Design and Operating Factors Which Affect Emissions from Residential Wood-Fired Heaters: Review and Update

Paul E. Tiegs
OMNI Environmental Services, Inc.
5465 SW Western Avenue, Suite M
Beaverton, Oregon 97005

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INTRODUCTION

Residential wood-fired heaters (RWH) have long been known to be significant polluters, especially in the category of PM10 -loading to localized airsheds. In many western valley areas of the United States, woodstove-generated particulate and carbon monoxide are major components of wintertime National Ambient Air Quality Standards (NAAQS) violations. Excessive woodsmoke loading to local airsheds also causes nuisance odors and degrades visibility and vista values.

The physical and chemical characteristics of RWH emissions has further accentuated problems in this source category. RWH generated particulates are virtually all submicron-sized organic condensate materials. In addition, several of the organic compounds found in woodsmoke have demonstrated carcinogenic and mutagenic properties (1). A 1986 study by OMNI also showed stove emissions to be highly acidic (pH 2.5 to 3.8), with high acidity persistence (i.e., buffering) due to organic acids (2).

Subsequent to the major increases in RWH use in the early 1980s and the evolution of widespread woodsmoke pollutant problems, the RWH industry embarked on the development of low emissions technologies. The industry's fast response to the developing problems produced RWHs that emitted 60 to 80% less emissions, under laboratory test conditions, than the original "conventional" RWHs sold and in use during the early 1980s. These were the first reduced-emission woodstoves which qualified for the first state-wide woodstove certification programs promulgated by Oregon and Colorado. In 1987, the U.S. Environmental Protection Agency (EPA) promulgated an even more stringent 2-stage, national standard for the reduction RWH emissions. This New Source Performance Standard (NSPS, 40 CFR Part 60, Subpart AAA), mandated that RWH appliances manufactured after 1990, have laboratory-tested emission reductions that represent more than an 80% reduction from the conventional woodstoves of the early 1980s.

The RWH manufacturing industry responded anew with appliances that generated even lower emissions. RWHs that were built and sold in the early 1980s generated laboratory-tested particulate emission factors ranging from 30 to 60 grams per kilogram (g/kg) of dry fuel burned. They are now being replaced by models which generate less than 7.5 g/kg (at weighted-average dry burn rates of about 1.4 kilogram per hour).

This paper reviews known operating factors which affect wood-fired heater emissions with updated test results and analyses of new technology design concepts. Batch-loaded cordwood, as well as processed wood-pellet parameters are analyzed. A review of batch-load versus air-to-fuel-mixture controlled technologies and reporting units are included in the main body of this discussion paper.

All values reported in this paper, unless otherwise noted, were obtained at the laboratories of OMNI Environmental Services, Inc., using the Oregon Department of Environmental Quality (ODEQ) "Standard Method for Measuring the Emissions and Efficiencies of Residential Woodstoves," June 8, 1984 edition, the methods stipulated by the 1987 EPA NSPS, or the OMNI Automated Woodstove Emissions Sampler procedures which have had EPA performance audits performed four times over the last seven years.

It is important to note that if non-standard methods and protocols are used to operate woodstoves or to measure and calculate performance and emissions parameters such as fuel loading densities and configurations, efficiency algorithms, particulate sampling systems, or laboratory altitude, there can be significant differences in results. Care should be taken when comparing data generated using different procedures or methods unless equivalency has been demonstrated and appropriate correction factors are applied.

BACKGROUND

The Combustion Process

Wood-fuel combustion in a RWH involves complex chemical processes which include the pyrolysis and oxidization of volatile, semi-volatile, and solid carbonaceous components of wood fibers. As in all combustion, the burning of wood requires that the four conditions or process elements of combustion (i.e., time, temperature, turbulence, and the air-to-fuel mixture ratio) be optimized for the combustion process to take place efficiently (i.e., complete oxidation of all fuel materials).

From a process control perspective, combustion in a batch-loaded cordwood-burning RWH is made more complex than most applications by the fact that from the time a fire is first started, with paper and kindling, until the last char-ember has ceased burning, all firebox conditions and combustion reactions are changing: Fuel chemistry and physical properties, fuel geometry, air supply, and temperatures, all change dramatically throughout a RWH burn cycle (i.e., the burning of a whole batch-fuel load).

Time is required to allow thorough air and fuel mixing, for energy-releasing chemical reactions, and for heat transfer to occur. If the residence time of heat-generated fuel-gases and oxygen mixing is too short, combustion will not be complete and the transfer of heat from combustion gases to stove and pipe walls will be inefficient. If residence time is too long, gas velocities in the combustion chamber are too low, and the driving mechanism for the mixing of air and fuel gases will be weak. This also leads to incomplete, inefficient combustion.

Temperature is important since the rates of the chemical reactions, which are the essence of the combustion process, increase exponentially with temperature and the driving mechanism for producing flue draft and gas flows through the whole system is dependant on heated flue gases. Generally, high temperatures in the combustion zone ensure complete combustion. In industrial gas, oil, and coal-fired systems, and in internal combustion engines, however, excessively high combustion temperatures can also generate increased nitrogen oxides pollution. RWH combustion processes typically produce relatively low combustion zone temperatures because overall air-to-fuel ratios are more air-rich than utility or commercial boilers and because the typical RWH combustion chamber also serves as a major part of the appliance's heat exchange system. Heat therefore, is radiated and convected away from the combustion zone rather rapidly.

Turbulence is an important factor because wood-derived fuel-gases and air must mix to attain ignition and, in order to sustain the combustion process, the burning and already-burned gaseous materials must mix with fresh fuel-gases and air. Oxygen molecules must forcefully collide with fuel molecules to have heat-releasing chemical reactions in combustible mixtures take place. The frequency of molecular collisions and the force of collision are both governed by temperatures and turbulence. Nearly all industrial combustion chambers, and many residential combustors are "mixing controlled." That is, the rate at which the mixing processes take place, controls the overall burn rate: "if it's mixed, it's burned."

In large utility and commercial boilers, mixing is aided by mechanical blowers or fans. In most RWH appliances, naturally generated "draft" is the primary driving force for mixing combustion gases and for powering air supply and exhaust systems. Natural draft occurs when negative pressures are generated by low density (buoyant), heated combustion gases in the RWH firebox and chimney. RWH natural draft is a relatively weak driving force (generally less than 0.1 inches water column [25 Pascals]) in comparison to blowers and fans and provides the most difficult process control challenges. A major challenge in RWH design is to use the smallest amount of draft so as to reduce heat (i.e., sensible stack) losses up the chimney or to incorporate a mechanical draft system which is reliable and compatible with wood combustion aesthetics and objectives.

