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# The Engineer's Guide to Efficiency Requirements for Wood Burning Appliances

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## Introduction

The Environmental Protection Agency (EPA) has developed proposed revisions to the New Source Performance Standard (NSPS) for wood burning appliances, which is expected to be published in late 2012/early 2013. The new regulations will substantially expand the list of products that will be included under the regulations to include the currently covered wood stoves and pellet-burning room heaters, but also hydronic heaters, forced air furnaces, single-burn-rate stoves, and masonry heaters.

While other wood burning appliances such as factory-built and masonry fireplaces, cook stoves, camp stoves, outdoor fireplaces, pizza ovens and coal stoves will not require emissions testing, they will require identification labeling.

The new regulations will undoubtedly include tighter emissions limits. These include new limits for particulate emissions released by wood stoves and pellet-burners will most likely be 4.5 g/hr for non-catalytic and 2.5 g/hr for catalytic stoves, as currently required by Washington state.

A broader scope of appliance types and tighter limits have been expected for some time. The proposal will likely require minimum efficiencies of 70% for room heater type appliances and 75% for hydronic heaters. These are quite high considering that the current minimum efficiency required by the Department of Energy for gas-fired room heaters and hearth products ranges from 61 to 67 percent.

Table 1.
Anticipated NSPS Proposal Limits

| Appliance Type | Emission Maximum | Efficiency Minimum* |
|---|---|---|
| Wood Stove – Non-Cat | 4.5 g/hr | 70% |
| Wood Stove - Calalytic | 2.5 g/hr | 70% |
| Pellet Burner – Non-Cat | 4.5 g/hr | 70% |
| Pellet Burner - Catalytic | 2.5 g/hr | 70% |
| Hydronic Heater Level 1 | 0.32 lb/mmBtu Output | 75% |
| Hydronic Heater Level 2 | 0.15 lb/mmBtu Output | 80% |
| Single Burn Rate Stove | 3.0 g/hr | 70% |
| Forced Air Furnace | 0.93 lb/mmBtu Output | NA |
| Masonry Heater | 0.32 lb/mmBtu Output | NA |

*It is presumed that the proposed efficiency requirements are based on the fuel higher heating value (HHV).

The EPA has stated that the proposed efficiency limits will result in reduced carbon monoxide (CO) emissions, however there is little evidence to support this contention. While CO production represents a chemical loss that affects the appliance efficiency, CO emissions in appliances that meet the particulate emissions requirements, are quite low and typically represent less than 1% of the energy loss. Heat transfer efficiency is more significant and has no direct relationship to CO production.

EPA regulations are based on limits that reflect "best demonstrated technology" (BDT).  This means that there must be a substantial data set showing a proposed limit can be met by a significant number of existing products.

There is limited data available for wood burning appliance efficiency, which can be attributed to the lack of recognition by the EPA of any test method for determining heating efficiency for the past 24 years that the current NSPS has been in effect.  A test method did once exist in the form of CSA B415.1, but it was not widely used. Therefore, many of the currently certified appliances that would meet the proposed particulate emissions limits have not been evaluated for efficiency by a recognized test method. Available data suggests that most catalytic and a majority of the non-catalytic cordwood stoves currently on the market would meet a 70% minimum weighted average efficiency, but it is uncertain whether any existing data will pass as the basis for future acceptance under the new NSPS. Re-testing of these products under current test methods has the potential to produce significantly different results.

Hydronic heaters (boilers) are another matter. With the exception of a number of test reports indicating impossibly high efficiencies, the weighted average efficiencies of appliances meeting EPA Phase II emissions limits average 55%, and none have efficiencies at or above the 75% level to be proposed by the EPA. Even a 65% minimum would eliminate all but 2 or 3 of the currently listed models. In addition, the EPA has indicated that they are planning to impose even lower emissions limits (0.15 lb/Million Btu Output) and higher efficiency (80%) for a Level 2 limit that would be phased in a few years after the initial regulation has taken effect.

Once the EPA publishes the proposed NSPS, there will be time allotted for public comment. If the efficiency levels required for specific product types are found to be unreasonable and unattainable, the result could be devastating to the industry.  It therefore seems imperative to build a database of documented accurate efficiency data on appliances that would also meet the EPA proposed emissions limits.  Manufacturers should consider testing the products which they except will comply with the revised NSPS for efficiency, and provide the data to help build a database that could support a realistic determination of efficiency BDT.

