



# *BIOMASS AND ALTERNATE FUEL SYSTEMS*

*An Engineering and Economic Guide*

Edited by

**THOMAS F. McGOWAN**

Associate Editors

**MICHAEL L. BROWN**

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**JAMES L. WALSH, JR.**

**AIChE<sup>®</sup>**

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## PREFACE

**WE** ARE ONCE AGAIN IN an energy and fuels crisis, with costs escalating dramatically and supplies tight. This has happened before and, once again, the economy and industry will adjust to new conditions.

This book is about how to adjust to this difficult situation by using renewables for industrial applications, while cutting operating costs. In addition to providing economic benefits, the switch to renewable wood and agricultural fuels reduces greenhouse gas emissions, as these renewables are assigned a zero greenhouse emission factor and are considered “carbon neutral.”

Some of the material in this book is from *The Industrial Wood Energy Handbook*, written in 1984. This book is an update and expansion of that work, adding information and broadening the scope to include agricultural feedstocks and the use and production of liquid fuels such as ethanol from cellulosic (noncorn) feedstocks. It also covers fireside slag treatment (not a small issue in wood and agricultural combustion systems!), has up-to-date equipment vendor information, more detail on the furnace grate systems that are the heart of many biomass and wood combustors, and information on hot oil systems and hot air, introductory material about sustainable biomass yields, as well as the basics of greenhouse gas emissions calculation methods.

You will find this book to be useful in choosing the right equipment the first time, producing feasibility studies that define project economics, and cutting industrial fuel costs while reducing greenhouse gas emissions.

THOMAS F. MCGOWAN

Atlanta, Georgia  
January 2009

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# INTRODUCTION TO ALTERNATE FUELS

## INTRODUCTION

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Fuel costs rose sharply in 2005 due to hurricane damage to offshore platforms and refineries in the Gulf of Mexico. This was followed by a drop in the strength of the U.S. dollar in 2007 and 2008, international developments in the oil supply, and increased demand. Competing fuels—coal and natural gas—rose in price in lockstep. Natural gas has risen in cost, and has been reported by clients to be as much as \$17/MM Btu for industrial use in the northeast, and the cost of a 42 gallon barrel of oil hit \$140, which is \$3.33 per gallon just for the raw material.

Operating firms with fuel bills that are a high percentage of their costs are seeing profit margins erode, and one solution to the problem is fuel switching and use of alternate, sometimes overlooked, lower cost fuels.

There are many alternate fuels available to replace the big three—gas, oil, and coal. These include biomass, in particular, wood, but also including bagasse, fast growing switch grass, agricultural feedstocks, and used cooking oil. Other alternate fuels are covered in this book as a point of comparison and in less detail than biomass, and also because they may be cofired with biomass fuels. They include used/recycled oil, tires, and solid waste.

Parts of this chapter were excerpted by special permission from *Chemical Engineering*, March 2006. Copyright © 2006 by Access Intelligence, New York, NY 10038.

Some combustion systems were set up for multifuel firing and can be easily changed over, whereas others can be refitted and adapted to new fuels.

Heat recovery is the other option—adding heat exchangers to current processes, or changing over to new types of equipment, for example, from an elevated flare to a thermal oxidizer with a heat recovery boiler to recoup useful heat. This approach can be used to cut greenhouse gas emissions while saving on fuel costs.

This section covers the heating value, costs, and other properties of alternate fuels and fossil fuels, the changes required to fire alternate fuels, and options for heat recovery. It also addresses in brief the regulatory aspects of fuel switching and impacts on emissions. In addition to information on the *use* of alternate fuels, this section also covers *production* of secondary fuels from biomass feedstocks, for example, ethanol from cellulosic feedstocks and transportation fuels from agricultural feedstocks.