Air-to-fuel ratio is expressed as the mass of air (lb or kg) used to burn a unit mass of fuel (lb or kg). Air-to-fuel ratio is important for accomplishing efficient combustion for several reasons. In general, the overall air-to-fuel ratios in virtually all combustion applications are higher than the theoretically-exact, chemical-reactant (stoichiometric) ratios needed. A rule of thumb is that fuels that are more difficult to burn, require higher air-to-fuel ratios. For industrial boilers, the amount of excess-air (above stoichiometric) required to burn natural gas efficiently is about 5%, to burn oil about 10 to 15%, and to burn pulverized coal about 20 to 25%. These amounts represent just enough excess-air to assure that all the fuel molecules find oxygen molecules with which to react. For industrial wood burners, the recommended amount of excess-air is not quite as well defined, though well engineered systems are found to operate in the range of 50 to 100% excess-air. Usually, the "ideal" amount of excess-air can be identified by looking for the "knee" in a curve of carbon monoxide exhaust emissions versus air-to-fuel ratio.

Too much excess-air is detrimental to efficiency, since, as noted above, excessive air leads to low flame temperatures and inefficient oxidation of the fuel; that is, the "combustion efficiency" is affected. Combustion efficiency is a measure of the completeness of the combustion process or the conversion of the available chemical energy in the fuel to sensible heat in the firebox.

Too much excess-air also affects thermal efficiency, or overall efficiency, which is the percentage of the fuel chemical energy which is actually transferred to the space or medium being heated. If excess-air is too high, the increased flow rate carries a higher proportion of the liberated heat energy up the exhaust stack where it is lost. Furthermore, the higher-than-needed flows reduce residence time and reduce the time available for heat transfer to take place. Heat transfer potential of these gases is also reduced because the heat content and hence temperature of the combustion gases is diluted by the non-essential excess-air. Thus, good combustion design requires using only as much excess-air as is necessary.

Although all industrial and residential boilers operate air-rich, small localized pockets of fuel-richness unavoidably occur. These pockets are characterized by the production of carbon monoxide and the formation of solid and condensed aerosols. Flames in these regions usually exhibit an orange color due to thermal radiation from the aerosols. If the flame is well mixed, and thus well aerated throughout, its burning gases will appear blue in color. Sometimes the blue color is difficult to see, however, because it is overwhelmed by red-to-orange thermal radiation emanating from the hot aerosols.

Even though conventional, naturally drafted RWHs usually operate very air-rich, because of poor mixing, most of the excess-air never becomes intimately Even though conventional, naturally drafted RWHs usually operate very air-rich, because of poor mixing, most of the excess-air never becomes intimately mixed with the fuel gases. Thus the flame is yellow in appearance and contains large amounts of solid carbon and unburned condensate aerosols. Even if the excess-air does become mixed with the other gases, the resulting air-rich mixture is frequently too cool to allow completed reactions.

In order for fuel to burn in a RWH, the design and operation has to address the four elements of combustion discussed above. The extent to which all of these elements are optimized throughout a RWH burn cycle governs the efficiency and emission characteristics of the RWH.

REPORTING UNITS FOR RWH EMISSIONS

One significant difficulty which emerged early in the efforts to develop RWH emissions control and reduction regulations and which has also caused some controversy and confusion over the last 15 years, is the units for expressing the amount of emissions from RWH appliances. The two primary reporting-unit candidates considered since the regulation of RWH emissions began in the early 1980s, are:

1) The emission factor; i.e., how much (mass) of pollution is discharged per mass of fuel burned, expressed in grams per kilogram (g/kg), and

2) The emission rate; i.e., how much (mass) of pollution is discharged per unit of time, expressed in grams per hour (g/hr).

A third candidate, mass of pollution discharged per unit of useful room heat produced by an a RWH appliance expressed as grains per British thermal unit (gr/Btu, or in SI units; grams per Megajoule (g/MJ)) had been considered in the early days of regulation development. However, because a verified method for measuring efficiency did not exist at that time and it was thought that an acceptable and accurate measurement method would be very expensive, this unit of measure never gained favor by regulators or the RWH appliance manufacturing industry.

The basis for controversy between using either of the two primary-candidate reporting units is whether one or the other provides better information for ranking one RWH appliance against another and/or whether one or the other provides better and more useable information for modelling the relationship between the amount of RWH pollution being discharged into an airshed and how the RWHs are being operated. It would be simplified and ideal if RWH appliances discharged pollutants at constant rates or even consistent rates for any given burn rate or heat output level. The only RWH appliances which can emit pollutants at close to constant rates are the pellet stoves. Pellet stoves and other residential heating appliances, like oil or gas furnaces and most large combustion sources like electric power utility boilers, have controlled air supplies and fueling rates to optimize combustion processes at or near a "steady state" conditions. Having the ability to operate at optimized steady-state conditions can maintain nearly constant, low-pollutant emission rates over long periods of time.

If cordwood-burning RWH appliances had steady-state combustion conditions and constant and consistent emissions rates, relatively simple calculations could be used for developing good estimates or models of airshed pollutant loading caused by RWH appliances. But the fact is that no RWH appliances, except pellet stoves, discharge pollution at a constant rate from the beginning to the end of a complete burn cycle or even consistent rates from one burn-rate/heat-output level to the next. As mentioned earlier, during the burn cycle of a cordwood-fuel load in an RWH appliance, its physical and chemical characteristics change dramatically as do the amount and the physical and chemical nature of the pollutants being produced and discharged. Everything is always changing in a cordwood-burning RWH appliance including combustion-influencing parameters like temperatures, fuel weight, and fuel-load geometry.

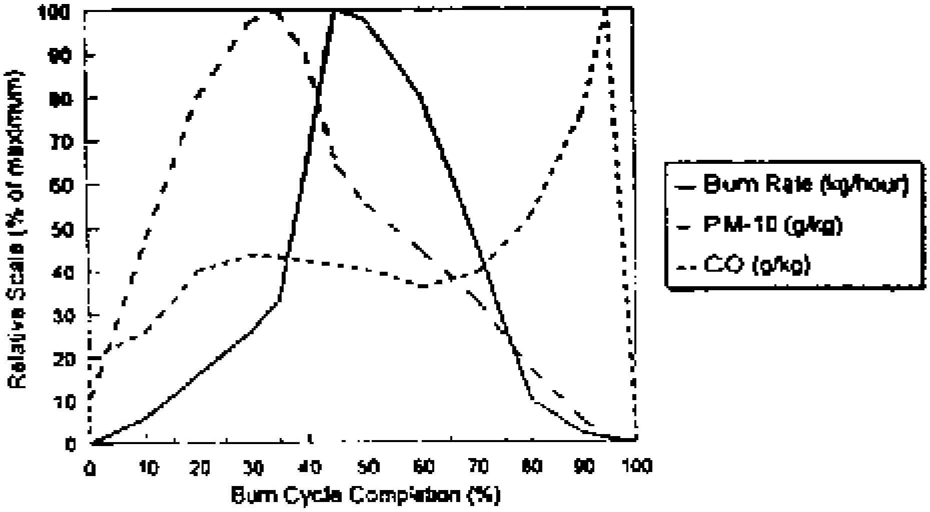

Figure 1 Gram per kilogram (g/kg) emissions versus burn cycle completion.