## What is heating efficiency?

'Heating efficiency' of fuel burning appliances is the ratio of heat delivered to the heated space to the heat content of the fuel burned, expressed as a percent. Simply stated, it is the heat output divided by the heat input, times 100.

When discussing efficiency testing for wood burning appliances, the industry refers to two types of test methods:  *direct* and *indirect*. For boilers and furnaces delivering heat by circulation of a heated media, such as water or air, direct measurement of heat output is fairly straight forward.

For appliances that deliver heat to the surrounding space primarily by radiation and convection, direct measurement is not as simple. It requires a "calorimeter room" where the heat output can be determined by measuring the energy extraction rate required to keep the room at a constant temperature. Years ago, several calorimeter rooms existed and were used for wood burning room heater efficiency testing. This method was expensive and presented many problems, including the need to keep the room sealed while also maintaining a neutral pressure balance. Additionally, difficulty arose trying to measure heat output accurately when the appliance output was not constant. Calorimeter rooms fell out of favor due to the difficulty and expense required to operate them, and none remain in operation today.

## Direct Test Method for Furnaces and Hydronic Heaters

A direct test method accurately measures the temperature change and flow rate of the heating media, and calculates the heat gain from the mass flow rate, temperature difference, and specific heat of the heating media. However, when boilers or furnaces are located within the heated space, there may be a significant amount of useful heat provided by radiation and convection directly to the space around the appliance. This is commonly referred to as *Jacket Loss* measurement, which is determined through both direct and indirect test methods.

The recently published standard ASTM E2618 covers efficiency and emissions testing for Outdoor Hydronic Heaters. This procedure uses a water-to-water heat exchanger to determine a direct measurement of heat output through measurement of water flow rate and temperature change in a simulated heat load. Four tests are run to determine product performance at the rated maximum output as well as three lower heat output rates spanning the appliance's range. These results are used to determine a weighted average based on typical seasonal heat demands. Since any "jacket loss" from an outdoor unit is not useful heat, only the direct measurement is needed to determine the "delivered heating efficiency." For indoor appliances, it is not clear if EPA will allow jacket loss to be included in the efficiency determination.

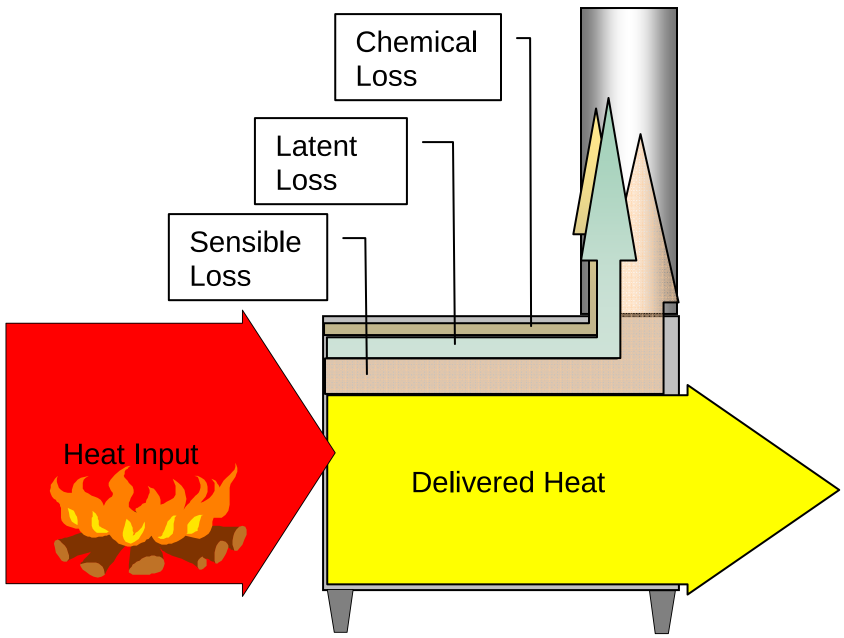
## Indirect Test Methods

Indirect efficiency test methods are based on the principle of conservation of mass and energy (Figure 1). Heat output of the appliance is determined by measuring the heat escaped through the chimney and subtracting it from the heat input. This is a process analogous to basic accounting; if we know how much money is deposited in an account and how much is withdrawn, it is easy to determine the current balance in the account.

