Choosing the Right Replacement Boiler in Low-to-Moderate Income Multifamily Buildings--An Update of Current Practice and Research

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Most centrally-heated multifamily buildings in low-income areas of this country are still operating with their original central heating distribution systems. Up to 50% of the buildings receive boiler replacements when they participate in energy saving retrofit and weatherization programs in Chicago. Technical assistance providers in energy-conscious retrofit programs for steam-heated multifamily buildings must constantly wrestle with a number of boiler-related issues. The first issue is whether to specify repair or replacement of the existing boiler. If replacement, what type: a boiler with an atmospheric burner or a power burner? How does the building owner's management and maintenance style affect the boiler treatment choice? These issues are particularly important in retrofit programs which must satisfy the economic criteria of: a) the participants are investing their own money in their buildings and b) the program sponsors.

These issues are addressed by first reviewing the current energy audit procedures used in Peoples Conservation Loan Fund (PCLF) and Weatherization Assistance Program (WAP) in Chicago and by presenting some of the guidelines that have evolved based on experience with over 500 retrofitted buildings. Also presented are the results of available measurements of the part-load efficiency of various steam boilers in Chicago and in other cities. These results are synthesized into current best estimates on replacement boiler part-load efficiency. Operation and maintenance and capital cost data and assumptions are summarized and are shown to have a relatively small effect on the incremental life-cycle cost analysis of the higher performing replacement boiler option.

The results call for more boiler replacements and for making the additional investment in higher efficiency power burner-based systems for all but the smallest multifamily buildings. Further work is necessary to document the actual part-load performance of the high efficiency boiler options and to document the sensitivity of the boiler replacement options to varying quality of operation and maintenance.

Introduction

Centrally-heated multifamily buildings comprise a substantial portion of the low-to-moderate income housing stock in northern cities. These 6 to 50-unit buildings typically have the original steam heating systems. In Chicago, at least 40% of the boilers are the original 70+ year old brick-set equipment that has been successively converted from burning coal to oil and finally to natural gas. Another 10% are steel jacketed fire-tube boilers ranging from 30 to 50 years old. The balance of the boilers are cast-iron sectionals with atmospheric burners that were installed within the last 25 years. In the local Weatherization Assistance Program (WAP) and the utility-sponsored Peoples Conservation Loan Fund (PCLF) program, boiler replacements occur for up to 50% of the participants.

The technical assistance providers in these programs for steam-heated multifamily buildings must constantly wrestle with a number of boiler-related issues. These issues are particularly important in retrofit programs which must implement retrofit treatments that satisfy the particular agenda of participants who are investing their own money in their buildings and also the cost-effectiveness criteria of the program sponsors.

This paper addresses these issues by first presenting how they are currently handled in the energy audit procedures and software used in PCLF and WAP programs in Chicago and by presenting some of the guidelines that have evolved based on experience with over 500 retrofitted buildings. Also presented are the results of Gas Research Institute (GRI)-sponsored field measurements of the part-load efficiency of a wide range of existing boilers in Chicago. These results, together with measurements taken by others, are synthesized into updates of part-load efficiency data needed to make the proper boiler treatment and replacement decisions. Operation & maintenance assumptions and capital cost data are used to determine general guidelines for assessing the economics of investing in the higher performing boiler.

Finally, a summary is included of the outstanding research and development issues to be resolved from the perspective of the technical service provider.

Current Practice

The Service Delivery Context

In Chicago, there are two large-scale energy conservation programs for multifamily buildings. The utility-sponsored demand side management program for gas heated multi-unit buildings is the Peoples Conservation Loan Fund (PCLF) for buildings housing low- to moderate-income tenants. The Weatherization Assistance Program (WAP) for multifamily buildings which has recently been expanded to include central heating system repairs and replacement. Both these programs have boiler replacement rates approaching 50% (Katrakis and Wharton 1992). The high boiler replacement rate in the PCLF program, will make it the single largest ECM expense in the entire program. The availability of low-interest loans make it attractive for owners to consider such large capital investments while they are in the program. In WAP, owners get grants of up $800 per unit to go towards heating system retrofits and boiler replacement--also an inducement towards replacing the boiler. Thus, the combination of available financing at below-market rates and the large and long-term capital expense associated with a new boiler make most participants who enter these programs consider replacing their boiler.