## WHAT FUELS ARE USED?

---

Conventional fossil fuels rule the marketplace. They include natural gas, propane, fuel oil, and coal. Alternate fuels include:

- Wood and other biomass and agricultural feedstocks
- Reclaimed oil
- Petroleum coke
- Solid wastes
- Biogas (methane from bioprocesses, used on-site)
- Used tires
- Used cooking oil
- Ethanol from wood or agricultural feedstocks
- Plant and refinery gas (used on-site)

Table 1-1 shows heating values and costs for industrial use of alternate fuels and selected fossil fuels, which are the benchmark for comparison on prices and heating values. Establishing a fuel price is not as simple as it might seem, as database figures must be adjusted to match the application, location, and time of year, and taxes, transport, broker fees, and market must be taken into account to come up with representative prices paid by the end user. The type of contract, for example, interruptible service for natural

**Table 1-1.** Heating values and costs for fuels

Fuel	Gross heating value (Btu/lb)	Approximate cost (\$/MM Btu)	Comment (source, date)
Natural gas	23,896	\$7.76	Industrial supply (EIA 2007)
Propane	21,523	\$12.51	\$1.13/gallon, wholesale (EIA, 2007)
No. 2 fuel oil	19,567	\$14.30	\$2.01/gallon, wholesale (EIA, 2007)
No. 6 fuel oil	18,266	\$7.89	\$1.25/gal, sale to end user; price varies with sulfur content (EIA, 10/07)
Coal	9,000–15,000	\$1.78	\$39/ton; cost based on 11,000 Btu/lb. U.S. industrial delivered average (EIA 2007)
Wood waste	~4,250 at 50% mc	\$0.90	\$9–10/ton, delivered (Ref. Timber Mart South, third qtr 2005)
Wood, whole tree chips	~4,250 at 50% mc	\$3.20	Mid to high \$20s per ton (Ref. Timber Mart South, third qtr 2005)
Wood, tub grind waste material	~4,250 at 50% mc	\$2.60	Low to mid \$20s per ton (Ref. Timber Mart South, third qtr 2005)
Wood planer shavings	~7,650 at 10% mc	NA	Dry planer shavings, sander dust. Light and hard to transport; mainly used on-site
Used/recycled oil	~17,500	\$9.50	\$1.20/gal, or 70% of No. 2 oil based on cost/gallon. Derived from engine lube, cutting oil, etc. Typically, viscosity is No. 4 fuel oil equivalent. Density ~7.2 lb/gal
Pet coke	15,250 dry; 14,200 wet	\$1.29–\$1.94	\$36/ton (EIA 2007); \$50/ton (FERC 2007) Pet coke; varies in volatile content and heating value. Sulfur 4–6.5% (EIA), Ash ~ 1%
Tires	15,500 (metal free)	\$1.61–\$3.23	\$50–100/ton 96% metal free 2" top size. TDF chips (RB, 1/11/08). Sulfur content ~1.2%; contains ash from metal and glass/polyaramid cords

*(continued)*

**Table 1-1.** Heating values and costs for fuels

Fuel	Gross heating value (Btu/lb)	Approximate cost (\$/MM Btu)	Comment (source, date)
Used cooking oil	16,900–18,500	Local price variation, at or below #2 fuel oil	Need to decant water, filter grit. Price varies with time of year and local supply/demand
Ethanol	13,161	NA See at right	Ethanol from cellulosic feed stocks is in development via several routes; market prices do not exist
Biogas	Varies	NA	Biogas is typically 500–900 Btu/ft <sup>3</sup> , depending on source
Plant gas	Varies	NA	Heating value varies with upstream process and diluents, if any
Type 0 Trash	8500	NA	Incinerator Waste Standard
Type 1 Rubbish	6500	NA	Incinerator Waste Standard
Type 2 Refuse	4300	NA	Incinerator Waste Standard
Type 3 Garbage	2500	NA	Incinerator Waste Standard
Type 4 Human and animal remains	1000	NA	Incinerator Waste Standard
Type 5 By-product waste, liquid, solid, sludge	By test	NA	Incinerator Waste Standard
Type 6 Solid by product industrial waste	By test	NA	Incinerator Waste Standard

