EVALUATION OF FRONT-END BOILER RETROFITS IN TWO MULTIFAMILY BUILDINGS

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ABSTRACT

The performance of front-end boiler systems installed in two identical 12 unit buildings in St. Paul, Minnesota was monitored over the 1986-87 heating season. High efficiency condensing boilers were plumbed in parallel with the primary building heating loops to provide space heat in conjunction with the existing boilers. The heating systems were controlled by outdoor reset and system cutout controls. Domestic hot water for one building was provided by using a 40 gallon storage tank equipped with an internal heat exchange coil plumbed to the front-end boiler.

The system performance for each building was measured using the alternate mode methodology. Heating system performance data were analyzed using the Princeton University PRISM program. Compared to the existing boilers, the front-end boiler systems reduced the amount of gas used for space heating by 14 and 15 percent. Compared to a conventional tank type water heater, the front-end boiler/heat exchanger tank combination reduced the domestic hot water gas consumption by 19 percent. The performance of the front-end boiler system was modeled based on measured short term performance of the existing boilers. This model showed that the system efficiency dropped dramatically when the existing boiler was turned on.

The simple payback for each front-end boiler retrofit was 12 years, based on space heat savings only. With the addition of domestic hot water heating capability, the payback for one building was reduced to ten years. Because of the large fixed cost associated with installing a front-end boiler, shorter payback periods can be expected in larger buildings with greater domestic hot water and space heating loads. A boiler sizing calculation showed that the annual cost of natural gas plus boiler installation remained nearly constant for front-end boilers ranging from 50 to 100 percent the size of the existing boiler.

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INTRODUCTION

Multifamily buildings in the United States use 2.8 quad of energy annually. This is about 13 percent of the total energy used by all buildings and four percent of the total energy used in the United States (DOE, 1985). Performance monitoring of multifamily retrofits across the country show that heating system improvements are one of the most attractive options for reducing heating costs in these buildings (Goldman, 1986). This report presents an examination of the front-end boiler concept as a heating system efficiency improvement in two multifamily buildings located in St. Paul, Minnesota.

A front-end boiler is a high efficiency boiler installed to supplement an existing boiler. It may provide only space heat or space heat plus domestic hot water. A front-end boiler provides all of the space heat required by a building during the fall and spring seasons. During cold weather, when the heating load is larger, the front-end boiler operates continuously as a base-load boiler, and the existing boiler cycles to meet the remaining space heating demand. Because the majority of the annual space heating load in Minnesota occurs during moderate weather (above 30^{o}F), a front-end boiler sized to meet 25 to 50 percent of the maximum demand will meet from 60 to 90 percent of the annual load. See Figure 1.

RESEARCH DESIGN AND IMPLEMENTATION

Front-end boiler systems were installed in two identical 12 unit multiple zone hydronically heated buildings. Both buildings had an annual space heat load of about 500 MBtu. The existing steel fire-tube boilers in each building were designed for gas and equipped with 340,000 Btu/hour input atmospheric burners. The front-end boilers installed were high efficiency condensing "pulse" boilers with rated inputs of 150,000 Btu/hour. Both buildings were plumbed to provide a primary space heating circulation loop that did not pass through either the existing or front-end boiler. Two separate secondary circulation loops were then used to plumb each boiler in parallel with the primary loop. With this geometry, the front-end boiler can heat the building without the need to circulate water through the existing boiler. Such "primary-secondary" plumbing design allows the front-end boiler to heat the building during moderate weather, without the standby losses that occur if the water in the existing boiler is kept hot. In both buildings, the heating systems were controlled by an outdoor reset control that increased the boiler water temperature as the outdoor temperature decreased.

Domestic hot water was provided in each building by conventional 80 gallon tank-type gas water heaters. Water heater input rates were 199,000 and 85,000 Btu/hour for the A and B buildings, respectively. In addition, a 40 gallon insulated tank equipped with an internal heat exchange coil was installed in Building A, so that the use of the pulse boiler to provide domestic hot water could be examined.

Heating and domestic hot water systems were monitored using the alternate mode methodology for a period of nine months. Data acquisition systems in each building measured temperatures and equipment on-times, and printed out daily averages or totals for each parameter every 24 hours. To evaluate domestic hot water system performance, hot water volume was measured in ten gallon increments. Boiler and water heater gas consumptions were calculated using measured gas valve on-times and weekly utility meter readings.

Weather normalized annual savings based on measured gas consumption data were calculated for each building using the Princeton University PRISM program (Fels, 1986). Component and system performance of the front-end boiler design were analyzed based on short term measurements of boiler and water heater loss rates.

MEASURED ANNUAL PERFORMANCE

PRISM Program Analysis

The overall space heating system performance was evaluated using the Princeton Scorekeeping Method (PRISM, PC version 4.0) computer program. Files containing space heating data only and combined space and domestic water heating were prepared for analysis. PRISM analysis yielded R^2 values greater than .97, and standard errors of the NAC of less than four percent for all cases. The meter reading data were also analyzed using the two parameter NTL model (Robinson, 1986), so that the suitability of using PRISM to analyze alternate mode energy consumption data could be evaluated. The NTL model yielded normalized consumptions within one percent of the values obtained using PRISM, confirming the suitability of using PRISM to analyze these data. The NTL method is preferred for submetered space heat data, since it provides a better physical representation of actual energy use when the heating system is turned on by a cutout control. PRISM results are presented here, since this method is more widely recognized.