The technical assistance providers in these retrofit programs for steam-heated multifamily buildings must constantly wrestle with a number of boiler-related issues. The first issue is whether to specify repair or replacement. If replacement, what type: a boiler with an atmospheric burner or a power burner? What are the implications of the type of pressure vessel (cast iron or steel, wet-base or dry-base)? How significant are the variations in operation & maintenance requirements among the replacement boiler options? What is the appropriate replacement boiler type for the various ranges in building size, for the range of building ownership and management style? It is also important to have solid evidence that it is indeed worthwhile for the owner to spend the extra money to get a more efficient boiler.

The Energy Audit Process

In both the PCLF and WAP services for Chicago multifamily buildings, the basic decision-making tool is the Multifamily Audit Program (MAP) (Evens et al. 1986). The technical assistance provider uses this audit software to synthesize site-specific measurements of boiler performance with stored data on performance characteristics for various boiler types and boiler retrofit options. Required site-specific data include, but are not limited to: type of heating plant (hot water or steam); type of distribution system (one-pipe steam, two-pipe steam, hydronic, etc.; measured steady-state efficiency and gas input rate. Stored data include part-load efficiency curves for typical existing boiler types and for new boilers, boiler installation costs, routine servicing costs for various boiler types and expected lifetimes for various replacement boiler types.

The technical assistance provider also inputs into the MAP software their assessment of the repair needs of the boiler as well as any other site-specific treatments such as upgrading the combustion air source or adding a condensate receiving tank to increase boiler water storage capacity, etc. The audit software also requires data on the type of boiler controls, indoor temperature, building envelope conditions as well as current energy use data. Finally, the technical assistance provider selects which boiler treatment or replacement options are to be analyzed for the particular building. The resulting output from the software is a projected cost-effectiveness analysis of each selected option. The cost-effectiveness is shown both in terms of simple payback as well as in a Benefit-to-Cost ratio (BCR) based on a life-cycle cost analysis from the perspective of the participant (based on the retail cost of gas, full cost of retrofit, and any technical and financing fees paid by the participant).

In the PCLF program, the recommended package of interacted measures must have a BCR of at least 1.5. However, the average BCR over all the participants must be at least 2.3 in order for the program to meet the Total Resource Cost test specified by the Illinois Commerce Commission (ICC) for utility sponsored Demand Side Management (DSM) programs. The WAP program, focussed strictly on buildings with tenants that are within 150% of the poverty level, has a more generous cost-effectiveness criteria--the heating system treatments must each have a BCR greater than 1.

Available Options

The first decision to make of course is whether to retrofit or replace the existing boiler. If the existing boiler required repairs that amounted to one-third the price of a new boiler, the owner is advised to replace the boiler. This rule of thumb was developed during the early years of the precursor of the PCLF program--the Chicago Energy Savers Fund (CESF). It was based on comparing the MAP audit projections of the BCRs for the repair/retrofit option and the replacement boiler option.

Once the decision is made to replace the boiler, three options are available to the owner: an atmospheric draft cast-iron sectional boiler outfitted with pilotless ignition and a vent damper; a cast-iron sectional boiler with a power burner and sealed combustion system; a steel fire-tube boiler with a power burner and sealed combustion system. In a sealed combustion system there is no draft diverter to decouple the boiler from chimney system. The draft pressure is positive in the combustion chamber and, ideally, is neutral at the exit from the boiler. For buildings of 12 to 36 units, we recommend the cast-iron boiler/power burner system over the atmospheric cast-iron boiler. The cast-iron/power burner system is more cost-effective for the following reasons:

1. Expected higher steady-state efficiency because of: a) the innate ability of power burners to be tuned closer to the stoichiometric optimum ratio of air to fuel; b) the adjustable neutral pressure plates that are available to optimize boiler draft; c) the wet-leg construction which can provide more heat transfer surface area from the fireside to the waterside than the dry-leg construction.