Notes: EIA, <http://www.eia.doe.gov/>; Timber Mart South/UGA, Tom Harris, 12/6/05; RB Rubber Products, Pete Daly, 503-283-2261, Portland, OR.

gas, also affects final price. Many databases show current, 30 day spot pricing. An example is the NYMEX (NY Mercantile Exchange), which showed natural gas in the \$15/MM Btu range on 12/8/05. This price is based on the Henry Hub in Louisiana, and does not include delivery and markup. This is a higher price than that found in longer-term contracts, which tend to smooth out short-term spikes and dips. Based on EIA data, the Henry Hub price for natural gas went up 63% from January 04 to January of



2009 (projected price). For more on forecasting and market movements see [www.eia.doe.gov/emeu/steo/pub/contents.html](http://www.eia.doe.gov/emeu/steo/pub/contents.html), and for relationships between gas and oil see [www.dallasfed.org/research/swe/2005/swe0504c.html](http://www.dallasfed.org/research/swe/2005/swe0504c.html).

Biogas (from wastewater treatment, conversion of manure, and from biological degradation in landfills) and plant and refinery gas are confined to use on-site or a short distance off-site and are not transportable. Setting a price for these fuels is difficult, as some of the cost may be attributable to regulatory requirements (e.g., regulations on landfill gas), whereas the rest might be allocated as internal cost to the end use. For example, most landfill gas must be collected and flared if it will not be used as a fuel for an engine or furnace. So the cost allocated for use as a fuel might be only that of any extra gas cleanup and extra fan or blower power and piping required to transport the biogas the extra distance to the engine.

Reclaimers throughout the United States produce used oil. It is frequently referred to as “spec oil,” referencing U.S. Environmental Protection Agency (EPA) terminology that allows its use as a product and takes it out of the waste category. See CRF 279.10 for more detail (<http://ecfr.gpoaccess.gov>, part 40, subparts 266–299) and Table 1-3 for EPA requirements. This EPA regulation also allows reuse of used oil on-site by a generator (e.g., blending with diesel fuel for use in the company’s vehicles), and under these conditions, the fuel is not subject to EPA used oil or waste regulations. Typical properties for used “spec oil” can be found in Table 1-2. The asphalt industry and industrial and utility boilers are major users of used “spec oil.”

With the exception of some cement kilns that feed whole tires, TDF (tire-derived fuel) is normally burned as chips in boilers and cement kilns. Prices range widely, based on state used-tire tar-

**Table 1-2.** Typical properties of used oil from reclaimer

Parameter	Value
Heating value	>135,000 Btu/gal
Water	<1%
Solids	<1%
Viscosity	90–120 SSU at 100°F
Flash point	>100°F

Source: Perma-Fix, Inc., personal communication, Doug McLain, 12/5/05.

**Table 1-3.** EPA 40 CFR 279.11, limits for used oil specification level<sup>(1,2)</sup>

Parameter	Value
Arsenic	≤5 ppm
Cadmium	2 ppm
Chromium	10 ppm
Lead	100 ppm
Flash point	≥100 °F
Total halogens	4000 ppm <sup>(3)</sup>

1. Used oil not exceeding any specification level is not subject to this part (40 CFR 279) when burned for energy recovery. The specification does not apply to mixtures of used oil and hazardous waste that continue to be regulated as hazardous waste [see § 279.10(b)].
2. Applicable standards for the burning of used oil containing PCBs are imposed by 40 CFR 761.20(e).
3. Used oil containing more than 1,000 ppm total halogens is presumed to be a hazardous waste under the rebuttable presumption provided under § 279.10(b)(1). Such used oil is subject to subpart H of part 266 of this chapter rather than this part when burned for energy recovery, unless the presumption of mixing can be successfully rebutted.

iffs, number of processors, and supply/demand. TDF prices are generally similar to coal.