## STACK LOSS EFFICIENCY

The indirect efficiency test method for fuel burning appliances is known as the *stack loss method*. This is the primary method used to determine the heating efficiency of gas and oil burning appliances, and is also applicable to wood burning, but considerably more complicated.

Figure 1.




The stack loss method process requires a determination of heat loss by three different mechanisms:

**Sensible heat loss** - amount of heat required to increase the flue gases from room temperature to the stack temperature
**Latent heat loss** - energy required to change the state of water in the flue gas from liquid to vapor
**Chemical heat loss** - the heat energy that was not released in combustion due to incomplete burning of the fuel

Determining these losses in wood burning appliances can significantly complicate the stack loss method, compared to gas or oil fire appliances.

In gas appliances, it is required that combustion be nearly complete as indicated by very low carbon monoxide limits. For oil fired equipment a simple "smoke spot" test is used to verify nearly complete combustion. Therefore we can assume that 100% of the fuel's heating value is released and available for transfer to the heated space. It is then only necessary to measure the flow rate and temperature of the flue gases and calculate the energy lost up the stack. Since the appliance will operate at a "steady state" after a warm-up period, the measurements only need to be made a few times, verifying the flue gas $CO_2$ concentration and temperature are stable.

The steady state efficiency can be accurately determined from these two measurements, or by using a chart or a single calculation.

For wood or bio-mass burning heating appliances, stack loss efficiency tests require determination of the fuel composition in terms of Carbon, Hydrogen and Oxygen percentages, higher heating value, moisture content and the amount of fuel consumed. Flue gases must be analyzed for Carbon Dioxide, Carbon Monoxide, and the temperature of the room air and flue gases must also be measured.

This data allows for calculation of all the variables needed to determine the energy loss up the stack. However, because most wood burning appliances do not operate at a steady state, the measured values are constantly changing, complicating the process. We can never know the true composition of the fuel that's burning at any single point in time. In addition, if the flue gas composition changes rapidly, the relative gas concentration measurements can be inaccurate due to response time differences between analyzers. Therefore, the required measurements must be taken frequently over the course of a burning cycle, and integrated to arrive at an accurate result.

The difficulty with wood burning appliance efficiency testing boils down to how accurately we can determine the completeness of combustion. Assuming that as much as 20 to 30% of the available energy in fuel can be lost due to poor combustion efficiency, it is very important to determine the combustion completeness.

Heat transfer efficiency determination is subject to less uncertainty as it depends primarily on the amount and temperature of gases flowing up the chimney, which can be very accurately determined. As appliance technology improves, so does combustion efficiency. Most units that meet EPA emissions regulations must operate at 95% combustion efficiency or higher. Fortunately, the difficulties determining stack loss efficiencies due to incomplete combustion become less significant as combustion efficiency approaches 100%. Essentially, the stack loss efficiencies determined for very clean burning appliances are quite a bit more accurate than those determined for old technology "dirty" appliances.

In pellet burning appliances, the stack loss method works more like it does with gas or oil appliances, due to the fact that the fuel is fed at a constant rate for a given heat output setting, and the appliance reaches an effective steady state where the fuel composition and flue gas concentrations and temperature are stable. Because these appliances can be finely tuned to balance fuel and air supply, many are capable of combustion efficiencies that approach 100%. The efficiency determination accuracy is dependent upon the determination of sensible and latent heat loss, which is straight forward and subject to minimal uncertainties.

It should be noted that the EPA Default Efficiency for Pellet-Burning appliances is 78%. This was based on data available at the time of the NSPS publication, issued February 26, 1988, which indicated about 80% of the products then available where at or above this level. But this data was not produced under the test method that EPA will likely reference in the new NSPS.

The EPA regulatory requirements led many pellet appliance designers to intentionally provide a lot of excess air at low burn rate settings. This allowed the appliance to be exempt from the EPA NSPS due to high air to fuel ratios, but it also lowers the appliance efficiency. The new NSPS will likely eliminate this exemption and therefore require pellet-burning appliances to be both clean and efficient.

## Current Test Methods

CSA B415.1-2010 provides a suitable basis for certification of appliance efficiency for many types of solid fuel burning appliances. This Standard provides a detailed test method for conducting stack loss efficiency tests on wood burning stoves in section 13. This procedure has recently been substantially revised to reflect improvement to the process based on experience gained over the last decade. The revised stack loss method is much less sensitive to minor uncertainties in flue gas composition measurements and fuel composition data that the previous version. It has been applied successfully to furnaces, boilers, pellet-burners and wood stoves.

