AN INVESTIGATION INTO QUANTIFYING THE CONTRIBUTION OF WOOD STOVES TO SPACE HEATING ENERGY USE

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ABSTRACT

Wood stoves have become a relatively prevalent source of space-heating energy in residences in the Pacific Northwest. The impact of wood stoves on conservation savings is potentially very large. However, to date the ability to monitor the contribution of wood stoves toward space-heating needs of a particular residence has been limited to measurements of the amount of wood burned, guesstimates of the relative efficiency of various wood stove makes, and guesses as to the relative BTU content of various types of wood. This method has left much to be desired. Within the Hood River Conservation Project (HRCP), identifying the contribution of wood stoves both before and after insulation retrofit became very important once the high incidence of wood stoves was fully known. Constrained by limited data channels with which to collect information on the performance on the building and heating equipment, BPA contracted with Lawrence Berkeley Laboratories and Shelton Energy Research to attempt to identify a means of tracking the BTU contribution of the wood stove to space heating using only one data channel. This paper will describe the need for this research, the means by which the research was conducted, and finally the results.

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INTRODUCTION

The Hood River Conservation Project (HRCP) is an aggressive test of the potential to acquire conservation within a confined geographic area over a very short period of time. The conservation potential is measured by the number of homes which participate and thus receive installed weatherization measures and the amount of the electricity actually saved by virtue of conservation measures. These savings can be strongly affected by changes in usage of wood stove for supplement heating.

A major problem associated with monitoring the overall energy performance of single-family residences is to determine the energy contribution of wood-burning appliances. Because the heat content of wood is variable and the efficiency of a stove changes with operating conditions, the energy contribution cannot be accurately determined by monitoring the amount of wood burned.

There are at least two relevant scenarios in which usage of wood for space heating can impact the calculations of electricity savings due to conservation. The first scenario is based upon heavy usage of wood as a substitute for electric space heating before weatherization, followed by almost exclusive reliance on electricity for space heating after conservation measures have been installed. In this scenario the pretreatment electricity use is unexpectedly small due to the heavy reliance upon wood for space heating. If wood usage is constant, one might expect to see a further decline in electricity usage following weatherization due to the conservation measures. Instead one observes an increase in electricity usage due to the change of the fuel mix. The second scenario is one in which a wood is used moderately as supplemental fuel for space heating before weatherization and is used as the primary fuel after weatherization. In this case the electricity savings measured as a result of the weatherization appear larger than expected.

In either case the homes have the potential for using much larger amounts of electricity were the wood stoves not used. That potential can result in misleading information to the planning process of the utility. The possible rapid shift away from wood or toward wood as the primary or supplemental space heating fuel can dramatically change loads of an electric utility. For this reason BPA chooses to ignore the actual use of wood heat in its savings calculations. BPA thus proceeds to weatherize a house using wood heat as if it were totally electrically heated. This reduces the potential for wide swings in electricity usage due to changes in choice of fuel by the consumer. Despite this policy, it is important to understand the interplay between these two fuels. This is especially desirable in research such as is contemplated in the HRCP.

The research in Hood River includes determining the impact of conservation on transmission and distribution requirements, individual customer load characteristics and actual versus estimated savings from conventional heat loss methodologies. Without data on the contribution of wood stoves toward space heating requirements, calculation of the total impact of the conservation measures would be nearly impossible given the two potential scenarios noted above. Within these circumstances, electricity conserved via weatherization may be more properly considered capacity savings since the opportunity to rely solely upon wood for space heating could result in virtually no immediate electricity savings. This lack of measured savings could be improperly construed as no savings. However, the potential to use electricity as the fuel of choice at any point in the future does exist. The unweatherized home, in choosing to shift away from wood and toward electricity as the space heating fuel, would use a significantly larger amount of electricity than the weatherized home making the same shift. Thus, while the immediate savings of electricity are not available in weatherizing wood-heated homes, the savings are nevertheless available should the home select electricity as the fuel of choice at any point in the future. This difference is essentially the difference between energy and capacity in utility terminology.