2. Projected higher seasonal efficiency due to the lower vent losses during the off-cycle because of the tightly closed air intake damper on the burner. Also, the burner air intake damper closes on each cycle whereas most vent dampers remain open on pressuretrol-induced cycles.

3. Longer lifetime due to the considerably thicker cast-iron sections used in the power burner-equipped boilers. Modern cast-iron boilers tend to fail due to thinned cast-iron sections that eventually are worn through by the high velocity steam and by the corrosive action at the water line.

4. Easier maintenance of the pressure vessel because of the availability of low blow-down outlets for each of the wet-legs. The barrel shape of the combustion chamber also means that any sludge is likely to fall down the sides of the chamber wall and into the wet legs and therefore will be less likely to inhibit heat transfer.

5. There is not a significant difference in installed cost between the two options. The cast-iron/power burner option appears to cost less than the atmospheric boiler option for buildings with more than 24 units.

For the larger buildings--over 36 units--we frequently recommend the steel fire-tube boiler with power burner. In these larger buildings it is more likely that there will be a building opening large enough to accommodate bringing in an assembled steel boiler from the street level into the boiler room. If this access is available in these larger buildings, the prices for the cast-iron and steel boilers are roughly comparable. Steel fire-tube boilers have several advantages over the cast-iron sectional boilers. The steel boilers have lower repair costs and therefore longer lifetimes because their pressure vessel can be repaired using conventional and affordable welding techniques. Also, the steel fire-tube boilers have slightly better thermal efficiency because of the better heat exchange from the fire-side to the water-side.

In buildings with 6 to 9 units, the optimal decision is less clear. Figure 1 presents the bid prices as a function of boiler capacity. As building size decreases below 20 units, there is an increasing price premium of the power burner system over the atmospheric boiler. For a six unit building in Chicago, the trend indicates that a cast-iron/power burner system has an $1800 price premium over an atmospheric boiler.

Some vendors and contractors recommend against installing boilers with power burner systems in these buildings because:

1. The power burner systems do not provide sufficient energy savings compared to modern atmospheric boilers equipped with pilot-less ignitions and a vent damper to warrant paying for their higher first cost.

2. The power burner systems have more sophisticated and costly maintenance requirements than atmospheric boilers.

3. The power burner systems are more affected by poor maintenance. Some argue the thermal and seasonal efficiency advantage over the cast iron/power burner system over an atmospheric system can only be maintained with proper maintenance. Since there is no guarantee that the boilers in these buildings will

