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EVALUATIONS OF A "SUPER TUNE-UP" PILOT PROGRAM FOR FORCED AIR FURNACES IN SMALL COMMERCIAL BUILDINGS

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Introduction

Background

A utility in southern Wisconsin contracted with Building Resources Management Corporation (BRMC) to conduct a furnace efficiency improvement pilot program for light commercial businesses. The pilot program incorporated a package of designated permanent improvements for existing forced-air furnaces (rooftops and upflows) and associated duct work. The program sought to reduce gas use by improving the overall operational efficiency of both the furnace and the delivery system. Improvement was measured by increases in steady state and cycle efficiency, and by increases in the amount of heat delivered to occupied space relative to the amount of gas burned.

Program technicians, trained in a special set of furnace improvement procedures, visited interested businesses. On site, the technicians followed a step-by-step procedure (designated in form R) to diagnose each furnace and make appropriate improvements. Technicians documented each step, measuring and recording critical parameters before and after working on the furnace by completing forms associated with form R.

To assess likely savings, monitor the quality of the work, and continuously improve the program, the forms technicians completed in the field were reviewed by a supervisor. The supervisor provided feedback to the technician on each furnace, and independently inspected a percentage of the furnaces completed by the technician.

To evaluate the accuracy of energy savings estimates, BRMC implemented a monitoring program. The program recorded data from 13 furnaces with a data acquisition system (DAS) before and after the technicians made improvements. BRMC used the DAS information to create a profile describing how the furnace operates. The DAS information and profile enabled reviewers to closely assess the savings generated by different measures.

Objectives

The monitoring program aimed to evaluate the effectiveness of the furnace program by closely studying the effects of specific furnace improvements. It asked these questions:

- What is the efficiency of the furnace for different cycle lengths?
- What are the efficiency effects attributable to different furnace improvements for the furnaces studied?

Besides answering these contemplated questions, the pilot program revealed significant unanticipated information about the condition of gas forced-air equipment in this market segment.

Methodology

Site Selection

Preferred monitoring sites exhibited these characteristics:

- A stand-alone building (*i.e.*, not part of a strip mall)
- Two rooftop furnaces

- No other source of auxiliary heat.

BRMC telephoned potential monitoring program participants. After informing the owner about the pilot program, BRMC asked the owner about the type of heating system and the number of heating units. If the location met the above criteria and the owner agreed to participate in the monitoring program, BRMC offered the owner pilot program services at no cost.

Equipment Characteristics

Widespread and extreme maintenance problems characterize heating equipment in this market segment. These maintenance problems often pose potentially serious dangers to building occupants. Their presence greatly complicated the pilot program. It appears that safety and maintenance problems commonly arise because equipment is not properly or regularly serviced. Neither the business operator nor the building owner exhibited much interest in maintaining equipment.

Significant disincentives undermine their potential commitment to operating equipment safely and efficiently. Small business operators generally rent the space from which they operate. Heating-cooling equipment often is included with the lease. Utility costs generally are paid by the business operator, but the operator has no ownership interest in the equipment.

This means that, for the *business operator*, who is simply renting a space from which to conduct business, an investment in the efficiency of the heating equipment is an investment in a piece of equipment that *belongs to someone else*. Similarly, for the *building owner* who rents the space to the business operator, a heating system efficiency investment is an investment *to reduce operating costs that are already paid by someone else, i.e.*, the tenant business operator. Neither party has much incentive to maintain equipment. It appears that both parties often ignore heating-cooling equipment until it completely fails.

As you would expect, failure to regularly or properly maintain equipment may lead to safety and efficiency problems. Table 1 describes safety problems that plagued the pilot program. More than 14% of the furnaces encountered had to be "red tagged" because of situations the sponsoring utility deemed to be immediately hazardous.

Sometimes multiply safety problems occurred in the same furnace. Of special concern is the presence of carbon monoxide (CO), which is potentially deadly. The field data show that it is generated surprisingly often by gas-burning appliances in small commercial buildings.

Table 1. Percent Occurrence of Furnace Safety

Safety Item	Percent of Occurrence
Gas leaks	6.4%
Carbon monoxide	14.0
Roll-out	3.8
Flue gas spillage	1.0
Cracked heat exchanger	11.5
High limit failure	2.5

Data Collection

Researchers equipped each monitoring site with a data acquisition system (DAS), installing thermocouples in the furnace supply, return, and flue to record operating temperatures. To record measured operation times, researchers wired relays in parallel with gas valves and blower motors. The DAS recorded and stored data.