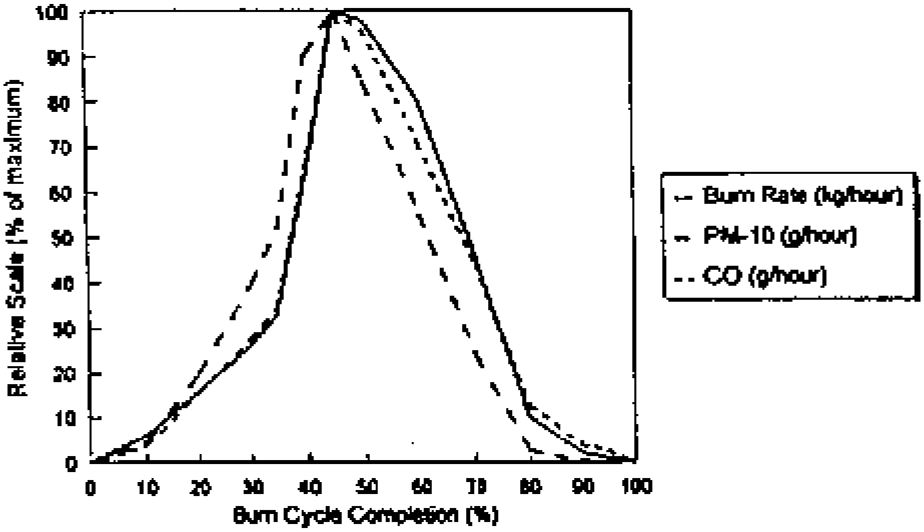

Figure 2. Gram per hour emissions versus burn cycle completion.

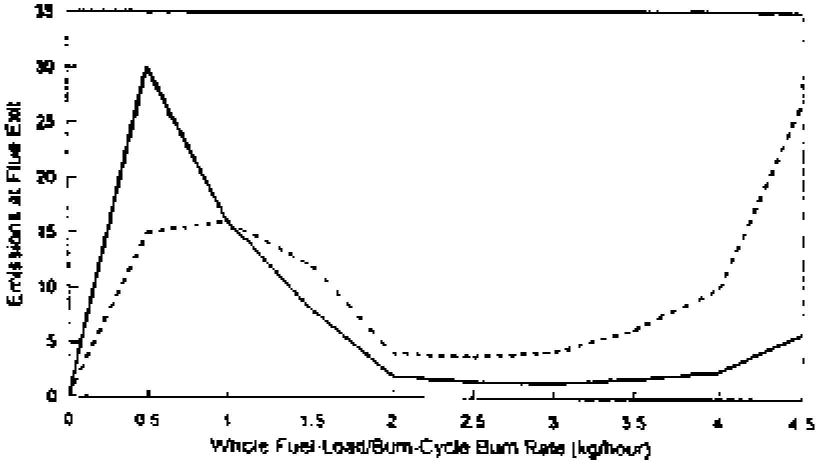

Figure 3. Gram per hour (g/hr) and gram per kilogram (g/kg) PM-10 emissions versus full fuel-load/burn-cycle burn rate.

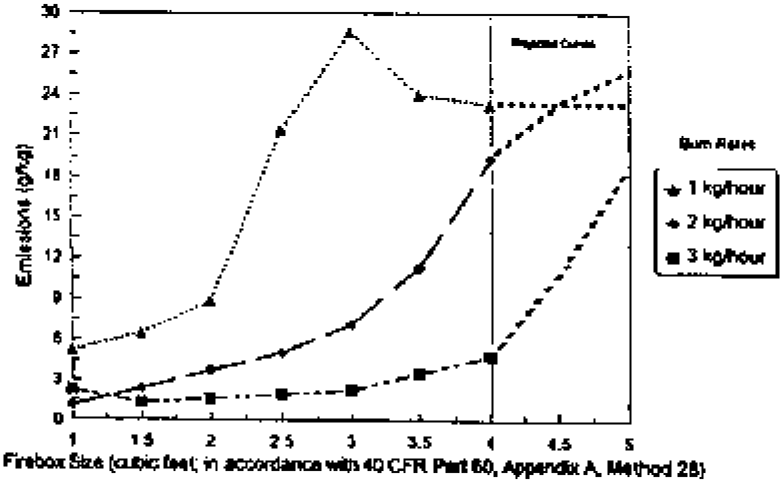

Figure 4. Firebox volume (fuel-load size) versus g/kg-emission factors for three whole-fuel-load/burn-cycle rates. All fuel loading densities were at or near 7 pounds per cubic-foot of firebox volume.

Analysis of Cordwood-Burning RWH Emissions Dynamics

Figure 1 is a generalized illustration showing how particulate and carbon monoxide emission factors (g/kg) change as well as how the burn rate itself changes as one, full cordwood fuel load is burned (i.e., one "burn cycle") and the RWH appliance is operated at one air supply setting. A percentage (relative) scale is used on the "y" axis to show the maximum for each graphed parameter. This illustration demonstrates how each parameter changes relative to the minimums and maximums of the other graphed parameters.

The fuel load is ignited at 0% fuel-load consumption. The burn rate begins slow at this point but increases rapidly to a maximum fuel consumption rate (i.e., kg/hr) at a point when about 50% of the fuel weight has been consumed. This is also the time when the greatest amounts of volatile and semi-volatile materials (i.e., fuel-gases) are being driven from the solid wood fuel. Emission factors (g/kg) for both particulate and CO emissions begin rising right at the point the fuel is ignited. At the beginning of a burn cycle, particulate emission factors (g/kg) increase more rapidly than the emission rate (g/hr), however, as volatile and semi-volatile materials in the fuel load are heated and vaporized by the increasing amount of heat being generated.

Because all RWH appliances, except for pellet stoves, are batch-loaded fuel processors and rely on very weak, naturally drafted air supplies, it is unavoidable that periods of time will occur during a burn cycle when at least a portion of the combustion zone will have un-optimized, imperfect combustion conditions (e.g., not enough oxygen, residence time, or the mixing and/or temperature conditions are not optimum). State-of-the-art, low-emission RWH appliances optimize the average combustion conditions of the burn cycle using combustion-air distribution systems which are powered by natural draft forces. They also use enhanced firebox heat management designs for optimized average thermal performance. But, even with this "new" technology, it is impossible without expensive auxiliary (e.g., electrically) powered control designs to avoid all imperfect combustion conditions that can occur with a batch-loaded process. It is the unburned or incompletely burned volatile and semi-volatile materials resulting from these imperfect combustion conditions that escape the firebox and form particulate emissions as they cool and condense on their way up the chimney.

Analyzing Figure 1 further shows that after the particulate emission factors (g/kg) are maximum at a point when about 30% of the fuel load has been consumed, they decrease due to improving, more vigorous combustion conditions in the firebox (i.e., higher temperatures and more mixing). Particulate emission factors (g/kg) then decrease further after about 60% of the fuel load is consumed due to decreasing volatile and semi-volatile contents of the fuel. The stage of the burn cycle after which the volatile and semi-volatile contents of the fuel have been depleted is sometimes called the charcoal stage of a burn cycle and is characterized by low particulate emissions.