Coal and coke can be used in industrial equipment, and both have been fired in cement kilns [1]. Pet coke (petroleum coke) prices are in the range of that of coal. Shipping dictates that there is a price advantage for users near the refineries and coke plants that produce this material as a byproduct of heavy-oil refining. It should be noted that this material tends to be high in sulfur content, and any combustion system using it needs to have equipment capable of dealing with the SO<sub>2</sub> emissions. More detail on pet coke can be found in the referenced EPA report [2].

Biomass fuels are becoming a more common alternative fuel source to fossil fuels as conventional energy prices rise. The primary biomass fuel is wood waste; however, bagasse (sugar cane residue), ag-fuel, or fuels derived from straw, rice hulls, and shell hulls, biomass grown as a fuel crop (e.g., switch grass) and other agricultural sources are becoming more popular. Plywood, lumber, OSB (oriented strand board), and related plants have long used bark, wood waste, planer shavings, and sander dust from plant operations to provide process heat for drying and pressing of boards rather than fossil fuels. However, biomass fuels are finding appli-

cations in nonforest products industries as well. Biomass fuels are used to replace up to 5–10% of coal during cofiring in some utility boilers at power plants. The reason for replacing only a portion of the fossil fuel is that generally wood fuels have a lower heating value and higher moisture content, so that only a portion of coal fuel can be replaced without significant loss of boiler performance and output.

Advantages to biomass are lower fuel cost and lower emissions, since wood fuels are much lower in sulfur content than most typical coals. They also contain ash, which has alkali components that can react with and remove some sulfur dioxide. In addition, in those countries that have ratified the Kyoto Protocol, the use of naturally derived fuels as opposed to fossil fuels is a common method to reduce the emission of “greenhouse gases” and obtain CO<sub>2</sub> emission credits, since renewable fuels from plant sources are considered “CO<sub>2</sub> neutral” under this accord. This is common in Europe and is an emerging market in itself, with wood pellet producers in the United States shipping their product across the Atlantic. Fossil fuels are burdened with associated CO<sub>2</sub> greenhouse gas emissions. Although company-wide studies can cost thousands of dollars to count direct and indirect CO<sub>2</sub> emissions, when it comes to burning a fuel, the math is really quite simple: Multiply the fuel weight per year by the carbon fraction of the fuel, then multiply by 3.66 (3.66 is the molecular weight of CO<sub>2</sub> divided by that of carbon) and divide by 2000. This result is the tpy (tons/yr) of CO<sub>2</sub> generated. The carbon fraction in the fuel can be found in reference texts or via lab work. Basic chemistry can also be used to calculate the carbon fraction. For example, for methane, the carbon weight is 12, when divided by the total weight of 16, the result is 0.75, or 75% carbon.

## **COMBUSTION ISSUES AND APPLICATION TO EQUIPMENT**

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Burning alternate fuels requires going back to the basics. We have to know fuel properties, as the chemistry of the fuel dictates the final stack-gas flow and products of combustion. For example, higher sulfur will mean more SO<sub>2</sub> generated, and for some fuels, such as wet wood hog fuel, higher excess air (in the range of 50%) is required using air swept stokers, much more than for oil and gas, which are usually in the 15–25% range, or lower when O<sub>2</sub> trim or mass flow control is used.

### Application to Equipment

Some equipment is easy to alter for firing of alternate fuels. For example, boilers set up for natural gas are also sold with gas/oil firing systems. Installation of oil tankage, fuel trains and atomizers, and substitution of an oil gun for the gas spud may be all it takes to change over. Changing from No. 2 fuel oil to heavy oil or reclaimed used oil will require the addition of steam or compressed-air atomizers and oil-heating equipment.

Changing to solid fuel is much more difficult. For example, compact boilers set up for gas/oil are simply not compatible with solid fuel firing, unless a gasifier is used to convert the fuel upstream. Very large dryers and calciners are more amenable to such a change, as they were designed to handle particulate matter, and have pollution control systems that remove particulates. Some manufacturers are working on a new generation of mid-sized (100–200 MM Btu/hr) pulverized coal burners to respond to emerging markets and applications that can tolerate particulates.