Wood heating is very heavily used for space heating in the Hood River Valley. In a series of interviews conducted in February and March 1982 (GMA 1982), 33 percent of the sample of 150 residents reported using wood stoves or wood furnaces as their primary heat source. In contrast, 26, 24, and 5 percent, respectively, reported electric baseboard heaters, electric forced air, or electric heat pumps as their primary heat source. In addition, 14 percent of the sample of 150 residents reported using wood stoves or wood furnaces as their secondary heat source while 20 and

12 percent respectively reported using electric baseboard heaters and electric forced air. Other sources of electric heat, including portable heaters and ceiling cable heat, totaled to an additional 10 percent as secondary heat sources. Of the very small number of people who had changed their primary heat source, the vast majority changed to wood stoves or furnaces. This prevalence of wood heat poses special problems for a project which hopes to document savings available from higher levels of conservation measures than are normally offered in BPA's regionwide conservation programs.

Many attempts have been made to monitor the overall energy performance of energy-efficient homes, retrofitted homes, and large statistical samples of single-family residences. Even when the manufacturers efficiency rating is available, the heat output of a stove can not be accurately determined by monitoring the amount of wood burned. The heat content of the wood varies within a large range and the efficiency of a stove varies with different operating conditions.

The goal of this research was to find a single-channel sensor that provides an output which can be correlated with the heat output of a wood stove. Such a sensor could then be used to monitor the heat output of stoves in the Hood River Conservation Project. To accomplish this, five wood stoves typical of those found in the Hood River Valley were tested.* Each stove was monitored simultaneously with thermocouples and radiometers while being operated in a calorimeter room. The sensor readings were then compared with the heat output measured by the calorimeter room, using several physical models to describe the heat transfer from the stove. The stoves are of different sizes and shapes and are of the radiant type, except for one fitted with a convective blower.

EXPERIMENTAL DESIGN

The experimental procedure was to correlate the output of various sensors to the heat output of a stove as measured in a calorimeter room. To test different monitoring strategies, each stove was fitted with five surface-mounted temperature sensors (thermocouples), and was monitored by radiometers in three locations. The measured heat input to the calorimeter room serves as the basis of comparison for all of the monitoring strategies.

* The stoves were selected by contacting the major wood stove distributors and retailers in Hood River to determine which stoves were the most popular.

The heat generated by a stove is removed from the 2.4 by 3.6 m (8 ft by 12 ft) calorimeter room by circulating air at a temperature slightly below that of the room surrounding the calorimeter. The high air flow maintains the calorimeter room at a relatively constant temperature close to that of the surrounding room. The air is blown vertically between two metal meshes along all four walls of the room. Blowing the air along the walls allows the heat output of the stove to be removed without changing the convective heat transfer at the stove surface. The mesh isolates the walls from direct radiation from the stove and augments the convective heat transfer with the cooling air. This reduces the required wall insulation and improves the room's time response to changes in wood-stove heat output. The result is a room with a short response time, which enables one to track changes in wood-stove heat output (i.e. the instantaneous output of the stove).

Two types of sensors were chosen as possible candidates for a single-channel wood stove monitor: surface temperature sensors and infrared radiometers. By measuring surface temperature one can expect to determine the heat output,knowing that heat is transferred from the stove by radiation and natural convection. The radiometers measure a representative sample of the radiative flux leaving the stove and thus should correlate with the heat output.

For the temperature sensors, five locations on the surface of the stove were chosen: the top, the two sides, the front, and the back of the stove. The temperature at each location was monitored continuously during all tests. By using multiple locations, one can look for differences in correlation and possibly find an optimal location. In addition, tests were performed to map the variations in temperature on a given face of the stove. These tests determine the sensitivity of the results to the exact placement of the sensor.

All tests were performed with three radiometers in place, one pointed toward a front corner of the stove, the others pointed toward a rear corner from different distances. Data from the three locations was used to determine an optimal location and the variation between locations. The sensitivity of the radiometer reading to angular or radial displacement was also checked by rotating the sensor and changing the distance between sensor and stove.

For each stove, at least two tests were performed including one when the stove was operating at high output and one at low output. By examining both high power and low power operation, one can look for a systematic change in sensor/output correlation with power. For some stoves, additional tests were performed to help measure the fluctuation between tests. All tests were between 11 and 22 hours long, including start-up, a period of reasonably steady burning, and the tail of the dying fire and cooling stove.