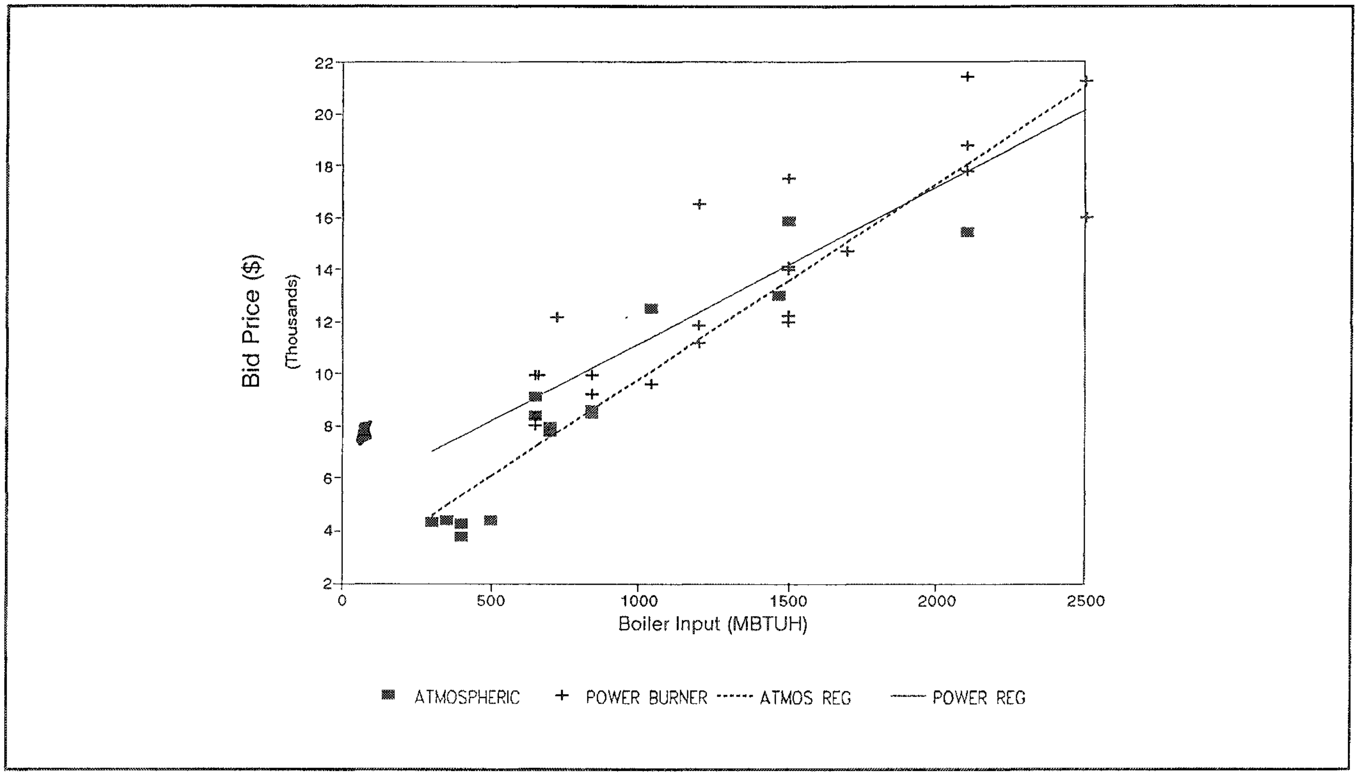

Figure 1. Capital Costs Cast-iron Boilers, Atmospheric vs. Power Burner Systems

receive proper maintenance, there is no point in installing a boiler that is relatively more sensitive to the quality of maintenance.

4. The power burner systems are more noisy. One contractor with apparently substantial experience installing power burner systems recently recommended against a power burner system for a building owned by a condominium association because of the noise that may annoy the owners living immediately above the boiler room.

Analysis

Methodology

We chose to focus our evaluation on what is the appropriate replacement boiler for the 6 to 18-unit buildings. It is this building size range where there is the most uncertainty about which is the most appropriate option. As described above, in this building range there are two main boiler replacement options: a sealed combustion power burner system with a cast-iron sectional pressure vessel, or a cast-iron sectional with an atmospheric burner and a site-installed vent damper.

Our approach was to attempt to define, based on the best available information, the performance differences of the two boiler replacement options based on good maintenance practices.

The results would then determine whether it is worthwhile to further investigate how sensitive the boiler options are to variations in maintenance quality and/or whether its worth striving to improve available maintenance services for clients of the retrofit programs.

Expected Seasonal Fraction On-Time

The actual fraction of on-time that a boiler is operating at is an important determinant of the actual seasonal efficiency of the boiler. As shown in Figure 2, boiler part-load efficiency drops off rapidly as the seasonal average percent on-time drops below 15%.