For larger, long-term commitment to solid fuels, the best fix may be the purchase of new equipment designed for its use.

Beware that some elements in fuels can cause major problems even in small amounts. These include sodium and potassium that can form low melting point ash, and sulfur and chlorine that form acid gases. An additional issue is fuel bound nitrogen, which forms  $\text{NO}_x$ . These problems can cause equipment outages due to fouling and corrosion, and raise emissions.

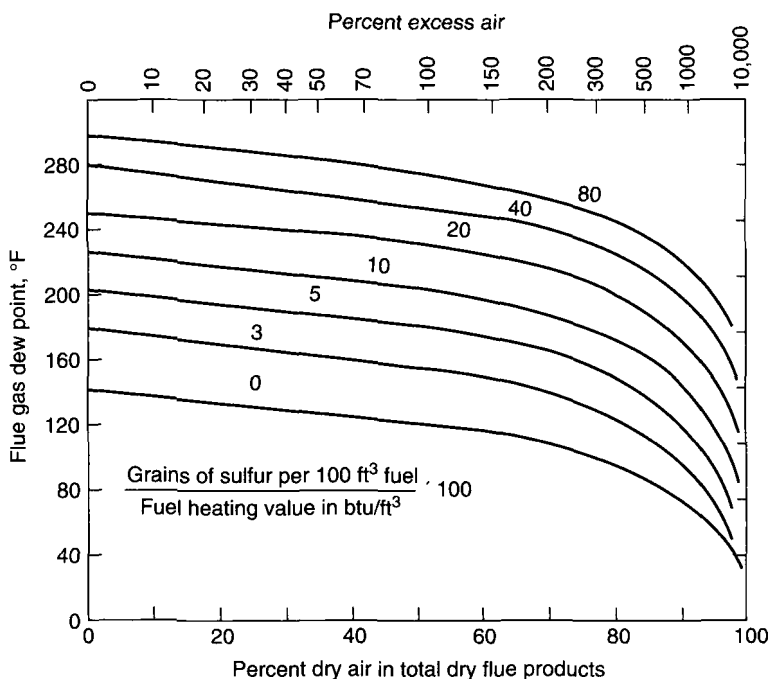
One issue with biomass fuels is their alkali ash compounds, which form salts in the combustion process and/or may lower the ash softening points, causing fireside fouling problems. This is particularly true with agricultural biomass, while wood-based biomass has lower alkali concentrations when compared to many agricultural feedstocks. Still, for any biomass fuel, it is advisable to analyze for alkalis, and make a determination of the fuel's fouling and slagging potential. Also, any heat recovery equipment must be properly designed to minimize the potential any of these fuels have for fouling. Fireside additives have been used, generally with good effect, to reduce fouling problems and slagging of grates.

### $\text{SO}_2$ , Acid Gas Dew Point, and Heat Recuperation

Heat recuperation is used for many processes, and more of these systems are being added today to reduce fuel costs. Higher sulfur

fuels can harm heat recuperators, as heat recuperation lowers stack-gas temperatures and can cause dewpoint condensation of acid on heat exchanger surfaces, causing rapid corrosion. This is particularly an issue for air preheaters and economizers used to preheat boiler feed water via heat exchange with stack gases. Figure 1-1 addresses this subject and will help keep you out of trouble. It provides the acid-gas dewpoint based on sulfur loading in the fuel.

For example, a fuel with 20 grains (there are 7000 grains per lb) of sulfur per 100 ft<sup>3</sup> of fuel (fuel gas) divided by the fuel heating value in Btu/ft<sup>3</sup> of the fuel gas will have an acid-gas dewpoint of 242°F at 20% excess air. Heat exchanger wall temperatures below that will result in liquid acid on the metal surface, and heat exchangers will experience high rates of corrosion. Graphs of acid-gas dewpoint are available in many references, such as ASHRAE's *Handbook of Fundamentals* [4].