Measured Space Heating System Performance

PRISM analysis results are summarized in Table I. For the A and B buildings, the front-end boiler system saved 15.2 and 14.3 percent, respectively, of the space heating energy. The estimated savings were 94 and 93 MBtu, or $470 and $465 per year at a natural gas price of $5.00/MBtu.

Table I. Summary of PRISM results.

Bldg	Use	System Mode Off NAC (MBtu)	System Mode Off Std Err (MBtu)	System Mode On NAC (MBtu)	System Mode On Std Err (MBtu)	System Savings (MBtu/yr)	System Savings (Percent)	Standard Error of Savings (percent)
A	Sp Ht	620	23	526	12	94	15.2	4.2
B	Sp Ht	651	21	558	18	93	14.3	4.2

Measured Domestic Hot Water System Performance

The performance of the internal heat exchanger water heater and the two conventional tank type water heaters was analyzed by plotting the input energy as a function of the output energy as shown in Figure 2. In this plot, the y-axis intercept is an estimate of the daily input standby loss for the domestic hot water system, and the inverse of the slope is an estimate of the thermal conversion efficiency of the water heating appliance.

Table II. Domestic hot water thermal conversion and system efficiencies obtained from the regression analysis shown in Figure 2. System efficiencies are based on an average daily domestic hot water output energy of 300,000 Btu/day. Standby loss is input standby loss. Standard errors for each value are shown in parentheses.

Bldg	Water Heater Type	Thermal Conversion Efficiency	Standby Loss (MBtu/day)	System Efficiency	Hot Water Use (gal/person-day)
A	Conventional	.71 (.012)	.087 (.020)	.59 (.025)	24 (3)
	Heat Exchange	.88 (.016)	.073 (.006)	.73 (.016)	25 (2)
B	Conventional	.70 (.009)	.096 (.020)	.57 (.022)	31 (4)

The thermal conversion efficiency, system efficiency, and input standby loss for each water heating system are shown in Table II. The two conventional tank type water heaters had thermal conversion efficiencies of 71 and 70 percent, and system efficiencies of 59 and 57 percent, respectively. The system efficiencies are in good agreement with other measurements (Perlman, 1988). The heat exchange water heater is a 40 gallon storage tank with an internal copper heat exchanger plumbed to the front-end boiler as a source of heat. The thermal conversion efficiency of this tank/boiler system was 88 percent, with a system efficiency of 73 percent.

Based on a one-time measurement of storage tank jacket temperatures, we suspect that the large standby loss for the heat exchange tank was due to failed tank insulation. We estimate that without this failure the system efficiency for the heat exchange system would have been 79 rather than 73 percent. The measured hot water system performance for Building A is summarized in Table III. Compared to the conventional tank, the front-end boiler heat exchange tank combination produced an annual energy savings of 19.4 percent.

Table III. Summary of domestic hot water system annual performance based on data from Table II. All values are based on a daily hot water output energy of 300,000 Btu/day.

Bldg	Use	Water Heater Type				System Savings (MBtu/yr)	System Savings (Percent)	Standard Error of Savings (Percent)
		Conventional		Heat Exchange				
		Use (MBtu)	Std Err (MBtu)	Use (MBtu)	Std Err (MBtu)			
A	DHW	186	8	150	3	36	19.4	4.6

ESTIMATED ANNUAL PERFORMANCE BASED ON SHORT TERM MEASUREMENTS

Measured Existing Boiler Loss Rates

Several short term measurements were used to examine the performance of the existing boiler in each building. The purpose of the measurements was to examine the off-cycle flue and jacket losses so that an annual boiler efficiency could be estimated.

The thermal capacity of each boiler was determined by measuring the temperature rise of the boiler water during a 30 minute burner on-cycle. During this time the boiler was isolated from the primary building circulation loop, and the boiler pump circulated water through the boiler only. Because jacket losses proved to be small relative to the input rate, they were neglected, and the thermal capacity of the boiler was found by applying a simple linear least-squares fit to the data. These results are summarized for both buildings in Table IV.

Table IV. Results of short term boiler measurements. Boiler loss rates were based on the net boiler water temperature (boiler water temperature -boiler room temperature). Boiler input rates and steady-state efficiencies were measured to be 339,000 and 338,000 Btu/hour, and .84 and .82 for the A and B buildings, respectively. The closed flue cooling time constant for building A was not measured and is assumed to be the same as for building B.

Bldg	Thermal Capacity of Boiler (Btu/^{o}F)	Time Constant (1/hour)		Boiler Loss Rate (Btu/hr-^{o}F)	
		Flue Open	Flue Closed	Flue Loss	Jacket Loss
A	1694	.067	.050	28	85
B	1647	.074	.050	40	82

After the completion of the above heating cycle, each boiler was turned off and allowed to cool. For the boiler in Building B only, the flue was closed half-way through the cooling cycle. This allowed for the separation of the flue and jacket losses shown in Table IV. A linear least-squares analysis of the semi-log plot in Figure 3 was used to determine the open and closed flue cooling time constants for the boiler in Building B. Using the thermal capacities and cooling time constants found above, the total heat loss coefficients for the existing boilers were calculated to be 113 and 122 Btu/hr-^{o}F for Building A and B, respectively. It should be noted that these measurements were made during warm weather (outside temperature of 55^{o}F), and that they may underestimate boiler losses during colder weather.