For the purposes of comparing the seasonal efficiency of the various boiler replacement options, we assumed a conservative average percent on-time of 18% for all replacement boilers. This is based on measurements made at eleven typical buildings prior to retrofit which had an average percent on-time of about 19% (Biederman and Katrakis 1989). It also assumes that the building envelope

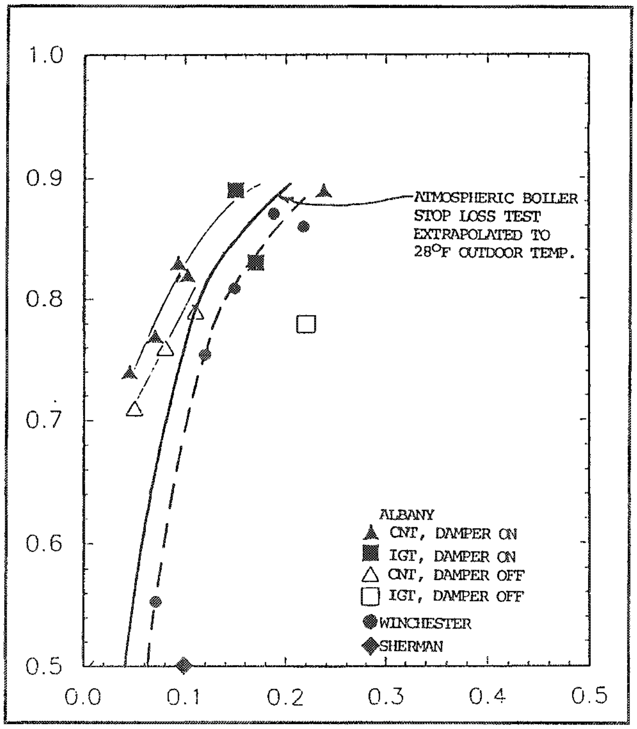

Figure 2. Part-Load Efficiency Measurements by TMS, Stop Loss and Flue Loss Methods

treatments will result in a 5% decrease in the building heat load. The result is that the average boiler after a comprehensive retrofit will be oversized compared to the building heat loss requirements by at least a factor of 70%. Figure 3 shows the projected percent on-time for a properly sized boiler (with a pick-up factor of 1.33) and the projected on-time for the 70% oversized boiler. The projections also assume a balance point of 65°F in the building.

Measured Part-Load Boiler Efficiency

Replacement Boiler Options. The actual seasonal efficiency of an installed boiler is determined by a number of factors: type of boiler, the extent to which it is oversized, the type of venting system and combustion air source, and the type of boiler control. Whereas a boiler tested in the laboratory according to ASTM standards may have an AFUE of 65%, the same boiler under actual operating conditions in the field may have a seasonal efficiency of only 51%. Therefore, an accurate measurement of the seasonal efficiency of an operating boiler in the field is extremely valuable information.

There are few data available on the actual part-load efficiency of the two replacement boiler options. Figure 2 includes the results of two different measurement methods used by Biederman and Katrakis (1989) on a cast-iron atmospheric boiler with a vent damper and pilotless ignition. The flue-loss method based on ASTM procedures was used by the Institute of Gas Technology (IGT) and the time-to-make steam (TMS) method was used by the Center for Neighborhood Technology (CNT). Note that the trends indicate that the vent damper results in about a 6% increase in the part-load efficiency. This boiler was one of the two most efficient of the eight atmospheric boilers that were tested. This result is consistent with the range of savings observed by in other vent damper tests (Hewett, et. al, 1988). We will extrapolate a part-load to steady-state efficiency ratio, E of 0.88 at the identified fraction on-time of 0.18.

The stop loss method was used by at the Center for Energy and the Urban Environment (Bohac et. al., 1990) to derive a part-load efficiency for a steel fire-tube atmospheric boiler with automatic secondary air inlet dampers. Its projected part-load efficiency is 89.9% at a fraction on-time of 0.187. Therefore, at the fraction on-time of 0.18, its expected part-load efficiency would be 89.5%. The results of these tests are surprisingly close considering the different methods used as well as the different boiler systems. We will assume that the atmospheric boiler option will have a part-load efficiency of 89% at a fraction on-time of 0.18.