**Figure 1-1.** Influence of sulfur oxides on flue-gas dewpoint. (Chart © ASHRAE, *Handbook of Fundamentals*, 1993, used with permission ASHRAE, www.ashrae.org.)

## ABOUT EMISSIONS AND REGULATIONS

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In brief, the regulatory problems involved in fuel switching are:

- Sulfur content/SO<sub>2</sub> emissions
- Ash content/particulate emissions
- Chlorine content/HCl and Cl<sub>2</sub> emissions
- Nitrogen content/NO<sub>x</sub> emissions

If the original permit allowed firing of other fuels (e.g., No. 6 oil as alternate to natural gas), then no repermitting is required to switch to fuel oil. However, it would be worth checking the permit application, the operating permit, any language in the facility's State Implementation Plan (SIP) permit or Title V permit (number of hours of operation may have been limited to reduce NO<sub>x</sub>) that may need to be modified, thus requiring the facility's operating permit to be reopened and subsequently reissued.

Furthermore, depending on whether the area in which the facility is located is in attainment or nonattainment with the national ambient air quality standards (NAAQS), coupled with the magnitude of the emissions increase that may occur as a consequence of the fuel switching, New Source Review (NSR) permitting applicability could be triggered. This could result in additional permitting complexity (beyond just simply reopening the facility's Title V permit) that could involve additional requirements to install postcombustion controls and/or acquire internal or external emission offsets in order to permit the modification. Thus, the important first step in evaluating any project that may involve fuel switching is to first undertake a permitting analysis to assess the underlying regulatory requirements the facility is subject to, and establish the optimum path-forward permitting strategy.

Some alternate fuels emit less pollution. For example, tests with used cooking oil firing boilers showed lower CO and NO<sub>x</sub> emissions than with fuel oil. Thus, substituting this alternate fuel may require only notification to the regulators.

In the end, your relationship with the regulators is a critical element. If you have an ongoing, positive relationship, you may find that it may not take all that much paperwork to change fuels, as long as emissions do not rise past regulatory thresholds.

EPA's AP-42 guide to emission rates may prove useful when exploring fuel switching. It contains a compilation of air pollution

estimates for industrial stationary sources and other air pollution sources. It is available online, and provides emissions for various applications (e.g., boilers and cement kilns), by industry and by fuel. Useful URLs can be found in reference [4].

Note that the above discussion applies to fuels and nonhazardous waste. It does not apply to firing of RCRA “hazardous waste,” for which much more stringent rules apply and permitting can take years.

## REFERENCES

---

- [1] “Cemex, Power Play, Expensive Energy? Burn Other Stuff, One Firm Decides,” John Lyons, *The Wall Street Journal*, September 1, 2004, Page A1.
- [2] EPA Pet Coke report, 1999, [www.epa.gov/ORD/NRMRL/pubs/600r01109/600R01109appA.pdf](http://www.epa.gov/ORD/NRMRL/pubs/600r01109/600R01109appA.pdf).
- [3] ASHRAE, *Handbook of Fundamentals*, Mark S. Owen, Editor, ASHRAE, Atlanta, GA, 2005.
- [4] U.S. EPA AP-42, emission factors, by chapter, fuel type, [www.epa.gov/ttn/chief/ap42/ch01](http://www.epa.gov/ttn/chief/ap42/ch01); for natural gas, including boilers, <http://www.epa.gov/ttn/chief/ap42/ch01/final/c01s04.pdf>; by industry, [www.epa.gov/ttn/chief/ap42/](http://www.epa.gov/ttn/chief/ap42/).