With the DAS in place, researchers ran furnace cycle tests before and after making furnace efficiency improvements. A cycle test involves recording the furnace characteristics every 15 seconds for specific "gas on" cycles of 5, 10, and 20 minutes. The information recorded and computed is:

- gas on time
- gas off time
- fan on time
- fan off time
- supply temperature
- return temperature
- flue temperature
- heat rise
- cumulative input
- cumulative output
- cumulative efficiency

The data acquired as a result of these tests provide a blueprint of furnace characteristics, showing how the furnace performs cycle after cycle. This paper reviews the cycle test data for each site, and makes program recommendations based on that data.

Data Analysis

Calculation of cumulative efficiency. The furnace input for each 15-second segment is calculated by the formula:

When the gas is on:

$$Input = \frac{elapsed\ time\ (sec) \cdot Input\ (Btu/hr)}{3600\ sec/hour}$$

When the gas is off:

$$Input = 0$$

The furnace output for each 15-second segment is calculated by the formula:

When the blower is on:

$$Output = Input \cdot S.S\ eff. \cdot \frac{HR_{avg}}{S.S\ HR}$$

When the blower is off:

$$Output = 0$$

Where:

HR_{avg} = the average temperature rise between the delivery and return for the previous 15 seconds;

S.S.Eff. = combustion efficiency at 20 minutes of continuous operation; and

S.S.HR = the temperature rise between the delivery and return temperatures at 20 minutes of continuous operation

The cumulative efficiency at any time in the cycle is calculated by the formula:

$$Cumulative\ Efficiency\ at\ time\ t_n = \frac{\sum_{0}^{n} Output}{\sum_{0}^{n} Input}$$

which is the sum of all the 15-second outputs from the time the gas comes on until the time t_n divided by the sum of all the inputs until time t_n. The cumulative efficiency for one site at any point in the cycle is shown in Figure 1. Lower fan-off temperatures create higher efficiency.

Calculating savings. We calculated savings based on cumulative efficiency, before and after the improvements were completed. The formula below describes this calculation.

$$Savings = \frac{Cumulative\ eff.\ after - Cumulative\ eff.\ before}{Cumulative\ eff.\ after}$$

Field Data Results Summary

Data from 13 furnaces were reviewed and evaluated. From these data, conclusions can be drawn as to which measures effectively improved furnace efficiency and which did not. Closely monitored data also provide a real-world basis for refining energy savings estimates for field activities. Observations made in the field point to additional opportunities to generate energy savings in the light commercial market.

Energy Savings Measures

Adjusting Fan-off Temperature. The energy savings value of lowering the fan-off temperature for residential upflow furnaces has already been extensively documented by Proctor (Refs. 3 and 4). This project's field data confirm that similar savings are available from fan-off adjustments to intermittent-fan furnaces in commercial settings.

Fan-off temperature adjustments create energy savings by scavenging usable heat left in the heat exchanger at the end of the furnace cycle. Once the fan is turned off, remaining usable heat from the heat exchanger is lost up the flue. Running the fan longer reduces this loss. The target fan-off temperature for this project was set at 80°F.

Notably, this relatively low fan-off temperature did not produce any comfort complaints from the owners or their clients. We believe that complaints did not materialize because registers usually were located in drop ceiling panels. This delivery configuration prevents relatively cool air from the register from blowing directly and immediately on people. Most commercial air delivery systems are similarly organized.

In residential settings, the target fan-off temperature for furnace programs similar to this pilot project is 90°F. During the pilot, BRMC used a target fan-off temperature of 90°F for buildings with residential type delivery ducts located in the walls. Technicians lowered fan-off temperature two ways. For furnaces with temperature-controlled fan switches, they adjusted the temperature by adjusting the fan switch dial. This dial usually has three