There are no data available for modern sealed combustion cast-iron boilers with wet-legs such as the type that are being installed in the PCLF retrofit program. At present, it is only possible to extrapolate from tests on similar boilers. Bohac provided test results from two steel fire-tube hydronic boilers with power burners. For one boiler with a dry base and an average seasonal fraction on-time of 0.175, he derived a part-load efficiency of 94.2% to 96.1%. The other boiler was of wet-leg construction with an average seasonal fraction on-time of 0.19 and a corresponding part-load efficiency of 97.1%. We will assume that a wet-leg hydronic boiler with a power burner will have a part-load efficiency of 96.5% at an average fraction on-time of 0.18.

If the same type of boiler is used to produce steam, it can be expected that the off-cycle jacket and vent losses will be higher because of the higher temperature of the heat transfer medium. It is assumed that the average temperature of the steam boiler would be 50 to 70°F higher than for a hydronic boiler. We estimate that the off-cycle losses for the steam version would be up to 50% higher than for the hydronic boiler. Therefore, since the hydronic wet-leg boiler with a part-load efficiency of 96.5% has a total of 3.5% of off-cycle losses, we project that the steam version will have up to 5.25% in off-cycle

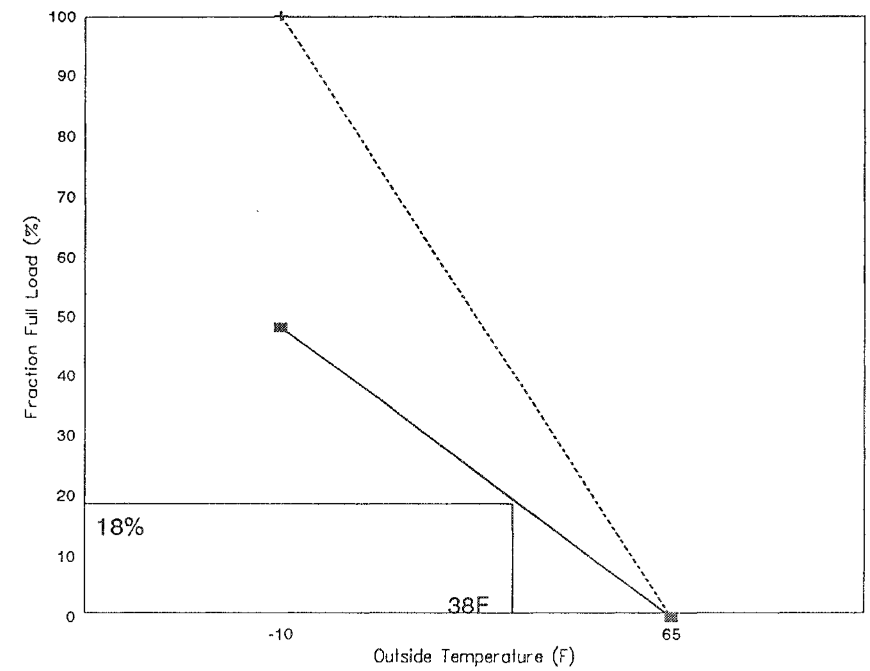

Figure 3. Projected Seasonal Percent On-Time for Replacement Boilers

losses. Since these numbers are based on the stop-loss method, they do not reflect performance under actual operating conditions. Therefore, we will round-up the off-cycle losses to 6% to account for the effect of real operating conditions such as boiler cycling. Therefore, the projected part-load efficiency for a steam boiler with a sealed combustion power burner is expected to be about 94%+/-2%. At present it is not possible to distinguish between a cast-iron and steel fire-tube boiler design.

Repair vs. Retrofit. A common issue in these older buildings with original brick-set firetube boilers is whether to replace or repair them. It is possible to tune-up these boilers to achieve steady-state efficiencies (not including jacket losses) of over 80%. Because of their steel construction, they can be indefinitely repaired, whereas it is costly to repair a leak or crack in the newer cast-iron sectional boilers.