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## *FUEL PROPERTIES AND COMBUSTION THEORY*

### **IT'S ALL ABOUT COMBUSTION**

---

Webster's dictionary [3] defines combustion as, "a usually rapid chemical process (as oxidation) that produces heat and usually light; an act or instance of burning." In more simple terms, it involves mixing oxygen and a fuel, producing heat and products of combustion. The question is what fuel to use, and what effect will fuel switching have on emissions and performance?

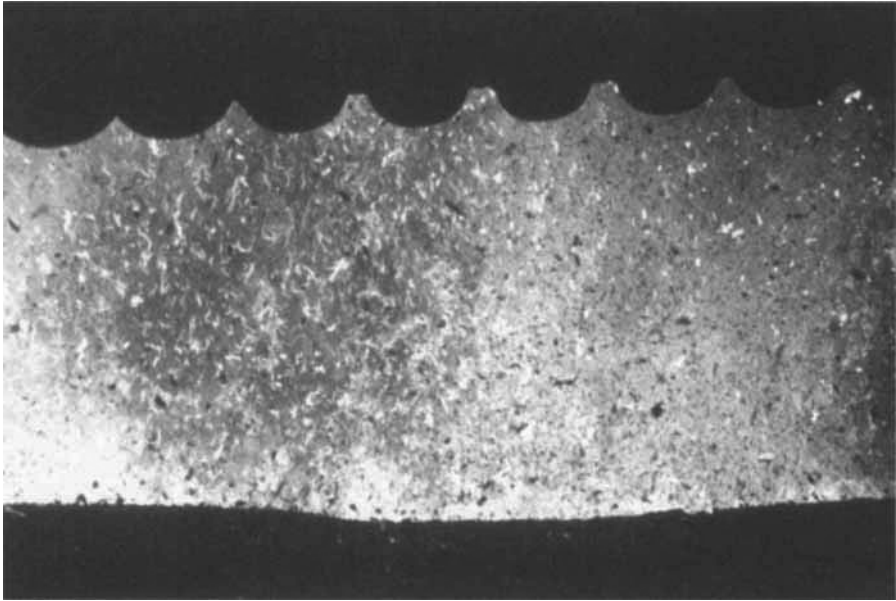
Major industrial fuel users include the following:

- Boilers
- Cement kilns
- Process heaters
- Hot oil heaters
- Furnaces (for heat treating, glass making, steel, etc.)
- Dryers and calciners
- Pollution control (oxidizers)
- Waste to energy (incineration)

### **COMBUSTION BASICS**

---

The chemistry of combustion is focused on the primary reactions of oxidizing carbon and hydrogen to  $\text{CO}_2$  and water vapor, respectively. The reader is referred to more detailed texts (e.g., North American Manufacturing Co.'s two-volume *Combustion Handbook* [4], and the B&W *Steam* book [5]) on the subject; the basics are covered below.



**Figure 2-1.** Some like it hot—photo of 500 MM Btu/hr furnace on a hog fuel boiler at a pulp mill.

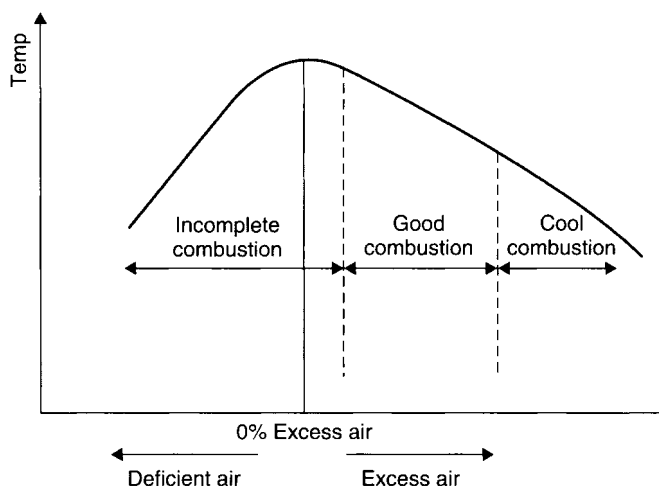
Always keep in mind the three Ts of combustion:

- Time
- Temperature
- Turbulence

If all three exist in adequate amounts, plus the right amount of oxygen, good combustion will occur. If one or more of these are in short supply, or oxygen is lacking, bad combustion (e.g., production of soot and excessive amounts of CO) will result. Figure 2-2 shows the classic combustion temperature curve plotted versus the amount of combustion air.