Estimated Existing Boiler Performance

The daily efficiency of the existing boilers in each building was estimated based on the measured steady state efficiencies and the heat loss parameters shown in Table IV. First, the total daily boiler energy loss was found from the daily boiler off-cycle time, the daily average net boiler water temperature, and the measured boiler loss rates. Next, this loss was subtracted from the boiler output (the measured input times the steady state efficiency) to find the net daily output. Dividing by the measured daily boiler input then yielded the daily boiler efficiency.

The results of this analysis for the boiler in Building A are shown in the upper curve in Figure 4. Similar results were found for Building B. Figure 4 shows that the boiler efficiency decreases as the daily boiler on-time decreases, since the off-cycle losses become a larger fraction of the total boiler input. Based on these data, annual efficiencies of 79 and 76 percent were found for the existing boilers in Building A and Building B, respectively. Since it is believed that the boiler loss rates are underestimated, these efficiencies may not actually be this large.

The effect of not resetting the boiler water temperature was examined by repeating the above daily efficiency calculations for building A assuming a constant boiler water temperature of 180°F. These results are shown by the lower curve in Figure 4. Here the increased standby losses substantially reduce the daily boiler efficiencies for on-times of less than 30%. In this case, the annual efficiency was calculated to be 75 percent. Compared with the annual efficiency calculated above for a boiler equipped with a reset control, 79 percent, this represents an annual energy savings of about four percent. Since the measured boiler loss rates may be underestimated, actual reset savings could be larger than this. This estimated savings is due to reduced boiler losses only, and equals about one-half of the total measured reset control savings (boiler plus distribution system) reported by Hewett (1984).

Estimated Front-end Boiler System Performance

The performance of the front-end boiler system in Building B is shown in Figures 5 and 6. Figure 5 shows the on-times for the front-end and existing boilers, as well as a calculated system efficiency curve. The pulse boiler on-time curve shows the boiler coming on at a cut-out temperature of 60°F. After the front-end boiler is enabled by the cut-out control, it is called by the reset control to maintain the system water temperature. As the outside temperature decreases, the run time increases until the front-end boiler is locked on by a second cut-out set at 30°F. Below this temperature the existing boiler is enabled, since the front-end boiler can no longer meet the entire space heating demand by itself. When enabled, the existing boiler is also called by the reset control to maintain the system water temperature.

In order to examine the front-end boiler system efficiency, the daily efficiencies of the existing boilers were calculated using the same method as used to prepare the efficiency curves in Figure 4. Pulse boiler performance was estimated using the manufacturer's efficiency curve, the measured boiler water inlet temperature, and the assumption that standby losses could be neglected. Daily efficiencies were then used to find annual boiler and system efficiencies. For both buildings, the annual efficiency of the pulse boiler operating in the front-end mode was found to be 87 percent. This efficiency is below the factory rated 90 percent annual fuel utilization efficiency (AFUE). This occurred because for most of the heating season the system water temperature was above the 130°F return water temperature required for condensing operation.

The front-end boiler system efficiency curve resulting from the above analysis for Building B is shown in both Figures 5 and 6. The efficiency of the system at outside temperatures above 60°F approaches 95 percent, since the return water temperature is low enough for the pulse boiler to operate in the condensing mode. As the outside temperature falls below 60°F, the efficiency decreases, until at 40°F it levels out at about 86-87 percent. The knee in the system efficiency curve at this point is due to the transition of the pulse boiler from the condensing to non-condensing mode of operation. The efficiency below 40°F remains relatively constant until the existing boiler comes on at 30°F. At this point the system efficiency drops as the existing boiler losses are brought into the heating system.

Figure 6 shows the efficiency curves for both the front-end boiler system and the existing boiler for Building B. It needs to be emphasized that the existing boiler efficiency curve is for the existing boiler operating by itself, and that this efficiency curve is altered when the existing boiler becomes a part of the front-end boiler system. The curves in Figures 5 and 6 were calculated by adjusting the losses of the existing boiler so that the calculated percent savings for the front-end boiler retrofit would agree with the measured percent savings shown in Table I for Building B. For this calculation the flue loss was set at the measured value of 40 Btu/hr-°F, and the jacket loss was doubled to 164 Btu/hr-°F. For these boiler loss rates the annual efficiency of the existing boiler operating by itself was found to be 71 percent, and the efficiency of the front-end system was found to be 83 percent. These values yielded an annual savings of 14.5 percent, giving the desired agreement with the PRISM result of 14.3 percent as shown in Table I. A second calculation was done in which no adjustments were made to the measured boiler loss rates. For this case the annual savings were found to be 11 percent, still within the standard error of the measured savings.

Figure 6 shows that when the existing boiler comes on the system efficiency drops to a little above the existing boiler efficiency and then levels off with it. This performance may be understood by thinking of a boiler as having only one efficiency parameter, the steady-state efficiency. Beyond this parameter, the boiler thermal loss rate is required to quantify boiler performance. The average boiler performance is determined by the steady-state efficiency, the thermal loss rate, and the boiler operating on-time. In Figure 6, when the existing boiler comes on its entire thermal loss rate is added to the heating system. This thermal loss is then made up by the existing boiler and front-end boiler operating together, since they share a common water loop. Because of this, after the existing boiler comes on, the system efficiency cannot exceed the existing boiler efficiency by more than the difference between the steady-state efficiencies of the two boilers.

