/H_B is between 1.25 and 1.75, then use the 1.25 column or interpolate between the 1.25 and 1.75 columns. If H_S/H_B is between 1.75 and 2.5, then use the 1.75 column or interpolate between the 1.75 and 2.5 columns. If H_S/H_B is greater than or equal to 2.5, then use the 2.5 column. If the minimum distance Z is between two distances in the row headings, then use the lower value. For example, if Z = 250 feet, then use the 200-foot distance row in Table 9.

Table 9. *Annual ambient impact ratios* in units of (lb/hr) / (micrograms/m^3).
H_B = height of neighbor's building, H_S = exhaust stack height.

Distance Z (ft)	H_B = 10 ft			H_B = 20 ft		
	H_S = 12.5 ft	H_S = 17.5 ft	H_S = 25 ft	H_S = 25 ft	H_S = 35 ft	H_S= 50 ft
25	0.0085	0.022	0.159	0.032	0.084	0.679
50	0.0087	0.022	0.159	0.032	0.084	0.679
75	0.0096	0.022	0.159	0.032	0.084	0.679
100	0.011	0.023	0.159	0.033	0.084	0.679
200	0.020	0.040	0.159	0.042	0.084	0.679
300	0.030	0.053	0.178	0.059	0.113	0.679
400	0.040	0.065	0.171	0.077	0.140	0.679
500	0.051	0.077	0.189	0.094	0.164	0.679
600	0.063	0.091	0.222	0.112	0.188	0.746
700	0.075	0.104	0.241	0.130	0.211	0.812
800	0.089	0.119	0.257	0.148	0.235	0.768
900	0.103	0.134	0.264	0.167	0.258	0.770
1000	0.119	0.151	0.272	0.187	0.282	0.800
1500	0.209	0.245	0.318	0.290	0.406	1.080
2000	0.311	0.350	0.383	0.408	0.539	1.256

(Source: Michigan Department of Environmental Quality Report: Air Pollution Control Rules, Part 2. Air Use Approval As Amended July 1, 2003.)

Table 9 (continued). *Annual ambient impact ratios* in units of (lb/hr) / (micro-grams/m^3). H$_B$ = height of neighbor's building, H$_S$ = exhaust stack height.

Distance Z (ft)	H$_B$ = 30 ft			H$_B$ = 40 ft		
	H$_S$ = 37.5 ft	H$_S$ = 52.5 ft	H$_S$ = 75 ft	H$_S$ = 50 ft	H$_S$ = 70 ft	H$_S$= 100 ft
25	0.075	0.220	1.603	0.152	0.421	2.941
50	0.075	0.220	1.603	0.152	0.421	2.941
75	0.075	0.220	1.603	0.152	0.421	2.941
100	0.075	0.220	1.603	0.152	0.421	2.941
200	0.082	0.220	1.603	0.157	0.421	2.941
300	0.099	0.221	1.603	0.174	0.421	2.941
400	0.126	0.268	1.603	0.200	0.421	2.941
500	0.153	0.318	1.603	0.243	0.505	2.941
600	0.181	0.368	1.603	0.287	0.588	2.941
700	0.208	0.413	1.603	0.328	0.664	2.941
800	0.235	0.459	1.608	0.370	0.740	2.941
900	0.261	0.502	1.672	0.411	0.812	2.941
1000	0.289	0.545	1.786	0.452	0.883	2.959
1500	0.428	0.756	1.953	0.654	1.214	3.521
2000	0.573	0.965	2.304	0.861	1.534	3.731

Distance Z (ft)	H$_B$ = 50 ft			H$_B$ = 60 ft		
	H$_S$ = 62.5 ft	H$_S$ = 87.5 ft	H$_S$ = 125 ft	H$_S$ = 75 ft	H$_S$ = 105 ft	H$_S$= 150 ft
25	0.263	0.736	4.630	0.412	1.114	6.098
50	0.263	0.736	4.630	0.412	1.114	6.098
75	0.263	0.736	4.630	0.412	1.114	6.098
100	0.263	0.736	4.630	0.412	1.114	6.098
200	0.266	0.736	4.630	0.413	1.114	6.098
300	0.282	0.736	4.630	0.426	1.114	6.098
400	0.312	0.736	4.630	0.455	1.114	6.098
500	0.351	0.743	4.630	0.498	1.114	6.098
600	0.409	0.838	4.630	0.545	1.114	6.098
700	0.468	0.951	4.717	0.625	1.269	6.250
800	0.528	1.064	4.803	0.705	1.429	6.410
900	0.585	1.168	4.854	0.781	1.572	6.579
1000	0.644	1.276	4.950	0.861	1.724	6.849
1500	0.924	1.761	5.376	1.232	2.404	7.042
2000	1.205	2.222	5.882	1.603	3.049	7.353

(Source: Michigan Department of Environmental Quality Report: Air Pollution Control Rules, Part 2. Air Use Approval As Amended July 1, 2003.)

Table 9 (continued). *Annual ambient impact ratios* in units of (lb/hr) / (micrograms/m³). H_B = height of neighbor's building, H_S = exhaust stack height.

Distance Z (ft)	H_B = 70 ft			H_B = 80 ft		
	H_S = 87.5 ft	H_S = 122.5 ft	H_S = 175 ft	H_S = 100 ft	H_S = 140 ft	H_S= 200 ft
25	0.606	1.656	8.621	0.839	2.242	8.333
50	0.606	1.656	8.621	0.839	2.242	8.333
75	0.606	1.656	8.621	0.839	2.242	8.333
100	0.606	1.656	8.621	0.839	2.242	8.333
200	0.606	1.656	8.621	0.839	2.242	8.333
300	0.614	1.656	8.621	0.845	2.242	8.333
400	0.641	1.656	8.621	0.868	2.242	8.333
500	0.683	1.656	8.621	0.909	2.242	8.333
600	0.741	1.656	8.621	0.967	2.242	8.333
700	0.808	1.672	8.621	1.040	2.242	8.333
800	0.901	1.825	8.621	1.111	2.242	8.333
900	1.000	2.016	8.621	1.235	2.488	9.091
1000	1.101	2.203	9.091	1.359	2.732	10.000
1500	1.577	3.106	9.615	1.953	3.846	11.905
2000	2.041	3.968	9.615	2.525	4.808	12.821

Distance Z (ft)	H_B = 90 ft			H_B = 100 ft		
	H_S = 112.5 ft	H_S = 57.5 ft	H_S = 225 ft	H_S = 125 ft	H_S = 175 ft	H_S= 250 ft
25	1.126	3.049	13.514	1.458	3.876	14.286
50	1.126	3.049	13.514	1.458	3.876	14.286
75	1.126	3.049	13.514	1.458	3.876	14.286
100	1.126	3.049	13.514	1.458	3.876	14.286
200	1.126	3.049	13.514	1.458	3.876	14.286
300	1.129	3.049	13.514	1.458	3.876	14.286
400	1.147	3.049	13.514	1.475	3.876	14.286
500	1.185	3.049	13.514	1.506	3.876	14.286
600	1.244	3.049	13.514	1.563	3.876	14.286
700	1.316	3.049	13.514	1.634	3.876	14.286
800	1.404	3.049	13.514	1.730	3.876	14.286
900	1.502	3.086	13.514	1.832	3.876	14.286
1000	1.634	3.289	13.514	1.931	3.876	14.286
1500	2.358	4.505	15.152	2.778	5.208	16.129
2000	3.049	5.618	16.129	3.597	6.494	18.519

(Source: Michigan Department of Environmental Quality Report: Air Pollution Control Rules, Part 2. Air Use Approval As Amended July 1, 2003.)

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