Like particulate emission factors (g/kg), CO emission factors (g/kg) increase in the early stages of the fire due to the increasing amount of fuel being burned with inadequate temperature and/or mixing conditions. CO emissions per kilogram of fuel being burned (g/kg) start decreasing after about 40% of the fuel is consumed which is when combustion conditions begin to improve. CO emission factors (g/kg) decrease slowly until a point at which the burning fuel is dominated by coals (which is characterized by both high carbon and low volatile and semi-volatile material content). At this point, there is usually sufficient temperature for good combustion. However, inadequate air and fuel mixing becomes the dominant combustion imperfection which causes the dramatic increase in the amount of CO produced for every kilogram of fuel burned at this final part of the burn cycle.

Figure 2 has similar axis scales to those in Figure 1 except that Figure 2 shows how particulate and CO emission rates (g/hr) change during a burn cycle and, as in Figure 1, it includes a curve showing how the burn rate itself changes during one full fuel-load burn cycle at a constant air supply setting. Since the emission rates are a direct function of burn rate,

i.e., burn rate (kg/hr) x emission factor (g/kg) = g/hr,

changes in both the particulate and CO emission-rate curves follow changes in the burn-rate curve very closely. This emission-rate graph (gr/hr) shows clearly that at the same time in the burn cycle when large changes in the amount of emissions being produced for every kilogram of fuel being burned are taking place (as shown in Figure 1), there is little evidence of whether combustion conditions are improving or deteriorating. Figure 2 is useful however, for showing that increasing fuel consumption rates do increase both CO and particulate emissions rates (g/hr).

Figure 2 (the gram per hour curves) also illustrates how good combustion conditions, and hence, low emissions per kilogram of fuel being burned can be masked by a high burn rate: i.e., lower g/kg emissions and optimum combustion conditions occur at the relatively higher burn rates but are not indicated by the g/hr curves. This is ironic because it is at the higher burn rates that the batch-loaded cordwood-burning RWH appliances universally have the best combustion conditions and the lowest amount of emissions per kilogram of fuel being burned. This also means that a good cordwood-burning RWH appliance design can consistently produce the best optimized combustion conditions but because it may have consistently high burn rates, and hence, more heat output, it can be kept from the market because of high g/hr emissions. With equal overall efficiencies and equal g/hr emission rates, a high burn-rate cordwood-burning RWH appliance would discharge less pollution to the atmosphere than a low burn-rate cordwood-burning RWH appliance delivering the same total amount of useful heat.

Figure 3 is a laboratory data graph that shows how both the PM_{10}-particulate emission rate (g/hr) and emission factor (g/kg) values change as full fuel-load burn-cycle burn rates change in a typical non-catalytic RWH appliance. Although the data used in Figure 3 are from non-certified stoves, the patterns shown are characteristic of all cordwood-burning non-catalytic RWH appliances with adjustable air supplies and hence, adjustable burn rates. Each data point in each curve represents a whole fuel-load burn cycle at one air supply setting. Therefore, it takes many tests to gather the data for these curves. The size of any particular stove (and hence its fuel-load size) will shift the kilogram-per-hour burn rate scale right or left but the resultant emission rate and emission factor patterns will stay the same. Even poorly designed woodstoves would have the same patterns but the scale for emissions rates and emission factors on the "y" axis would increase to show higher emissions at any given burn rate.

The emission rate (g/hr) curve in Figure 3 shows rapidly increasing emissions as burn rates increase in the very lowest burn-rate range below 0.4 kg/hr, followed by a continuing, although lower-slope increase to the 1.0 kg burn-rate level. The g/hr then shows a decrease as the burn rate increases in the mid-ranges to 2.0 kg/hr. The rapidly rising g/hr emissions that occur when the burn rate increases in the lowest burn-rate range below 0.4 kg/hr, are due to large relative increases in burn rate with concurrently increasing emissions reaching the atmosphere for each kilogram of fuel being burned. There is an increase in emissions discharged to the atmosphere as burn rates increase at these very low burn rates in spite of the fact that air/fuel mixing is improving and higher temperatures are being generated. This is because at the very lowest burn rates (i.e., less than 0.4 kg/hr on this graph) where the worst combustion conditions occur and the maximum amount of emissions are produced in the combustion zone for every kilogram of fuel burned, some of the emissions condense and get deposited on firebox and flue pipe walls before they can be discharged to the atmosphere. This phenomenon actually results in lower emissions to the atmosphere but a higher rate of creosote deposition in the chimney. Although always present in these low burn-rate ranges, the effect of flue-pipe creosote deposition on emissions discharged to the atmosphere decreases as the burn rates increase from about 0.5 kg/hour.

The emission-factor (g/kg) curve also increases in the burn rate range below 0.4 kg/hr. Since g/kg does not have a direct mathematical relation with burn rate like the g/hr units, the increase in emissions in this burn rate range is due only to the decreasing effect of creosote deposition as the burn rate increases.

The g/kg curve decreases after the 0.4 kg/hr burn rate because the effect of better air/fuel mixing and higher temperatures decrease the amount of emissions being produced for every kilogram of fuel being burned. Although the amount of emissions per kilogram of fuel being burned decreases, the g/hr curve continues to increase above the 0.4 kg/hr burn rate due to the fact that the large relative increase in burn rate offsets the relative decrease in the amount of emissions produced for each kg of fuel burned. For example, if there is a doubling of the burn rate from 0.5 kg/hr to 1.0 kg/hr and at the same time there is a 35% decrease in emissions produced by each kilogram of fuel being burned, the g/hr emission rate still increases 30%. That is,

0.5 kg/hr burn rate x 30 g/kg emission factor = 15 g/hr emission rate,

then doubling the burn rate and decreasing the emission factor by 35% gives:

1.0 kg/hr burn rate x 19.5 g/kg emission factor = 19.5 g/hr emission rate,

which is a ((19.5-15.0)/15.0) x 100 = 30% increase in the emissions rate when combustion and heat delivery conditions are actually improving.

y definition and by their direct mathematical relationship, the g/hr- and g/kg-curves cross at the 1.0 kg/hr burn rate. After these curves cross, the decreasing g/kg emissions overcome the relative increases in burn rate which then effect a decrease in the g/hr-curve. As the burn rate approaches 2.0 kg/hr the g/kg emissions decrease to a minimum due to optimized combustion conditions in the firebox. The height of the g/kg-curve at the point that combustion (or more appropriately, the quality of the burn) is optimized is a function of firebox/stove design. Better designs will have lower g/kg-curves in the combustion-optimization range.

An important fact about this part of the g/kg-curve is that the combustion-optimization segment of the curve covers a relatively large area of the mid- to high-burn-rate range and not the low burn- rate ranges. All EPA certified non-catalytic cordwood-burning RWHs must burn a large portion of each fuel loading within this range or they will not have a low emissions rate (i.e., g/hr). It is important to note again that even if the quality of the combustion process (i.e., g/kg) stays the same from one burn rate to the next in these stoves, just increasing the burn rate would increase their g/hr emissions rate. It is also important to note this low emission factor part of the g/kg curve because this is the burn-rate range where Colorado-approved masonry heaters always operate. This is also true for pellet-fired RWHs, however, instead of having one (high) burn rate in the optimized g/kg burn-rate range, pellet-fired RWHs adjust their fueling and combustion-air delivery rates to maintain the same relative fuel-load (burnpot) consumption rate.