In this model the front-end boiler can be viewed as an efficient "external" combustion source operating at an efficiency of 86-87 percent providing some of the standby losses that would have otherwise been provided at the steady-state efficiency of the existing boiler. Since the steady-state efficiency of the Building B boiler was measured to be 82 percent, the greatest difference between the system efficiency and the existing boiler efficiency below the cut-out temperature for the existing boiler would be about 4-5 percent as shown in Figure 6.

ECONOMIC ANALYSIS

Measured Economic Performance

The economic performance of the front-end boiler systems in buildings A and B is shown in Table V. For space heat savings only, the simple payback period is about 12 years for each building. For the case of space plus domestic hot water heating in Building A, the simple payback is about 10 years. Even though these payback periods appear long, the cost of conserved energy for every case is less than the current price for natural gas. This means that even though the installed systems were expensive they are still "producing" gas at a cost equal to or below the current market price.

Table V. Measured economic performance of front-end boiler systems. The simple payback is based on a natural gas price of $5.00/MBtu. The cost of conserved energy is based on a 15 year time period and a discount rate of two percent, yielding a present value factor of 12.9 for the investments shown.

Bldg	System	System Savings (MBtu/yr)	Cost to Retrofit ($)	Simple Payback (years)	Cost of Conserved Energy ($/MBtu)	Internal Rate of Return (percent)
A	Space Heat	94	5550	11.8	4.58	3.2
	DHW	36	1000	5.6	2.15	16.1
	Total	130	6550	10.1	3.91	5.4
B	Space Heat	93	5550	11.9	4.63	3.0

Optimum Equipment Size

It was shown earlier in Figure 1 that the fraction of the annual load provided by a front-end boiler rapidly increases as the size of the boiler is increased. Figure 1 shows that the first dollars spent on front-end boiler capacity save the most energy, and that as the boiler size approaches the design load little energy is saved as the boiler capacity is further increased. Because of this characteristic of the annual load curve, a life-cycle analysis was performed to determine the optimum front-end boiler size for the buildings in this study.

The results of the life-cycle analysis are shown in Figures 7 and 8. The economic parameters used in this analysis are the same as those used in Table V. The front-end boiler system cost, including equipment for domestic water heating, was assumed to be a $4060 fixed cost, plus an incremental cost of $18.44 per 1000 Btu/hr of boiler output. These figures are based on the actual installed cost of several front-end boiler systems. The efficiency of the front-end boiler was assumed to be a constant value of 87 percent, and the efficiency of the existing boiler was calculated using the same model as used in Figures 5 and 6. Efficiencies for domestic water heating were the measured values for Building A shown in Table II. Figure 7 shows the total annual cost for space heat. In this figure, the annual space heat cost for energy and capital is plotted against the front-end boiler output given as a fraction of the space heat design load.

The delta factor shows the effect of including domestic hot water as a part of the front-end boiler load. Here delta is defined as the ratio of the annual hot water load to the annual space heat load. For the buildings in this study, delta was about .2, and the boiler output to space heat design load ratio was about .5. While the curves seem to have a definite minimum, the annual life-cycle cost actually varies little over a wide range of boiler size. For boilers ranging from 50 to 100 percent of the demand load, the annual cost varies by less than $100 out of a total of about $3,400.

The initial increase in life-cycle cost shown in Figure 7 is due to the large initial cost required for a front-end boiler retrofit. Figure 7 further shows that the value of the boiler output to space heat design load ratio should be .5 or more. Additional plots of Figure 7 showed that this result was independent of the fixed system cost and building size for the performance and weather data used in this analysis.

The simple payback for a front-end boiler system is shown in Figure 8. The payback values shown in Figure 8 include both space and domestic hot water savings. The value of including domestic hot water is shown in both Figures 7 and 8. Here, as the ratio of hot water load to space heat load increases, the front-end boiler system appears more economically attractive. This occurs because the hot water savings are helping to amortize the investment in the front-end boiler system. The payback shown in Figure 8 for a boiler size of .5, and a delta of .2 is about 10.5 years, in good agreement with the value of 10.1 years shown in Table V.

FIELD OBSERVATIONS

The most fundamental observation is that front-end boiler systems are complex and require careful design and installation if they are to operate properly. It is very easy for both system controls and plumbing to be improperly installed. Thus, the use of a knowledgeable contractor, and quality control during design and installation is necessary. These problems may be reduced by selecting buildings and heating systems that allow for easy installation of new equipment and plumbing.

We found during the course of the research that additional site visits were required to keep the systems operating properly. On several occasions the condensing boilers would not start due to low gas pressure, requiring an adjustment of the gas pressure regulators. In addition, while the condensing boiler was heating domestic hot water, unintentional thermosyphoning circulated water between the condensing boiler and the space heating system.

Because of this, we recommend that front-end boiler systems be designed with positive flow control valves rather than the "pump/check valve" design used in the buildings examined here.

CONCLUSIONS AND RECOMMENDATIONS

The front-end boiler retrofits examined resulted in significant annual space heating energy savings, on the order of 14 to 15 percent. However, the measured savings were not as large as expected. The smaller energy savings can be attributed to two factors:

1. The annual efficiency of the existing boiler, when operating by itself, appeared to be higher than originally assumed. In addition, when operating with the front-end boiler, the efficiency of the existing boiler decreases significantly as off-cycle losses become a larger fraction of the total boiler input.