Also, prior to the GRI-sponsored research, the MAP software used part-load efficiency curves that showed the fire-tube boilers to have about as good a part-load efficiency as the newer atmospheric cast-iron boilers. There were building owners and managers participating in the PCLF program that were proud of how well they could maintain their original boilers, as there are proud owners of antique cars. These factors led us to recommend retaining the existing boilers if they were in good repair. However, as shown in Figure 2, the few part-load efficiency measurements on these types of boilers at Winchester and Sherman indicate that their part-load efficiencies are significantly lower than the values shown for conventional cast-iron sectional boilers.

These older boilers typically are very oversized and operate at low seasonal fraction on-times. The accompanying building envelope improvements such as attic insulation, storm windows, etc., act to further reduce the fraction on-time. As shown in Figure 2, the measurements for the brickset fire-tube boiler (Sherman) and the steel jacketed fire-tube boiler (Winchester) tend to show a steep drop-off in part-load efficiency below fraction on-times of 15%. These factors all contribute to the relatively low average seasonal efficiency of these boilers. Furthermore, as shown by Biederman and Katrakis (1989), derating these older boilers may not necessarily result in a significant improvement in seasonal efficiency. Although the fraction on-time increases, the part-load curve may shift downwards due to the increase in the percent of jacket losses (both on and off-cycle).

These findings again support the case for replacing the boiler with a properly sized unit.

Expected Steady-State Efficiency

By design, power burner boilers should have a higher steady-state efficiency than atmospheric boilers. Power burners are designed to achieve a better fuel-air mixture than atmospheric burners. While, atmospheric boilers can be tuned to apparent steady-state efficiencies of over 80%, it is likely that these high efficiency atmospheric burners are "over-achievers" that produce carbon monoxide (Biederman and Katrakis 1989). Atmospheric boilers performance is sensitive to the excess air conditions caused by the oversized chimney/vent systems typically found in these buildings. Sealed combustion power burner systems with field-adjusted neutral pressure plates are not as affected by oversized chimneys.

Atmospheric boilers may be less susceptible to becoming "out of tune". Because power burners have more moving parts than atmospheric burners, they may require more attention in order to maintain their higher efficiency.

Table 1. Comparison of Projected Energy Efficiency of Atmospheric and Power Burner Boiler Systems

	Atmospheric w/Vent Damper	Power Burner
Steady-state efficiency	77	79
Steady-state Jacket losses	1	1
Thermal Efficiency	76	78
Part-load Efficiency at 18% on-time	89	94+/-2%
Seasonal efficiency at 18% on-time	67.6	73.3 (71.8 to 74.9)

Projected increase in efficiency: 8.4% (6.2 to 10.8%

Summary of Projected Boiler Efficiencies

Table 1 summarizes our best estimate of the energy-related performance of the two replacement boiler options. Energy savings were projected for a range of efficiency improvements and a base energy intensity of 0.85 therms per square foot of conditioned space in a building with an atmospheric boiler with a vent damper. Retail energy prices were used: $0.50/therm for natural gas delivered to the boiler and $0.11/Kwhr for the electricity used by the power burner fan.

Operation & Maintenance Assumptions

Operation & maintenance costs were developed for each of the two replacement options. The O&M costs have three components:

1. Routine preventive maintenance costs that are incurred every two years. This includes a routine inspection and a clean and tune of the boiler.

2. Major component replacement costs. For the atmospheric boiler it is assumed that the major component replacement that will occur during the life of the boiler will be the site-installed vent damper or pilotless ignition. These are currently assumed to have a 7 year lifetime. For the boiler with a power burner, it is assumed that the major component replacement during the life of the boiler will be the electro-mechanical burner controls such as the purge cycle controller, electrode, or UV flame sensor. It is assumed that these components have a lifetime of 10 years.

3. Boiler replacement costs. It is assumed that the wet-leg cast-iron boiler with a power burner will last 30 years versus 20 years for the atmospheric cast-iron boilers. The wet-leg cast iron is heavier and the design of the wet-let makes it less prone to damage on the water side from corrosion and from scale build-up.