Masonry heaters are all designed to burn fuel at one burn rate in the mid- to high-combustion-optimized range to obtain the most heat production and lowest emissions possible. The whole curve for a masonry heater would be one point or would only cover a small segment in the combustion-optimized segment of the burn-rate range. This is because masonry heaters are only designed to have one burn rate. If a masonry heater firebox is designed poorly, the g/kg-curve (point) would be higher in this combustion-optimized part of the curve and the curve (i.e., point) would be lower in a well designed masonry heater. Well designed pellet stoves on the other had would have a constant, flat, no-slope, curve all the way across the whole range of burn rates.

Again, by definition and because of the direct mathematical relationship between g/hr and g/kg, the g/hr-curve increases throughout the combustion-optimized segment of the burn-rate range. This is due to the fact that although the g/kg curve is constant (flat) showing no change in the quality and efficiency of the combustion process taking place in this burn-rate range, merely increasing the burn rate causes the g/hr-curve to increase. For example, keeping the g/kg emission factor constant while the burn rate changes from 2.5 to 4.0 kg/hr will increase the g/hr emission rate by 60%. That is,

5.5 g/kg emission factor x 2.5 kg/hr burn rate = 13.75 g/hr emission rate,

then increasing the burn rate from 2.5 to 4.0 kg/hr gives;

5.5 g/kg emission factor x 4.0 kg/hr burn rate = 22.00 g/hr emission rate,

which is a ((22.00-13.75)/13.75) x 100 = 60% increase in the emission rate.

Therefore, it can be very misleading to assess the pollution characteristics of a cordwood-

burning RWH appliance, by only using a g/hr value. Any clean burning appliance design can have high g/hr emission rates just because it can be made to burn fuel fast. Even though they can be producing more heat with lower total emissions to the atmosphere, single, high burn-rate appliances such as masonry heaters are unfairly viewed by some regulators as high polluters when g/hr values are used for comparison to other types of appliances like adjustable burn-rate RWHs.

To conclude the g/hr- and g/kg-curve analysis, the increase in g/kg emissions at burn rates above 4.0 kg/hr is due to decreasing combustion efficiency which is caused, in most cases, by excess combustion-air cooling or by dilution of the combustible fuel-gases given off by the heated wood before they can burn. Depending on the firebox design, the fire can also become too fuel-gas rich because too much of the fuel load is being heated to high temperatures too quickly which creates large amounts of combustible fuel-gases without enough air for efficient combustion. In either of these cases the amount of pollution created by each kilogram of fuel increases and hence, the slope of the g/hr-curve increases even more. The g/hr-curve increase progresses at a steeper slope than the g/kg-curve because it is compounded by both an increasing burn rate and an increasing emission factor.

To get around the problems presented by the variable and constantly changing cordwood-burning RWH combustion and emissions parameters, the EPA and the Oregon and Colorado state certification testing programs, required that regulated RWH appliances be tested for emissions at four different burn rates ranging from low to high. Since each certification test-run emissions sample is taken/collected over an entire burn cycle, each test represents the average pollutant discharge that took place during the burning period for each of the four whole fuel loads. The results from each of the four separate tests are then weight-averaged together using weighing factors derived from the expected average annual residential heat demand of the average house in an average heat demand location in the U.S. (i.e., about 17,000 Btu/hour). Therefore, at the end of this certification process there is a single emission rate (in g/hr as required by EPA) for each model of regulated RWH appliance. This emission rate indicates the average mass of pollution that can be expected to be discharged on an hourly basis when the appliance is in operation.

It is important to note in this discussion that the g/hr and g/kg units are both resultant data from certification testing of RWH appliances. No additional testing is required to obtain either reporting unit. It's only a quirk of history that of the three options for reporting units, the EPA, and the states that have had certification programs, chose the g/hr units to establish regulatory emission limits for RWH appliances.

The use of g/hr units started in Oregon and then was adopted by Colorado and finally by EPA. During the NSPS negotiations, there was EPA resistance to change from the units used by Oregon and Colorado even with solid technical arguments supporting change. The record of EPA's New Source Performance Standard (NSPS) negotiations with the RWH appliance manufacturing industry clearly shows that the choice for g/hr was not made without challenging comments or good alternative recommendations. EPA argued that since their goal was only to develop a reliable ranking system for comparing regulated RWH appliances to one another, the already-used g/hr units would be chosen.

Clearly the most useful reporting units would have been in grams of pollutants discharged to the airshed per unit of useful heat output from the RWH appliance. The real advantage of this unit-of- measure is that it would take into account the overall thermal (both combustion and heat transfer) efficiency of the appliance. If the g/hr and/or g/kg test results indicated that two RWH appliance models had equal emissions, the more efficient model would burn less fuel to heat the same space, and hence, emit less pollution to the airshed. As mentioned above, the heat output-based emission-rate units were not used since they would require the measurement of overall thermal efficiency and EPA felt the thermal efficiency measurement methods available at the time the NSPS was being negotiated were costly and not verified enough to use in EPA's certification program.

A very important point to note is that in all of the codified test methods for determining grams per hour (g/hr) reporting units for regulating RWH appliances, it is not required that the appliances being tested provide any useful space heating. All that is needed to determine g/hr is the measurement of total exhaust-gas flow rate and the pollutant concentration; i.e.,

g/m^3 x m^3/hr = g/hr.

Where: g/m^3 = grams of emissions per cubic meter of flue gas.

m^3/hr = cubic meters of flue gas flow per hour.

Neither the concept of g/hr itself nor the test method protocols to measure g/hr emissions, require the production of any useful heat, only that the appliance be able to burn specified fuel loads within 4 prescribed burn rate categories. To emphasize: The test methods do not use heat output categories, just burn rate categories.

During the New Source Performance Standards (NSPS) negotiations in 1986, EPA decided to assume standard thermal efficiency levels for all regulated RWH appliances. Considering their objectives, this approach to efficiency is somewhat reasonable since the definition of the appliances being regulated (EPA calls them "affected facilities") imposes physical and operating specifications like air-to-fuel ratio, weight, and firebox volume limitations which when used in combination with the required burn rate categories and the emission limits, result in the approximate EPA-assumed efficiency levels. This is not just coincidental but an engineering fact that if all the affected-facility definition criteria, test-protocol requirements, and emission limits are met, the overall thermal efficiency levels of the regulated RWHs will be close to EPA's assumed levels.

Most importantly, when discussing units of measure, the unique features of the EPA regulated RWH appliances (e.g., not including masonry heaters) that make the g/hr units useable in the regulation of these emissions are:

1) The heat output (burn rate) of the appliance is adjustable on a real time basis. If the user desires more heat, the air supply and/or fuel load is increased to increase the combustion process and if less heat is desired the air and/or fuel load is decreased, and

2) The production of heat in the firebox by the fuel-burning combustion process and the release of that heat to the surrounding space occurs at virtually the same time. There is no, or only a very small delay between heat production by the fuel-burning process and the transfer of that heat to the space being heated. RWH appliance firebox shells are virtually all made from either sheet metal or cast iron to accommodate this heat transfer. In either case, these high heat-conducting materials are used because they "transfer" heat from the firebox to the surrounding space as quickly as possible. Because the regulated RWHs are not designed for heat storage, there is no (or only very little) storage of heat in the mass of the appliance. Regulated RWH appliances make heat in the firebox and transfer it to the space being heated as soon as possible.