2. High return water temperatures (above 130^{o}F) prevented the high efficiency boilers from running in the condensing mode for the majority of the heating season.

The simple payback period for the two front-end boiler installations was quite long, 10 and 12 years. Because of the large fixed cost associated with installing a front-end boiler, shorter payback periods can be expected in larger buildings with greater domestic hot water and space heating loads. We recommend, based on this study, that buildings receiving front-end boiler retrofits have annual loads greater than those examined here (500 MBtu/year). Further work is required to verify this conclusion.

While having long payback periods, the cost of conserved energy for the two retrofits is still competitive with current price of natural gas. For the Minneapolis-St. Paul climate, it is most cost effective to install a front-end boiler that meets at least 50 percent of the design heating load.

The economic performance of front-end boiler systems is enhanced with the addition of domestic hot water heating capability. Heating domestic hot water using a front-end boiler provides large energy savings potential for relatively small additional cost. The payback period for adding the high efficiency domestic hot water heating system in Building A was 5.6 years.

Based on boiler savings alone, an outdoor reset control appears to be a cost-effective retrofit for existing hydronic boilers. It was estimated that the reset control increased the annual efficiency of the existing boiler by at least four percent.

Finally, condensing boilers need to be used with caution. They are not recommended unless the boiler return water temperature is below 130^{o}F, the temperature required for condensing operation. Because of this, both the building heating system and the domestic hot water heat exchanger need to be designed so that the boiler water return temperature remains below 130^{o}F.

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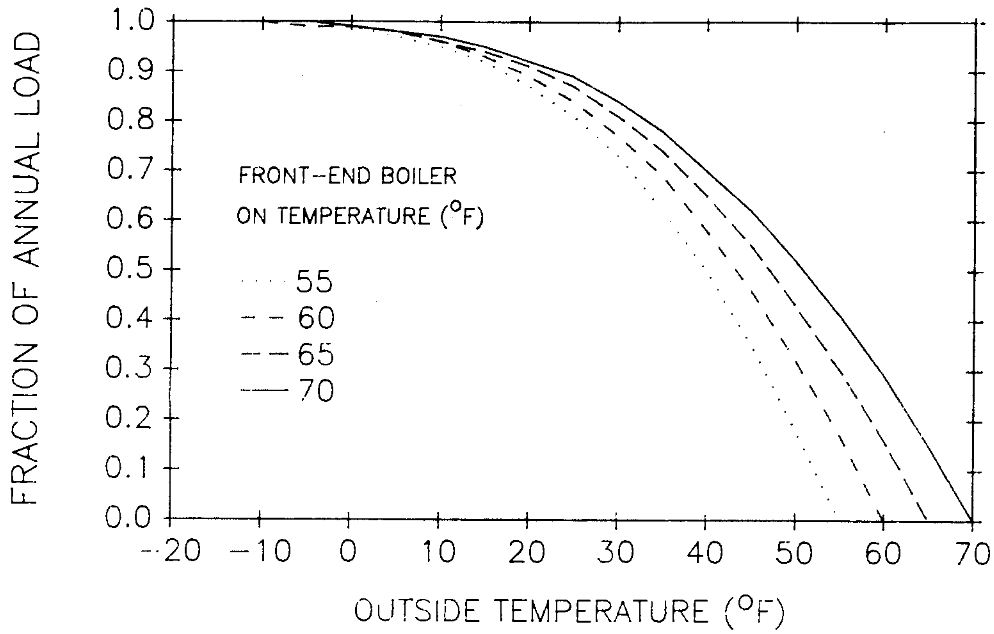

FIGURE 1. The fraction of annual load above a given outside temperature is shown for four balance point temperatures. A front-end boiler that turns on at 60°F, and will heat a building down to an outside temperature of to 20°F, will provide about 90 percent of the annual space heating load. Curves are based on bin weather data for Minneapolis-St. Paul, Minnesota. The temperature at which the front-end boiler is turned on depends on the balance point temperature of the building.