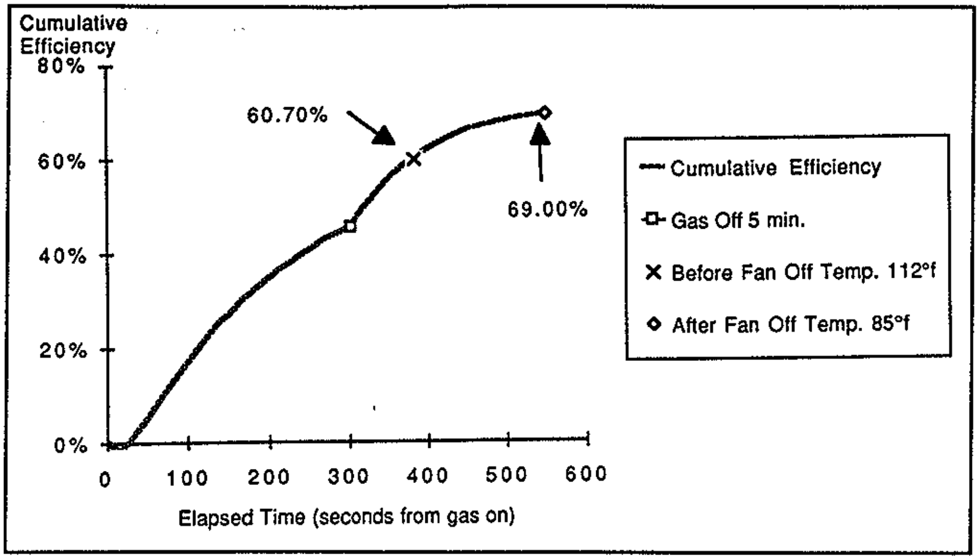

Figure 1. Cumulative Furnace Efficiency: Five-minute Cycle Furnace 3a

tabs that set the high limit, fan-on and fan-off temperatures. Technicians independently monitored actual delivery temperatures to assure that target fan temperatures were actually being achieved. This precaution is necessary because the fan settings on the switches often are inaccurately calibrated.

When temperature controlled fan switches were not available, technicians adjusted fan-off temperatures by adding or changing a time delay relay. They usually added a solid state interval timer. Extending fan run-times at the end of the cycle effectively lowers the fan-off temperature. Rooftop furnaces often control the fan-off temperature by turning the fan-off after a fixed number of seconds following the burn cycle. The interval timer extends the fan run-time in order to drop the supply temperature to the target value of 80°F.

Six of the 13 furnaces monitored used intermittent fans. Of the six, four exhibited target fan-off temperatures above the 80°F target. Technicians adjusted three to the target fan-off temperature. One could not be adjusted due to incompatible voltage between the solid state interval timer and existing furnace timer.

Table 2 describes savings achieved by adjusting fan-off temperatures for the three furnaces for which fan-off adjustments were available. Monitoring data indicate that for every 5°F the fan-off temperature is lowered, the furnace efficiency is improved by about 2%. This relationship is illustrated by the furnace efficiency equation for furnace 5b. The equation is:

$$Efficiency = 0.73 - 1.16 \bullet (\frac{FFT - 72}{GOT})$$

Table 2. Fan-off Savings (Five-minute Cycle)

Furnace number	Fan-off Before	Fan-off After	C.C. Eff. Before[a]	C.C. Eff. After	Percent Savings[b]
3a	112.0F	85.0F	58.1F	69.2F	12.00
5b	92.6F	84.2F	65.0F	68.2F	4.80
7a	100F	82.0F	58.1F	65.3F	10.80

[a] *C.C.Eff.= Cumulative Cycle Efficiency*

[b] $\text{Percent Savings} = \frac{(\text{C.C. Efficiency After}) - (\text{C.C Efficiency Before})}{\text{C.C Efficiency After}}$

Where:

FFT = Fan-off Temperature (°F)

GOT = Gas-on Time (seconds)

This equation relates furnace efficiency to fan-off temperature and gas-cycle length. (A complete discussion of furnace efficiency equations is given in the last section of this paper.) The equation describes the efficiency change due to fan-off temperature adjustments for rooftop and up-flow furnaces.

Costs associated with increasing efficiency by changing fan-off temperatures are very low. The interval timer costs about $18.00. Altering fan-off temperature where an interval timer is not needed has no associated material cost. It is critical, however, that correct procedures be followed to ensure that fan-off temperatures are correctly set and accurately achieved.

Rewire dual-fire gas valve to high-fire only. Technicians rewired five furnaces from a dual-fire (low/high) gas valve to high-fire only operation. Changes in the furnace efficiency for three of these five furnaces could be evaluated.

Manufacturers design furnaces to produce the best combustion efficiency during high-fire operation. During low-fire operation, the gas valve may deliver up to 50% less Btu/hr input. This reduction in gas is not compensated with a corresponding reduction in combustion air. The net result is a combustion mixture with excess air, resulting in poor combustion efficiency.