Combustion engineers routinely run heat and mass balances. They can be as simple as hand calculations on the back of an envelope, but more often are either custom programs used by the engineer for a specific application, or off-the-shelf commercial programs for combustion and/or process calculations.

Examples of ready-to-use heat- and mass-balance programs are:



**Figure 2-2.** Temperature and combustion air.

- Hauck E-Solutions, which includes rotary dryer burner sizing, furnace sizing, emissions conversions, orifice calculations, and heat transfer. Available free via [www.hauckmfg.com/solutions/](http://www.hauckmfg.com/solutions/).
- Heat and mass balance program, which includes calculations for incinerators and combustors. Free with purchase of *Introduction to Hazardous Waste Incineration*, 2nd Edition, Wiley, ISBN: 0-471-01790-6.
- HSC Software by Outokumpu. Performs equilibrium, heat and mass balance, and chemical formula calculations. Has thousands of chemicals in the database. Not for neophytes; it takes significant effort to learn how to use this software. Excellent for detailed process calculations in one or more phases. For description and purchase see <http://www.chemsw.com/>.

Remember that mass into a system must equal the mass out. If not, you have an error in the program. Volumes (air and fuel gas) are not always equal. Figure 2-3 is a heat and mass balance for combustion of methane with 100% excess air that shows the relationships of mass in/mass out, transformation from reactants to products, and amount of heat liberated. Note that in the figure, the mass into the system and out of it are the same. The volume of gas (in moles, or scf) in and out is the same for methane, but

(Methane with 100% excess air)

Input					
Methane	CH <sub>4</sub>	+2 × 2	(O <sub>2</sub>	+ 3.76N <sub>2</sub> )	→
Mols	1		2 × 2	2 × 7.52	
Wt.	16		2 × 64	2 × 211	
Lb/lb fuel	1		2 × 4	2 × 13.2	(Air = 34.4)

Out put								
	CO <sub>2</sub>	+	2H <sub>2</sub> O	+	15.0N <sub>2</sub>	+	2O <sub>2</sub>	Totals
Mols	1		2		2 × 7.53		2	20
Wt.	44		36		2 × 211		64	565
Lb/lb fuel	2.74		2.25		2 × 13.2		4	35.4
Vol. %, wet	5		10		75		10	
Vol. %, dry	5.54		N/A		83.3		11.1	
Wt. %	7.8		6.4		74.5		11.3	

Figure 2-3. Heat and mass balance for methane at 100% excess air.

this is not always the case. The concentration of CO<sub>2</sub> and O<sub>2</sub> can be used to back-calculate excess air levels and estimate stack gas volume. Both dry and wet basis O<sub>2</sub> and CO<sub>2</sub> concentrations are used; most test equipment produces dry basis readings. In situ oxygen CEMs are the exception, and they produce a wet basis O<sub>2</sub> concentration.

The same heat and mass balance can be run for wood or other fuels as long as the composition is known, particularly for C, H, and O. Alternately, handbooks provide mass-based ratios; for example, the stoichiometric air requirement is 765 lb per MM Btu of a particular fuel.

### Heating Value of Fuels

The heating value of fuel is the measure of heat released during the complete combustion of the fuel (with oxygen), from reactants at a given reference temperature and pressure to products at the same reference temperature and pressure.

Analytically derived formulas have been developed for prediction of the higher heating value (HHV) of coals. When compared with the wealth of knowledge generated concerning fossil fuels, interest in wood as a fuel has long been dormant. Exact calculations are available for all components of wood fuel that will oxidize; however, it is difficult to quantify the contribution of