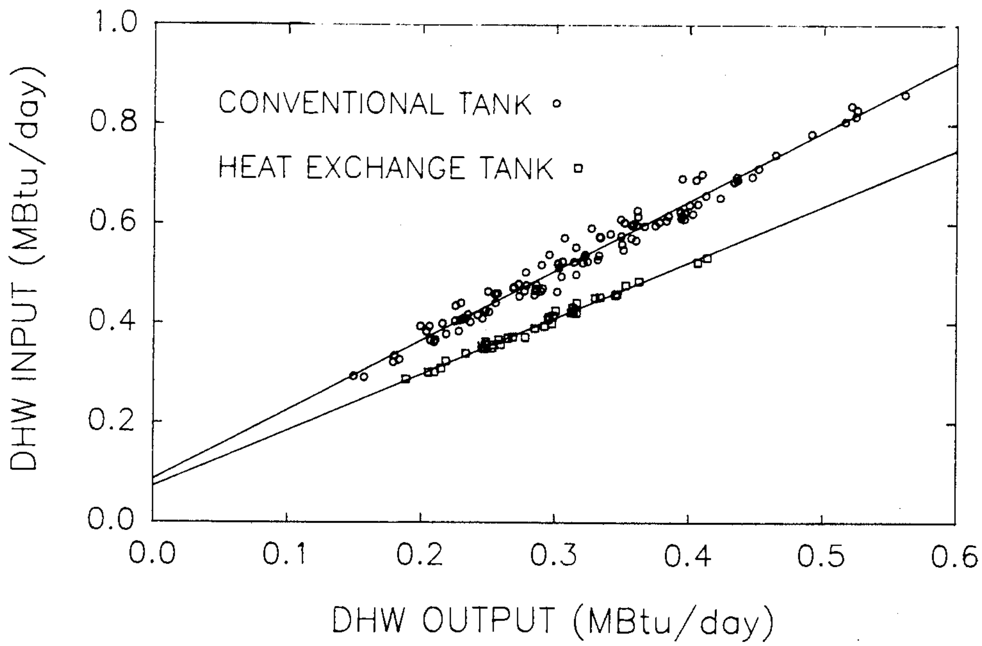

FIGURE 2. Performance of domestic hot water systems in building A. Daily values of input and output are shown. Input values are based on total daily gas consumption. Output values are based on the average temperature rise of the water for each ten gallon increment of hot water use. The thermal conversion efficiency and the input standby loss of each water heating system were estimated from the slope and intercept of the least squares fit lines shown.

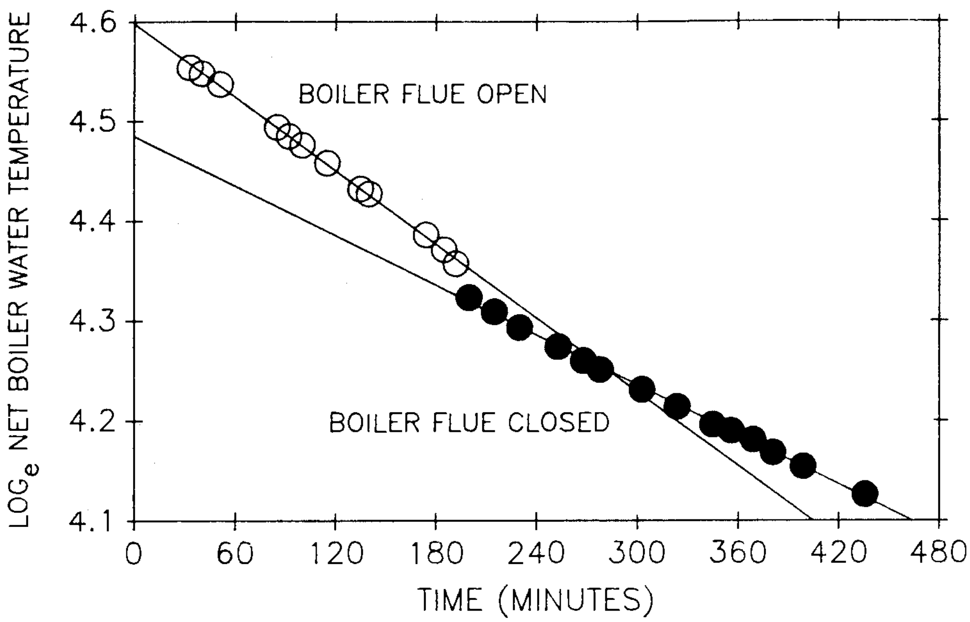

FIGURE 3. Boiler cool down curves for Building B. Semi-log plot yielded time constants of .067 and .050 per hour for the flue open and flue closed cases, respectively. Average outside temperature during the measurement was 55°F. Drop between open and closed circle data is due to an increase of 2°F in the average boiler room temperature.