These features allow the g/hr unit of measure to be applied to regulated RWHs, but applicable only because these features are unique to the regulated RWHs. This does not mean that g/kg or the mass of emissions per unit of useful heat output (e.g., g/MJ) could not be used or even be useful. In fact, either one of these reporting units could be used with at least as much and definitely more useful information being provided about the quality and efficiency of the combustion process taking place. No other appliances or EPA-regulated source types burning any other fuel for any other purposes can reasonably use the g/hr unit alone. No matter what the source, without production or process throughput data there is always serious potential for communicating incorrect information.

It is only the design specifications imposed by EPA's NSPS woodstove (affected-facility) definition in combination with the emission limits imposed on the regulated RWHs that allow the use of g/hr units. In addition, because of the definition and the emission limitations, regulated RWHs are, actually by default, regulated based on the amount of emissions produced per unit of useful heat output. This is because of the assumed efficiencies and therefore the assumed amount of useful heat output generated during the burning of test fuel at the rates required by the test protocols: e.g., virtually all regulated non-catalytic stoves burning 1 kg/hr will produce approximately 12,500 Btu/hr of useful heat to the surrounding room, and virtually all catalytic stoves will produce approximately 14,500 But/hr when burning 1.0 kg/hr of fuel. This is because the efficiencies for all of the regulated RWH appliances within each category (i.e., non-catalytic or catalytic), are nearly the same.

Masonry heaters were intentionally excluded from EPA's NSPS by EPA's specified weight criteria (affected facilities have to be less than 800 kg). EPA rationale was that masonry heaters would require time- and money-consuming development of new test method and operating protocols and most importantly because of their designed, consistent high burn-rate, would be clean burning anyway and would not present problems in local airsheds. In addition, if the EPA was to regulate masonry heaters, the reporting units for emissions would have to have been changed first.

The g/hr emission rate is not useful or appropriate for masonry heaters since masonry heaters only burn fuel during a very short part of their useful heat output cycle. In addition, if masonry heaters are to be ranked or compared to other RWHs, EPA's NSPS test-method operating protocol (Method 28, 40 CFR Part 60, Appendix A) would have to be changed. Since the primary burn-cycle mode of operation for masonry heaters is one fuel load burned at the full-high burn rate until all the fuel is gone, the test cycle would need to include the whole cycle including start-up and complete burn down (i.e., a "cold-to-cold" test-burn cycle). The test-method operating protocol would have to take into account the fact that useful heat output is produced by masonry heaters long after the fire has gone out.

Method 28 for woodstoves is a hot-to-hot test-burn cycle: a hot coal bed is established in a hot stove; a specified fuel load is then added to begin the test; and completion of the test is at the point in time when the added fuel is totally consumed back to the original, hot coal bed. This cycle is conducted at 4 different, and specified burn rates to make a complete certification test series.

It is important to realize the difference between testing an RWH appliance using a hot-to-hot test cycle as opposed to using a cold-to-cold test cycle. In 1986, Jay Shelton of Shelton Research in Santa Fe, New Mexico (personal communication) did a woodstove research project for the State of Colorado and found that emissions discharged during the cold start up phase of a woodstove equals 50 percent of the emissions discharged during a whole hot-to-hot test cycle. This means that the standard EPA test method misses up to 33 percent of the total emissions actually discharged by a regulated RWH appliance during cold startup operations.

This is not a criticism of the method, if it is kept in mind that the method was designed and adopted to rank stoves against one another and not to simulate actual and absolute in-consumer-use emission rates. It was felt by almost all of the regulators participating in the NSPS regulation negotiations, that ranking of stoves with an indicated relative emissions reduction was more important than trying to establish absolute or "real world" emission rates for certified stoves. That is, an NSPS limit of 7.5 g/hr for non-catalytic RWHs was a 75 percent reduction from the 30 g/hr which was considered by the regulators to be the emissions rate for the common "conventional" stoves in use at the time of the NSPS negotiations. The idea was that the 75 percent reduction indicated by the laboratory test method would translate to a 75 percent reduction in actual home-heating-use emissions to the atmosphere, regardless of what the actual or absolute emissions rates were. The objective was to get the 75 percent reduction. There was never any attempt or wish expressed by EPA in the NSPS negotiations to use RWH certification emissions values for estimating or modeling airshed emissions loading rates(3).

On the other hand, therefore, it should be kept in mind that contrary to the woodstove test protocol of hot-to-hot test periods, all standardized masonry heater testing performed by OMNI to date has sampled the whole burn cycle on a cold-to-cold basis (defined by flue-gas temperatures of less than 100°Φ). The Automated Emission Sampler (AES) used by OMNI Environmental Services in performing '*in-situ*' field and laboratory sampling of masonry heaters, collects emissions samples during all phases of the burn cycle, including start-up from cold (i.e., flue-gas temperature above 100°F) to cold, total-fuel burn-down. All fuel loads burned during the total sample period of one week or more, 24 hours a day, are sampled. Thus OMNI's data on masonry heaters is a "real world" emission rate that is not directly comparable to RWH certification data.

Secondary Combustion

Over the last 10 years, low-emission non-catalytic RWH appliances have been developed which exhibit weighted-average emissions well below the EPA NSPS - required 7.5 g/hour (approximate conversion to 5.4 g/kg). These appliances depend on fine-tuned firebox configurations and operating protocols which optimize the average, air-regulated batch-loaded-fuel combustion conditions over whole fuel-load burn cycles. Virtually all of the non-catalytic RWHs currently on the market have manual controls for setting air supplies and burn rates. One of the most notable non-catalytic RWH features is that none of them have thermostatic combustion controls. The lack of thermostatic control on non-catalytic RWHs is not some extraordinary coincidence of design. To date, no design mechanism or technology has been developed which can accommodate clean burning with the complex dynamics of batch-loaded-fuel combustion and air-supply-mediated burn rate control.

In addition, all EPA certified non-catalytic RWHs to date have utilized natural draft to drive the flow of combustion air through the combustion systems. None of the batch-loaded cordwood burning RWH appliances utilize externally powered fans for providing combustion air delivery to the combustion chamber. And, since combustion air control is the only method available for controlling the rate of combustion in batch-loaded-fuel systems, the only practical means available for modulating combustion is by the application of thermo-mechanical devices; i.e., devices which have a mechanical response to changes in temperature.