Dual-stage furnaces encountered in the pilot program operated on low-fire most of the time. Typically, furnaces operated on high-fire only when the thermostat demanded considerable heat, such as at the start of the work day, or when ambient temperature was extremely cold, *i.e.*, near design temperature. The remainder of the time, the furnaces tended to operate on low-fire at the lower steady-state efficiency.

Converting a dual-stage gas valve to high-fire only operation eliminates less efficient low-fire operation. Each furnace cycle then operates at the best possible combustion efficiency. Rewiring to high-fire only operation generates savings by eliminating runs characterized by low combustion efficiency.

Changing a furnace from dual-fire to high-fire only is simple and inexpensive. Wire is the only material required. A wire is jumped from the low-fire valve to the high-fire valve while insuring that none of the safety switches is by-passed. A call for heat, whether it is low or high, will then activate the furnace on high-fire.

The data demonstrate dramatic efficiency improvements from altering furnaces to high-fire only operation. Data are summarized in Table 3. With the exception of furnace 2a, which had a much faster blower installed, the only major change to the furnaces was wiring the gas valve to high-fire only operation.

Pending further study, it appears that a value of 5% would provide a reasonably conservative estimate of the efficiency improvement gained from rewiring dual-stage furnaces to high-fire only. If further investigation bears out the findings from the pilot program, it is likely that an even higher savings estimate is appropriate.

Since rewiring to high-fire only operation produced documented savings ranging from 4 to 18%, it is a very effective part of a furnace program. Many rooftop furnaces have dual-stage gas valves. The change can be made quickly and will last the life of the gas valve.

Other changes. Other furnace work included:

- Replacing filters.
- Cleaning the blower.
- Pulling and cleaning the burners if CO is present.
- Cleaning the evaporator coil.

Work on furnaces 2b, 3b, 4b, and 5a include several of the above items (see Table 4). No other changes were made to these furnaces. Significantly, the monitoring data revealed no change in furnace efficiency for furnaces that received only these typical tune-up type improvements.

Table 3. Savings Due to High Fire Operation

Furnace Number	S.S. Eff. Before[a]	S.S. Eff.After	Percent Eff. Change	Percent Savings
2a	66.7	74.9	8.2	10.9
4a	72.3	74.8	2.5	3.3
6a	62.8	77.0	14.2	18.5

[a]S.S. Eff. = Combustion Efficiency at 20 minutes of continuous operation.

Despite the fact that it does not produce measurable savings, maintenance of a furnace system should include all of these items. Replacing filters and cleaning the blower and evaporator coil help improve and maintain air flow through the furnace. Cleaning the burners when CO is present will eliminate CO in most cases. Furnace-tune ups typically include some or all of these items, depending on the contractor.

Reported Savings and Monitored Savings Compared

Technicians recorded work on each monitored furnace on the same form (Form R) as the pilot program. The furnace efficiency improvements reported during the program were derived from the data on form R. Table 4 compares savings estimates from form R parameters with the actual savings from the monitored data.

With two exceptions, calculated savings from form R closely tracked the actual monitored savings. In the exceptional cases—furnaces 2a and 6a—actual savings outperformed estimates from form R. The high performance of these furnaces is attributable to efficiency gained by switching the furnace to high-fire only operation. As discussed above, this change saved more energy than originally anticipated.

Table 4. Form R Savings vs. Monitor Savings

Furnace Number	Form R Savings(%)[a]	Monitor Savings(%)
1a	4.1	na[b]
1b	3.3	na
2a	4.0	10.9
2b	0.4	0.0
3a	11.7	12.0
3b	0.1	0.0
4a	3.2	4.5
4b	0.2	0.0
5a	0.0	0.0
5b	5.2	4.8
6a	3.7	18.5
6b	3.4	0.0
7a	8.6	10.8

[a] $Savings = \frac{(Efficiency\ Before) - (Efficiency After)}{Efficiency\ After}$

[b] na= not available

The furnace pilot program relies heavily on the furnace form (form R) to direct and document the technical work. Documentation of specific field operations is used to project savings. The results of the comparison charted above demonstrate that, with the exception of underestimating savings attributable to rewiring furnaces to high-fire only, form R accurately quantified real-world savings for each furnace.

Additional Potential Opportunities Identified

The furnace program worked primarily on rooftop furnaces. Many of these furnaces were in restaurants. Two problems encountered repeatedly were failed economizers and unbalanced kitchen exhaust hoods.