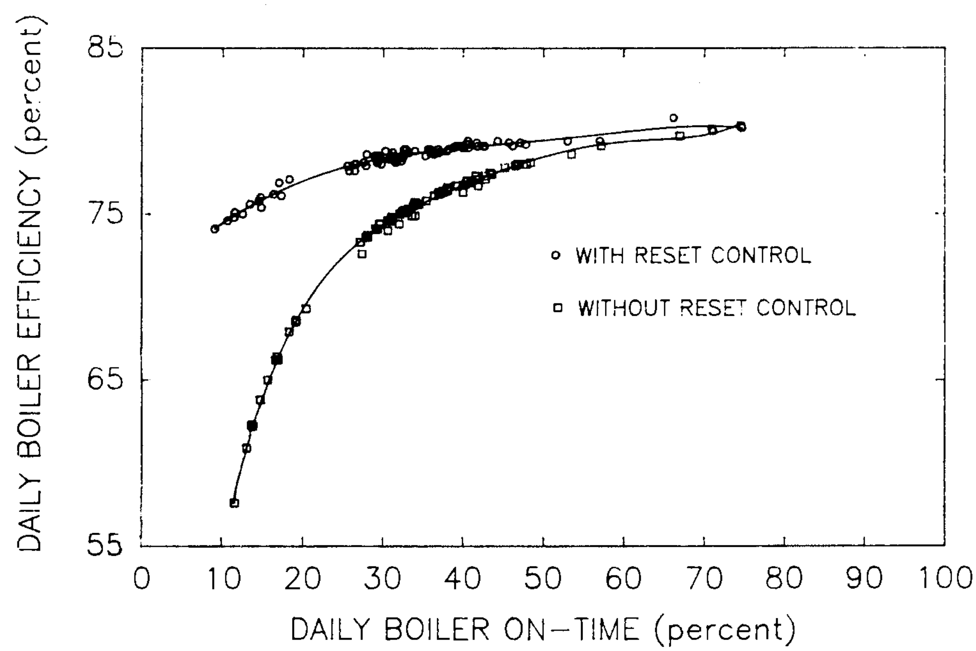

FIGURE 4. Boiler efficiency curves for building A. Daily efficiencies shown were calculated based on monitored daily boiler on-time and daily average net boiler temperature using the method described in the text. Boiler loss rates were based on the short term measurements shown in Table IV. Reset case is based on measured boiler water temperatures. For the case without reset, the daily boiler efficiencies were calculated assuming a constant boiler water temperature of 180°F. Efficiencies shown are probably too large, since boiler losses appear to be underestimated.

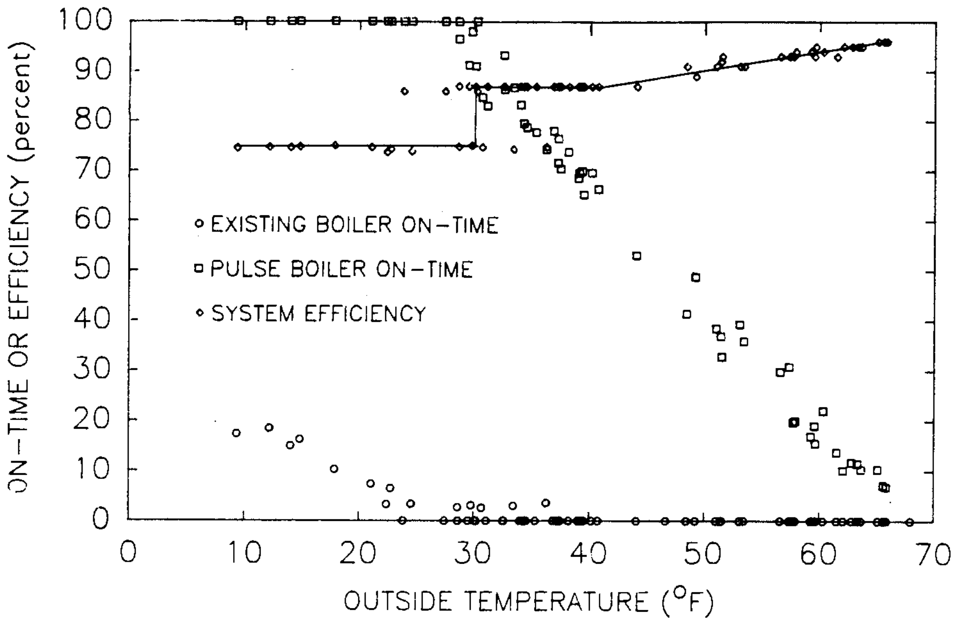

FIGURE 5. Daily boiler on-times and system efficiency for the front-end boiler system in Building B. The front-end boiler comes on at a cut-out temperature of 60°F, and is locked on by a second cut-out at 30°F. This cut-out also enables the existing boiler to come on. When enabled, each boiler is called by the outdoor reset control. Temperature shown is average outside temperature. Non-zero on-times for average temperatures above 60°F result when the boiler is enabled during those parts of the day for which the outside temperature falls below 60°F.

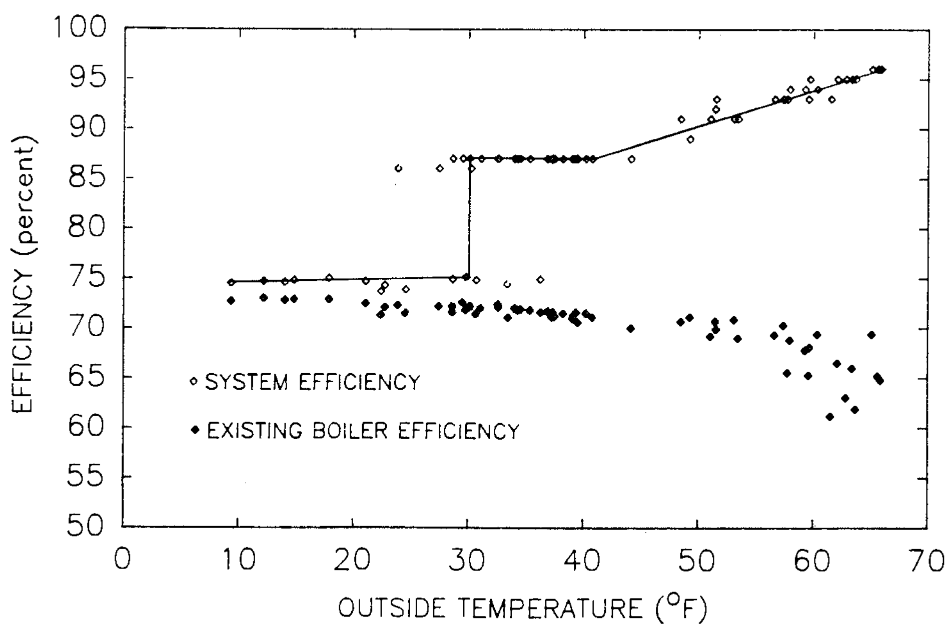

FIGURE 6. Daily efficiency curves for the front-end boiler system and the existing boiler in Building B. The system efficiency curve was calculated using boiler loss rates that yielded the observed system savings. The drop in system efficiency at 30°F is due to the increase in boiler losses that occurs when the existing boiler is turned on. The existing boiler curve is the efficiency for the existing boiler when it is operating only by itself.