DATA INTERPRETATION AND RESULTS

This study sought to provide a means of determining the total heat gain from a wood stove by monitoring a single sensor. The primary interest is in long-term (weekly or monthly) energy balances, rather than tracking the instantaneous heat output of a stove. The simplest way to obtain such a result is to find a relationship between the average heat output of the stove and the average reading of the sensor in question. The results presented in this report are based on the simplest relationship between the two variables--a single multiplicative constant determined from the ratio of the average heat flux to the average sensor reading. Mathematically, this correlation is referred to as a single-parameter fit, because the relationship between the two variables is saved in a single constant (parameter).

Having determined the correlation parameter for a particular stove, one can estimate the accuracy of this relationship as used for field measurements. There are many techniques for quantifying the accuracy of a correlation, such as the summation of residuals squared, or R^2, or the standard error of each parameter. The standard deviation of parameter values determined in separate laboratory tests was chosen. This measure of accuracy is consistent with the goal to predict the overall energy gain from a wood stove. The percentage fluctuations in the parameter for laboratory tests is a measure of the percentage error in overall energy gain to be expected in the field. The secondary measure of accuracy is the standard deviation of instantaneous heat output predictions when compared with measured heat outputs. This is a measure of how well the model (correlation) tracks changes in heat output. Although this comparison is most important for short-term energy balances, it also provides a measure of how well the single-parameter correlation describes the heat transfer from the stove.

When making a single-parameter fit of measured heat output to sensor measurements, one can use an equation:

$$Q = \alpha \quad X \qquad (1)$$

where
- Q is the dependent variable (e.g. the measured heat output),
- X is the independent variable (e.g. the sensor reading), and
- α is the correlation parameter.

The value of the correlation parameter α is determined by dividing the sum of heat output measurements by the sum of corresponding sensor readings.

The independent variable (X) in Equation 1, can have many different functional forms. That is to say, it need not be the exact sensor reading, but rather can be some function of the sensor reading. This is especially evident for surface temperature measurements. If one assumes that the rate of heat input to the calorimeter room is proportional to the radiation of heat from the stove, X will have the form $T^4 - T_a^4$, where T is the measured surface temperature and T_a is the interior temperature of the calorimeter room. If one assumes the the heat is input to the room by natural convection, X will have the form $(T - T_a)^{1.25}$. One could also assume that the heat loss is directly proportional to the temperature difference, in which case X is $T - T_a$.

For the five stoves tested, the correlation parameter α in Equation 1 was determined for the three radiometers and for the stovetop temperature sensor. The temperature sensor correlation was determined using radiative, natural convection and linear heat transfer models.

TABLE I presents the complete set of correlation parameters determined for the three radiometers. The first and third radiometers (LL1 and LL3) are directed toward the left rear corner of the stove from 183 cm (72 in.) above the ground. They are both 36 cm (14 in.) behind the rear of the stove, the first being 61 cm (24 in.) to the left, and the third 122 cm (98 in.) to the left. The second radiometer (LL2) is on the diagonal from the front left corner, 71 cm (28 in.) to the left, 71 cm (28 in.) in front of the stove, and 71 cm (28 in.) higher than the top of the stove.

A quick review of TABLE I shows that for each radiometer location, the correlations are quite consistent for separate tests of each stove. Also noted was the correlation for each radiometer location does not differ significantly between stoves. The exception to both these observations is the stove equipped with a convective blower. Its correlation parameters vary significantly between tests and differ considerably from those of the other stoves. The behavior of the stove can be understood to result from the forced convection blower it uses to remove heat from the stove. Because the heat is removed by convection, the radiative heat transfer being measured by the radiometer represents a much smaller fraction of the total heat transfer.

Excluding the convective stove (V), the average and standard deviations of the correlation parameter for the three radiometers are 89.0 +- 10.0 for LL1, 38.7 +- 6.7 for LL2, and 77.3 +- 8.5 for LL3. The standard deviation is thus between 11 and 17 percent of the average value, indicating that a single-correlation parameter can provide reasonable predictions of heat output. If one uses an individual correlation for each stove, the standard deviations of the correlation parameters drop to between 2 and 16 percent for LL1, between 1 and 21 percent for LL2, and between 2 and 16 percent for LL3; the accuracy improves.* These standard deviations indicate the errors to be expected in heat output measurements in the field.