Batch-loaded non-catalytic RWHs cannot accommodate modulated air supply while maintaining clean burning conditions because clean burning is dependant on maintaining the active high temperature combustion of fuel gases generated by the heated fuel load. When a thermostat decreases the air supply to the combustion chamber, the balance of air-to-fuel ratios and mixing turbulence is shifted which very often leads to cessation of gaseous combustion activity (i.e., flame). Under these circumstances, the unburned or incompletely burned gases leave the combustion chamber as emissions (i.e., smoke). No design factor has yet been devised for batch-loaded maintaining clean burning, efficient combustion in non-catalytic RWHs where the air supply is reduced during the combustion of a fuel load.

The typical batch-loaded non-catalytic RWH is configured with primary and secondary combustion chambers. The primary combustion chamber is sized to accommodate a cordwood fuel load and is located directly below the secondary combustion chamber. The structure separating the primary and secondary combustion chambers is typically called a baffle. The term "secondary" refers to the area or chamber where combustion of only gaseous fuel materials takes place. Typically the secondary combustion chamber is smaller than the primary combustion chamber and is constructed of materials which can contain and hold as much heat as possible so the elevated temperatures can be maintained as long as possible. Also typical is the addition of heated air to the combustion gases as they leave the primary combustion chamber and enter the secondary combustion chamber. This heated air is usually referred to as "secondary air." The size of the secondary chamber, the amount and temperature of added secondary air, and the temperatures and turbulence within the secondary combustion chamber govern the quality of secondary combustion which can take place.

If this primary and secondary combustion system is optimized for an air supply which is governed only by natural draft, it is very difficult to maintain the appropriate air-to-fuel ratio, temperature, and mixing conditions for sustaining active and clean combustion. This is especially true when the primary air supply is mechanically altered to reduce the overall combustion rate. Gaseous combustion ceases when air-to-fuel ratios drop below approximately 15:1 and when combustion gas temperatures drop below approximately 950°F. Once gaseous combustion ceases, temperatures, of course, fall rapidly and air-to-fuel ratios decrease as does turbulence which is needed for adequate mixing of the air and fuel gases.

Most catalyst equipped batch-loaded RWH appliances currently on the market, are also equipped with devices which provide thermostatic control of their combustion air supply. Thermostats utilized on these stoves are universally powered by the thermo-mechanical response of bimetallic coils. As temperatures on the surfaces or in the spaces where the bimetallic coils are placed change, the bimetallic coil physically expands or contracts. This mechanical action is then translated into supplying more or less combustion air to the combustion chamber.

The catalyst in catalyst-equipped RWHs replaces the secondary combustion chamber of non-catalytic RWHs. Some catalyst have a metal substrate base but most are manufactured with ceramic substrates and active catalytic coatings which contain mostly precious metal oxides such as platinum and palladium. Catalysts are available in a variety of overall shapes and sizes, from 2- to 10-inch squares and rectangles to 6- to 8-inch circles. Most of them are from 2- to 3-inches in depth along the path of combustion gas flow and have a monolithic, honeycomb structure with 4 to 6 cells per inch.

Catalytic activity works to reduce the temperature at which chemical reactions such as wood-gas combustion take place. The same amount of chemical energy is released from the combustion of wood generated gases when a catalyst mediates the chemical reactions but the temperatures at which the chemical reactions start taking place are reduced. Without catalytic mediation, the lowest temperature at which wood-gas combustion appears to be initiated is approximately 950°F. With the same gas mixtures, and when the gases are passed through a catalyst, this temperature is reduced to the range of 500 to 600° F. In addition, once catalyst mediated combustion is initiated the energy released generates temperatures in excess of the 950° F level so that wood-gases passing through the honeycomb spaces are combusted without coming in contact with the actual catalytically active surface. This phenomenon adds even more heat to the catalytic structure which is then capable of sustaining clean burning conditions under a wide range of catalyst inlet gas temperatures.

Most catalyst equipped RWHs also introduce heated secondary air to the gases leaving the primary combustion chamber. As in non-catalytic RWHs, this is done to ensure that adequate air-to-fuel ratios are maintained in the catalyst mediated combustion zone even if the primary air supplies are reduced by the action of a thermostat. Like non-catalytic RWH design features, catalyst equipped RWHs typically incorporate measures like insulating ceramic materials to conserve and hold heat in the secondary (catalyst) chamber. Because very high temperatures above 1000°F are maintained in catalysts for long periods of time during full fuel-load burn cycles, a wider range of air-to-fuel ratios and mixing turbulence can produce cleaner burning results than occur in non-catalytic RWHs

Firebox/ Fuel load size

The capacity of a woodstove to hold fuel is determined by the size, or usable volume, of the primary combustion chamber or firebox. Many RWH manufacturers report that the U.S. market requires large volume RWHs which enable consumers to load large amounts of wood fuel. The ability to maintain long burn duration without reloading or adjusting the air supply settings is commonly regarded as a major marketing feature. As a result, most RWHs sold in the U.S. market have firebox volumes of about 1 to 3.5 cubic feet (28 to 100 liters). Data from EPA certification tests and from previous studies on fuel-load/firebox volume burn rate, and PM-10 emissions relationships(3) were used to construct Figure 4.

All the data were from non-catalytic RWHs. The 1 kg/hour-burn-rate curve shows that emission factors are at approximately 5 g/kg in one cubic-foot firebox and increase rapidly as firebox sizes (and hence fuel load size) increase over two cubic feet. The small decreases in the 1 kg/hour emission-factor curve when firebox sizes increase to greater than three cubic-foot, are probably due to deposition losses of emissions on firebox and chimney walls.

Each of the burn rate curves exhibits dramatic increases in emission factors as firebox size increases. As the burn rates increase, the slope of the emission-factor curves decrease and the larger the firebox is when the dramatic increases occur: i.e., larger fireboxes, and hence, fuel loads, require higher burn rates to maintain low emission factors.

It should be noted that since the standard test procedures call for a fuel loading density of 7 pounds of fuel per usable cubic-foot of firebox volume, each RWH is loaded according to its specific size. If several RWHs are each burned at seven pounds per hour, at the end of one hour, a 2 cubic-foot RWH burns half of its fuel load, a 3 cubic-foot RWH burns one third of its fuel load, while a 1 cubic-foot RWH consumes its entire charge.

The size of the fuel charge appears to be the primary critical factor. The batch process involved in fueling an RWH requires an entire fuel charge to be placed in the firebox at once. As the fuel load is heated, gasification of the wood occurs. The larger the fuel load, the greater the amount of wood subjected to gasification, resulting in greater quantities of wood gas being released over a given time. At a fixed heat output level, more wood gas will be released from a large fuel charge than from a small charge. Lower mixing intensities and more cool areas in larger RWHs will result in higher emissions (per mass unit of fuel burned), especially under low-fire conditions. Catalyst equipped RWHs are not as susceptible as the non-catalytic RWHs to the effects of firebox/fuel-load size.

As discussed previously, because of higher sustained temperatures, catalyst assisted secondary combustion accommodates a much greater range of air-to-fuel ratios and air/fuel mixing conditions. As long as the catalyst is sized correctly and an appropriate amount of air is provided, a catalyst equipped RWH will have lower emissions under just about any burning conditions.