Economizers are designed to save energy by replacing return air with outside air when outside air could be used for cooling or when outside air would take less energy to heat. None of the economizers technicians encountered during field was operating properly. The mechanical and electrical controls for economizers had generally failed in such a way as to leave the outside air damper inoperable. Due to these failures, a great portion of the return air often was supplied directly from the outside all year long, regardless of outside temperatures. On cold winter days, economizers waste energy by allowing cold outside air to the heat exchanger, thus requiring more heat to be exchanged to achieve the building's target temperature.

The pilot program experience suggests that the potential energy savings the economizer was designed to produce may not materialize in the small commercial market segment. Instead, additional heating and cooling loads are placed on the building because economizers, like all components of the units, tend to be ignored. A program that could effectively address malfunctioning economizers could result in substantial energy savings.

Correcting unbalanced air flow presents another opportunity for generating substantial energy savings. The restaurants visited through this program were extremely depressurized. This depressurization often can be perceived simply by noticing the in-rush of air as one opens the door to enter the restaurant. Depressurization results from large range exhaust fans that are not balanced properly with make-up air units. Depressurization drives infiltration throughout the structure, thus adding to the building's heating and cooling load. It can also cause backdrafting of combustion gases into the building by drawing air down the flue. A program that would properly balance the kitchen ventilation system could substantially reduce the total building cooling and heating load, as well as increase safety by reducing or eliminating back-drafting of flue gases into the structure.

Program Design Recommendations

The major components of the furnace efficiency program that produce energy savings are:

- lowering fan-off temperature
- converting dual-stage gas valves to high-fire only
- eliminating massive CO
- ductwork sealing

The benefits of the first two were studied and quantified in this report. We were unable to precisely document the efficiency effect of eliminating CO because none of the 13 furnaces in the study group had CO. This is contrary to the trend established in the pilot program which had CO in 14% of the furnaces.

The effect of ductwork sealing cannot be evaluated through the cycle test data. The value of sealing ductwork has been studied by BRMC and others, such as Cummings (Refs. 1 and 2), and Tooley (Ref. 5). Savings averaging 18% have been documented as a result of duct sealing in residential settings. Enough data do not yet exist to be able to quantify the savings attributable to duct sealing in commercial settings. Broken economizers function as massive duct leaks, but the pilot program was not designed to repair them.

The items cited above are an important part of the furnace program. When a heating system needs one or all of these improvements, substantial savings are available. Combining these elements with the conventional tune-up improvements outlined above and instituting an administrative quality control system would create a furnace program capable of generating substantial energy savings.

Furnace Efficiency Equations

The furnace efficiency equation is developed through a linear regression of the 5-, 10-, and 20- minute cycle test data. The equation describes the relationship of furnace efficiency to cycle length and fan-off temperature. Table 5 lists the furnace efficiency equations derived from the data.

The efficiency equation most representative of the study group is 5b. This equation could be used to predict the effects of fan-off temperature changes for various cycle lengths for roof top furnaces.

Table 5. Furnace Efficiency Equations

Furnace Number	Stage	Equation[a]	R^2
2a	before	$Eff = \frac{0.66-2.07 * (FFT-68)}{GOT}$	96.6%
2b	before	$Eff = \frac{0.68-0.94 * (FFT-66)}{GOT}$	96.6%
	after	$Eff = \frac{0.66-2.07 * (FFT-68)}{GOT}$	96.6%
3a	before	$Eff = \frac{0.73-1.21 * (FFT-76)}{GOT}$	97.2%
4a	before	$Eff = \frac{0.70-2.02 * (FFT-64)}{GOT}$	98.8%
	after	$Eff = \frac{0.76-1.09 * (FFT-53)}{GOT}$	99.2%
5a	before	$Eff = \frac{0.75-0.81 * (FFT-17)}{GOT}$	99.3%
	after	$Eff = \frac{0.75-0.85 * (FFT-26)}{GOT}$	99.4%
5b	before	$Eff = \frac{0.73-1.16 * (FFT-72)}{GOT}$	98.6%
	after	$Eff = \frac{0.73-1.16 * (FFT-72)}{GOT}$	98.6%
6b	before	$Eff = \frac{0.76-0.97 * (FFT-46)}{GOT}$	99.9%
	after	$Eff = \frac{0.73-0.73 * (FFT-28)}{GOT}$	99.5%
7a	before	$Eff = \frac{0.66-1.09 * (FFT-64)}{GOT}$	97.2%
	after	$Eff = \frac{0.67-1.19 * (FFT-77)}{GOT}$	99.3%

[a]FFT = Fan -off temperature, GOT = Gas on time
* The equation is for the furnace on low fire.

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