A closer examination of TABLE I shows that the correlation parameters for radiometers LL1 and LL3 increase with decreasing heat output, and that the correlation parameters for LL2 decrease with decreasing heat output. The results for LL1 and LL3 are as was expected, because at lower heat outputs a smaller fraction of the heat leaves the stove by radiation. Because the radiometer measures only the radiant portion of the heat leaving the stove, its correlation parameter must increase as the fraction of convective heat input to the calorimeter room increases. Explaining the behavior of LL2 is less straightforward. One possible explanation is that more of the heat leaves the stove from the front because of changes in burn pattern at lower heat outputs.

* If one excludes stove III, the standard deviations of the individual stove correlations are all lower than those of the average correlations: 2-11% for LL1, 1-13% for LL2, and 2-12% for LL3.

TABLE I

Correlation Parameters for Radiometers

Stove/Test	Test Length [hr]	Average Heat Output [W]	Correlation Parameter [m^2] LL1	LL2	LL3
I					
1	13.33	6170	78.5	44.9	79.4
2	20.00	2160	90.8	37.3	82.8
II					
1	18.33	1250	70.8	35.6	74.3
2	20.00	1020	84.7	30.4	80.0
3	20.00	1250	82.4	37.1	73.7
4	20.00	1240	68.6	33.2	71.7
III					
1	22.00	2390	80.8	42.3	59.7
2	19.00	740	101.5	31.3	75.1
IV					
1	12.00	5330	n/a	n/a	n/a
2	12.00	5070	n/a	n/a	n/a
3	11.00	3310	n/a	n/a	n/a
4	19.83	1650	89.9	48.3	86.9
5	20.00	2030	92.4	47.6	89.3
V					
1	11.00	4830	100.3	84.1	104.8
2	11.00	2620	109.2	84.1	113.9
3	19.33	1500	154.6	51.6	134.8
4	16.67	2260	105.8	53.8	108.2

TABLE II presents the heat output correlations for the temperature probe (thermocouple) on top of each stove. Three correlations with heat output were made for each sensor. The first correlation uses $T^4 - T_{room}^4$, where T is the measured stovetop temperature and T_{room} is the average temperature of the calorimeter room. This correlation attempts to scale the total heat output of the stove to the radiative heat output of the stovetop. The second correlation scales the total heat output to the heat output by natural convection $(T - T_{room})^{1.25}$. The third correlation scales the heat output directly to the measured surface temperature. Although this last correlation could be interpreted as corresponding to heat transfer by forced convection, it is simply an empirical correlation because the actual heat transfer by forced convection is insignificant.

Several observations can be made from the results presented in TABLE II. The first is that the radiative correlation parameters are the most consistent within each stove's set of tests. Both the natural convection and linear correlation parameters change considerably with average heat output.* The radiative parameters do not change between tests at low output and high output, indicating that the radiative heat transfer model may be a better approximation of total heat transfer. Also observed was the variation in correlation parameters between stoves is much larger for all the temperature sensor correlations than for the radiometers (see TABLE I). This is to be expected because the radiometer correlations should be less affected by stove surface area.

To review the presentation of the test results, the summations of residuals obtained by comparing instantaneous correlation predictions with the measured heat outputs were examined. By examining these summations, we sought a measure of how well the correlations can track the fluctuations in heat output that occur during normal stove operation and found that the residuals were essentially the same for radiometer and temperature-sensor correlations.

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* Except for stove IV, for which the convective and linear correlations are at least as consistent as the radiative correlations.