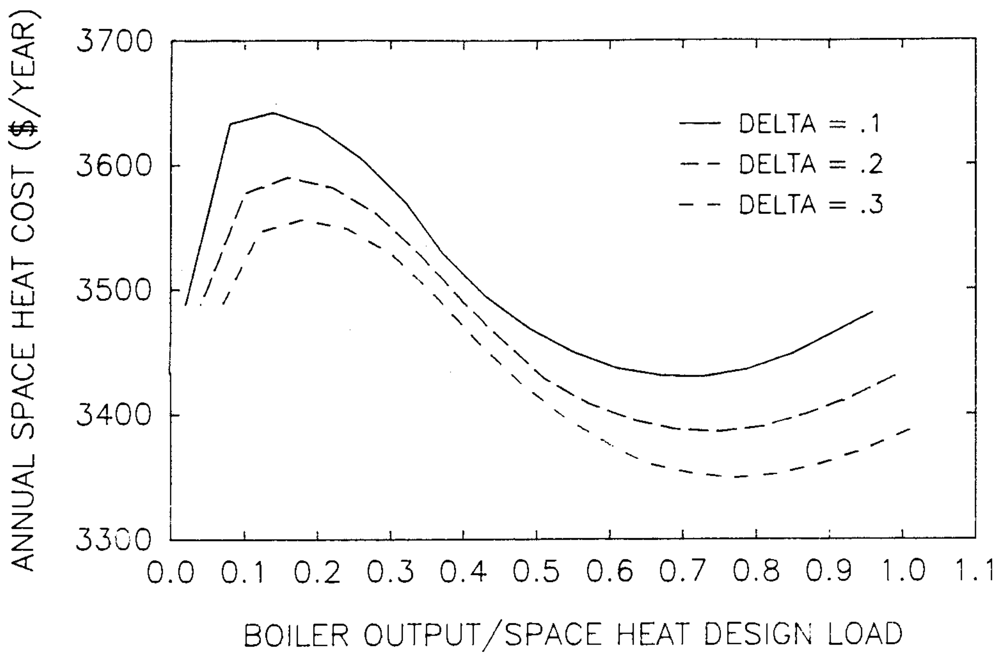

FIGURE 7. The total life-cycle cost for space heat provided by a front-end boiler system is shown as a function of boiler size. Economic parameters are the same as those given in Table V. Delta is the ratio of the annual domestic hot water load to the annual space heat load. For this study, delta was about .2, and the boiler output to design load ratio was about .5. Savings due to front-end boiler retrofit do not begin to exceed the initial investment until the boiler output to design load ratio exceeds about .2.

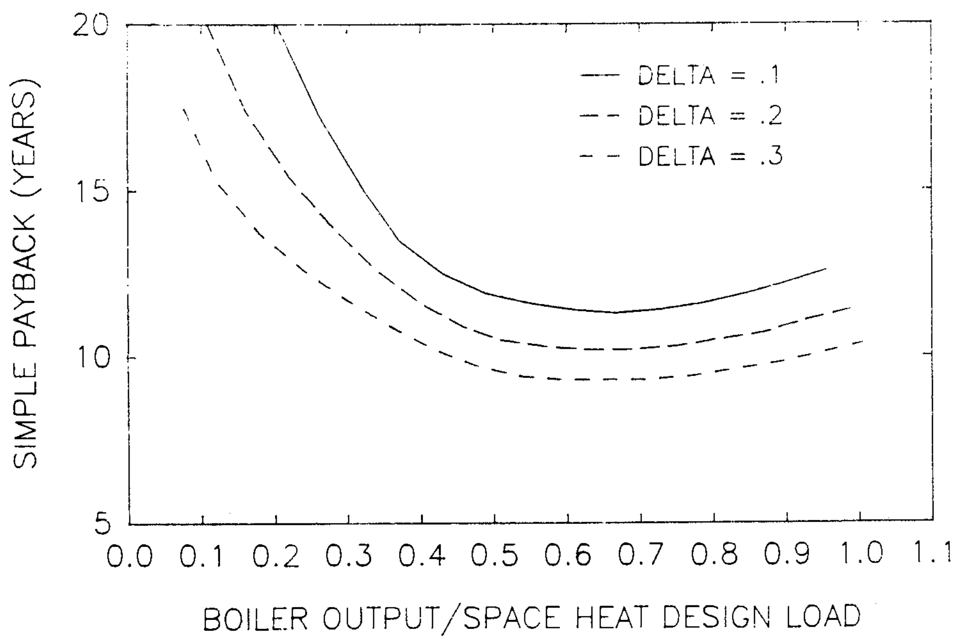

FIGURE 8. The simple payback for a front-end boiler system is shown as a function of boiler size. Payback is calculated based on space heat plus domestic hot water energy savings. Economic parameters are the same as those given in Table V. Delta is the ratio of the annual domestic hot water load to the annual space heat load. For this study, delta was about .2, and the boiler output to design load ratio was about .5.