Controlled Air Supply and Fuel Feed Rates

Efficient combustion is difficult to accomplish in traditional RWHs especially at low burn rates due to low combustion temperatures, poor air-to-fuel mixing, and variable combustion conditions. If air is mixed with fuel in a highly regulated and turbulent manner, higher temperatures and more efficient combustion can be achieved. Mechanical draft systems, in which air is forced or drawn into the combustion chamber, are used on many wood fired furnaces and all types of small, mid- and large scale commercial and industrial boilers.

A forced draft system moves air into the combustion chamber under positive pressure; i.e., higher pressures exist in the combustion chamber than in the surrounding space. Induced draft, on the other hand, draw exhaust gases out of the firebox, creating negative combustion chamber pressures. Both systems use fans to move the air and gases, hence the term mechanical draft. (Natural draft stoves are more properly "thermally drafted".) The use of a mechanical draft allows much greater control of combustion air flows and patterns, resulting in improved combustion conditions.

Both the induced and forced mechanical draft systems have advantages and disadvantages. Forced draft systems require higher quality construction methods to prevent combustion gases from leaking through doors and other openings into the surrounding space.

Induced draft systems do not require a perfectly sealed system, as most leaks will simply draw air into the combustion chamber or flue. Induced draft fans, however, must move hot and sometime dirty gases, requiring more care in selection and maintenance of fans and motors. In addition, mechanical draft RWHs will not operate without electric power to drive the fans, so these units can not be utilized during power outages.

Among RWH appliances currently available, virtually all mechanical draft stoves are designed to burn pelletized wood fuel. Pellets are typically ¼ inch to $^{3}/_{8}$ inch in diameter and about ½ inch in length. The composition varies among manufacturers, but is primarily sawdust and chips from forest products operations. Some pellets are composed of wood only, while others contain more bark and debris. Most are formed under heat and high pressure, and most use no binder. Heat content of the pellets are typically in the same range as cordwood (i.e., 8750 to 9200 Btu/dry lb), with a moisture content of 6-10 percent. Pelletized fuel has been successfully used as a substitute for coal in many small boiler applications.

The primary advantage of using pellets in residential combustors is the ability to control the amount of fuel involved in combustion at any one time. Air and fuel feed rates are then both controlled, providing optimized combustion conditions. Pellets can be fed at a constant rate into a combustion zone maintained at high temperatures and high turbulence by a forced or induced draft.

The mass of fuel involved in combustion at any time is very small, while oxygen supplies and turbulence are high. Pellet stoves can operate under steady state conditions as a continuous process, rather than the batch process of burning cordwood. The small mass of fuel burning at any given time promotes stable, near steady state conditions, which allows more efficient combustion. Pellet-fired RWHs with appropriate air-to-fuel ratios (i.e., in the rage of 15:1 to 19:1) have efficiencies and emissions comparable or better than catalytic RWHs.

On all existing pellet-fired RWH designs, fuel is stored in a hopper and moved into the combustion chamber/firebox with a motorized auger or cupped-wheel design. The feed rate is controlled by variable speed motors or automatic/electronic time-on switches. Pellets are pushed or dropped into a small cup-shaped tray which is surrounded by combustion air inlet jets, creating a concentrated and intense burn region. Air supply fan speeds can also be varied; some pellet-fired RWHs have combined single-control air and fuel feed rates while others offer combinations of independent fan and fuel feed rates controls, and continuous or intermittent operation. Most pellet-fired RWHs use a refractory lined combustion chamber in which the pellet "burnpot" and air supply ring are located. Gases are then vented from the combustion chamber through heat exchange baffles.

CONCLUSIONS

The combustion of wood in Residential Woodfired Heaters (RWHs) involves highly complex chemical processes which are sensitive to a wide variety of influences. Key elements required for efficient combustion include high combustion zone temperatures, appropriate air-to-fuel ratios, adequate air (i.e., oxygen) and fuel mixing, and adequate residence time. The batch process of wood combustion in the naturally drafted RWH presents special problems in that the entire fuel charge is involved in various and changing states of a complete combustion processes throughout the fuel-load burning cycle. Ideal conditions vary during each stage, making complete and efficient combustion of the entire fuel charge in a single RWH configuration very difficult. At best, present designers of naturally drafted RWHs provide optimized averages for the burn cycle: complete and efficient combustion for all stages of the burn cycle have not been perfected.

A variety of RWH technologies have been examined for their effectiveness in emissions reduction and for their appropriate measurement and reporting units. Conclusions drawn include:

1. The most useful and technically sound reporting unit for all RWH appliances and masonry heaters would be grams of emissions discharged per unit of useful heat produced. These units have not been used because no verifiable measurement methods were available at the time applicable regulations were being written.

2. The g/kg and g/hr reporting units must be used with caution when applied to the performance of EPA-regulated or EPA-exempted RWH appliances:

a) G/hr can be used to indicate the performance of EPA-regulated RWH appliances (EPA calls them affected facilities) only because of the limitations imposed by EPA's definition of affected facilities and the specificity of the test methodology utilized to measure their emissions performance. It is only because these limitations and specificity impose such a narrow range of sizes, design configurations, and test-condition operating protocols that the g/hr reporting units can be used for ranking one RWH against another. G/hr should not, however, be used to estimate the field performance of RWH appliances or typical real emissions.

b) The g/hr reporting unit is not appropriate for masonry heaters because burn times are short resulting in high g/hr values when g/kg values are low. G/kg is the most useful reporting unit for masonry heaters because it does directly reflect the quality of the burning process taking place. In addition, with g/kg data and defined construction specifications, masonry heaters can be fairly ranked against one another.

c) Since g/kg is the most useful unit for indicating the quality of the combustion process taking place, it would also be useful for comparing the currently regulated RWH appliances (i.e., woodstoves and pellet-fired stoves) with masonry heaters and any other wood burning appliances.

3. Smaller fuel charges required with smaller fireboxes reduce emission rates when compared to larger fuel loads consumed at comparable burn rates.

4. Air entering the firebox near or up through the coal bed ("underfire air") results in higher emissions.

5. Preheated secondary air, or more properly termed, additional wood-gas combustion air, introduced as combustion gases leave primary combustion zones and enter secondary combustion chambers can effectively reduce emissions.

6. Thermostatic air supply controls on non-catalytic RWHs cause air-starved conditions and high emissions when fuel load and firebox temperatures are high and the thermostat closes the damper.

7. Pellet-fueled RWHs utilizing mechanically assisted drafts have demonstrated emission rates below the most efficient cordwood burning RWHs. This is due to externally powered controls for fuel feed and air supply which maintain ideal air-to-fuel ratios and mixing conditions.

Wood combustion involves a large number of highly variable parameters which can cause a high degree of variability in pollutant emissions. Certification testing, conducted by any current or proposed method, necessarily allows a range of test conditions. For example, there are allowed ranges of wood moisture, fuel loading density, and starting and ending temperatures. Although in most cases these ranges are narrow, they do produce error ranges or "noise" in resulting data. This "built-in noise," combined with the variable conditions of wood combustion, makes statistically significant isolation and quantification of RWH design factors difficult. However, as presented here, generally consistent differences can be seen between many design variables using the currently available data base.

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