TABLE II

Correlation Parameters for Stovetop Temperature Probe

Stove/Test	Test Length [hr]	Average Heat Output [W]	Correlation Parameter $\Delta(T^4)$ [W]	Correlation Parameter $(\Delta T)^{1.25}$ [$W/K^{1.25}$]	Correlation Parameter ΔT [W/K]
I					
1	13.33	6170	1040	10.5	39.5
2	20.00	2160	1210	8.71	28.0
II					
1	18.33	1250	748	6.85	23.5
2	20.00	1020	776	5.17	15.5
3	20.00	1250	815	7.46	25.8
4	20.00	1240	833	7.99	28.4
III					
1	22.00	2390	499	5.90	23.3
2	19.00	740	518	3.58	11.3
IV					
1	12.00	5330	1150	9.63	34.7
2	12.00	5070	1110	8.97	32.1
3	11.00	3310	1400	9.67	31.3
4	19.83	1650	1110	8.44	27.5
5	20.00	2030	1070	8.30	27.7
V					
1	11.00	4830	n/a	n/a	n/a
2	11.00	2620	1640	11.0	33.5
3	19.33	1500	1160	7.68	23.2
4	16.67	2260	1290	11.0	37.9

CONCLUSIONS

The first and most important conclusion from this study is that a single-channel wood stove monitor is both possible and practical. Based on the limited tests of five stoves, it appears that a single-parameter correlation can predict full-cycle (start-up to cool-down) heat output to within 20 percent of the actual output. It was also seen that these accuracies can be much higher when using an individual correlation from multiple tests on a single stove.

Although the stated goal of this project was achieved (i.e., to provide a single-channel wood stove monitor for long-term energy balances), the experimental data have not been fully exploited. It appears that further analysis can provide more accurate, more general wood stove correlations. During the present analysis, some very promising analysis schemes were discovered. One scheme is to incorporate some of the physical characteristics of a stove (surface area, type of surface) into a single independent variable (X in Equation 1) that includes both convective and radiative heat transfer. This technique incorporates into one variable the changes in heat transfer mode (radiative vs. convective) that occur with changing heat output. It should thus be able to provide better tracking and consistent parameters within a single correlation. Another advantage is that by incorporating some easily determined characteristics of a stove into the correlation, the measured correlations can be more easily extrapolated to stoves that have not been tested. The validity of both this new correlation and the present correlations could be confirmed by further analysis and field tests of one or two of the stoves tested in the calorimeter room.

For the analysis so far, it must be concluded that both radiometers and surface temperature sensors are suitable as single-channel wood stove monitors. The above analysis shows that they both provide adequate accuracy and repeatability. Therefore, the recommendation to the Hood River Conservation Project must be based on other criteria. Temperature sensors are considerably less expensive, but they require considerable labor for packaging and mounting on the stove. Radiometers can be purchased commercially, and the mounting system for the radiometers requires considerably less assembly labor. Radiometers have been recommended for this project based on two considerations: (1) if one decides to use a single correlation for all stoves, tested and untested, the radiometer correlations show less variation between stoves; and (2) the long-term stability of mounting the surface temperature probe (magnetic mounts, glue, and straps) is less certain than the mounting of the radiometers. Finally, recommended was the LL3 radiometer location (and correlation) over the other two radiometer locations. The LL3 correlation has a lower percentage variation between stoves and tests than either LL1 or LL2. Although the LL2 correlation seems to track the heat output better, we are more interested in long-term heat output for this application. In addition, the location of LL2, in front of the stove, may be impractical in many situations.

EQUIPMENT

The radiometers selected for use on the project provide a 0.10 volt signal and require 0.05 pt. sensitivity. These radiometers are mounted on a pole lamp and the output is fed through an integrator. The integrator signal is fed through a pulse transponder and then through the house wiring for recording (Oliver, Peters, Peach, and Engels, 1984).

The wood heat sensors have been installed on a total sample of 100 homes. As each installation was completed, the stove was fired up to test the monitoring system. This sample has been selected within the random sample of 320 submetered homes scattered throughout the community. Of these 100 wood stove monitoring setups, 50 are on the monitored feeder (Oliver, Peters, Peach, and Engels, 1984).

The experience to date with the installation and operation of this equipment has been positive. The radiometer should give the BTU output of the wood stoves within 20 percent of the actual value. In addition, the other data points, including an indoor temperature space heating electric usage and outdoor weather conditions, will help to calculate the relative fuel choice between electricity and wood for the duration of the project.

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