- ASTM E2618 provides a consensus test method for evaluating the emissions and efficiency of hydronic heaters. It is virtually equivalent to EPA Method 28 WHH, currently used in the EPA Voluntary Partnership program. One notable exception is the Standard requires the use of actual cordwood fuel, instead of the EPA-required 4 x 4 cribs.

- ASTM E2779 has been developed for emissions testing of pellet-burning appliances and E2780 for cordwood appliances. Both Standards reference CSA B415.1-2010 for efficiency determination.

Since there are many deficiencies in the current EPA Method 28, it is expected that EPA will reference the voluntary consensus standards as the basis for testing under the revised NSPS. There is currently no recognized test method for determining efficiency of masonry heaters. However, it appears likely that EPA will base their acceptance on application of the B415.1-2010 stack loss method.

When discussing energy efficiency for wood burning appliances, manufacturers often overlook one issue: *What is the practical maximum?* When the heat input is based on Higher Heating Value, achieving a theoretical 100% efficiency would require complete combustion and recovering the latent heat, as well as the sensible heat. This would happen if the heat extracted was sufficient to return the flue gas temperature to the ambient room temperature. It also means that the water in the flue gases would be condensed back to a liquid state.
Burning one pound of wood with 20% moisture content will produce 0.7 pounds of water. It is not desirable to transfer heat to a degree that water begins to condense in the appliance or

chimney because it tends to cause corrosion problems and requires a system to collect and drain the liquid water. It is generally recognized that an overall efficiency of about 80 - 82% is an upper limit for wood burning appliances. It takes about 18 to 20% of the fuel's HHV to keep water from condensing – about half of that is the latent heat of the water and the other half is sensible energy required to keep the flue gases above the dew point.

However, these levels are rarely achieved in practice. Higher flue gas temperatures are usually necessary to provide sufficient natural draft to maintain a clean burn and prevent smoke spillage. Indirect heating equipment such as room heaters, burning at higher rates increases the flue gas temperature and reduces heat transfer rate and overall efficiency.

Efficiencies of around 80% are routinely achieved in industrial scale wood fuel combustion where conditions are relatively constant and tightly controlled, but efficiencies above about 75% are very rare in residential wood combustion appliances.

## Higher and Lower Heating Values

There has been some controversy regarding the fuel heating value to be used as the basis for determining efficiency. In North America all fuel burning heating equipment has been rated for efficiency based of the fuel's Higher Heating Value (HHV). In Europe, wood burning appliances have been rated for efficiency based on the fuel's Lower Heating Value (LHV). Lower Heating Values essentially disregard latent heat loss as "unrecoverable" energy. Therefore, LHV-based efficiency is a measure of the percentage of energy that can be recovered without condensing water that comes from combustion of hydrogen in the fuel and from the fuel moisture content. The net effect is that LHV-based efficiencies are about 8 to10% higher than HHV-based efficiencies. For example, if the HHV efficiency of an appliance is 70%, then the LHV-based efficiency will be about 75 to 77%.

There are two significant reasons to rate wood burning appliance efficiency on the HHV basis:

1. Other fuel burning heating equipment is required by the US DOE to be rated and meet minimum efficiency requirements based of HHV. Rating wood burning appliances based on LHV would distort performance comparisons across fuel types.

2. The premise that latent heat is unrecoverable is false. There is no technical roadblock that makes designing a "condensing" wood burning appliance impossible. Many modern gas and oil fired furnaces, boilers and water heaters incorporate condensing technology. HHV efficiencies for these appliances can be in the upper 90 % range. It would certainly be possible to design wood fired appliances to operate in a condensing mode, meaning that there is a potential for LHV efficiencies to be more than 100% – which implies violation of thermodynamic laws.

## Conclusion

It is clear that the EPA's pending New Source Performance Standard will have a substantial impact on the solid fuel appliance industry. Emissions limits will be stricter and appliance heating efficiency will have to meet minimum requirements. Since the timeline involved with proposal, publication and implementation of the new rules is about the same as required to develop new designs, **it is not too early to start the process.**

Many of the EPA's proposed requirements may be beyond what can actually be identified as Best Demonstrated Technology, but it will be very difficult to convince EPA that this is the case without a significant and credible database.

Companies who plan on being in the solid fuel heating appliance business for the long term should consider the importance of obtaining reliable test data on their products *now*.

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