The O&M cost and lifetime assumptions are summarized in Table 2.

Results

Figure 4 summarizes the effect of boiler efficiency increase and O&M cost variations on the cost-effectiveness of going from an atmospheric boiler to a power burner. The cost-effectiveness is defined as

$$NBCR = \frac{PVS(DE) - PVDTO\&M}{DIFFCC}$$

Table 2. O&M and Capital Cost Assumptions for Boiler Replacements

	Atmospheric		Power Burner	
No. Units/Bldg.	6	18	6	18
Routine O&M				
Cost ($/service)	200	309	400	619
Years between service	200	2	2	2
Boiler Capital Cost ($)	7,617	13,381	9,423	14,027
Lifetime (yrs)	20	20	25	25
Major Component Replacement				
Cost ($)	800	1,100	400	580
Lifetime (yrs)	7	7	10	10
Net Present Value ($)	8,218	13,266	10,149	15,167
Equiv. Annual Cost ($)	535	863	660	987
Difference in Routine O&M ($/yr)			100	165

where:

NBCR	=	net BCR of the investment in the higher efficiency boiler;
PVS(DE)	=	present value of the savings at a given percent difference in boiler efficiency (DE);
PVDTO&M	=	difference in the present value of the total O&M costs of the two boiler options;
DIFFCC	=	difference in current installed boiler costs.

Figure 4 shows lines of constant netBCR=1 and netBCR=2.5. These two BCR levels were chosen to reflect the corresponding cost-effectiveness criteria of the WAP and PCLF programs. It is assumed that these are the minimum values of netBCR that would warrant spending the additional money for the higher efficiency boiler in each of the programs. Also shown in Figure 4 is the expected range of percent increase in boiler efficiency resulting in going from an atmospheric boiler system to a power burner system.

These results indicate that at the low end of the expected increase in replacement boiler efficiencies and O&M costs, it is appropriate to install the higher efficiency power burner-based systems in buildings that are 12 units or larger. It is usually appropriate for 9-unit buildings but may not be appropriate for 6-unit buildings in the PCLF program with required average BCR of 2.3.

The lines of constant netBCR results appear to be relatively insensitive to significant variations in the difference in routine annual O&M costs. The efficiency variations and building size appear to have the greatest impact on the netBCR. If we use the high end of the expected range of efficiency improvement, then even 6-unit buildings would find the higher efficiency boiler to be cost-effective.

In terms of simple payback, without considering any O&M cost differences, the owner of a 6-unit building who invests in the higher efficiency boiler would get a 6.7 year payback. Assuming an annual difference of $100 in routine servicing costs, the equivalent annual cost difference in total O&M costs shown in Table 2 is $135. Therefore, if O&M considerations are included, the simple payback becomes 13.3 years.

The above findings are based on the incremental analysis of going from a building with a conventional atmospheric boiler (with vent damper) and a space heating usage index of 0.85 therms/sq.ft. to the higher performing boiler. Therefore, the results will vary depending on the actual pre-retrofit usage of the building as well as the actual space heating index of the building with an atmospheric boiler and the other energy improvements that would be added to the particular building. The findings are especially significant if the BCR of the entire retrofit package is close to the minimum allowed by the program.

Finally, we again must mention that these results assume that the necessary O&M work will be done over the life of each boiler option to maintain their performance. It is not clear what will happen if these systems are subject to minimal, or crisis-oriented maintenance.

Conclusions & Recommendations

1. Measure the part-load efficiency of various replacement boiler options to verify current assumptions used in the selection process. Also document the field performance and associated capital and O&M costs of some of the newer very high efficiency condensing steam boilers to determine if they are appropriate for these retrofit programs.

2. As part of the routine performance monitoring component of the retrofit program, measure the part-load efficiency of installed boilers to assess the extent of oversizing and actual seasonal efficiency. This will aid in determining if it is appropriate to get more aggressive in insuring proper sizing of replacement boilers.

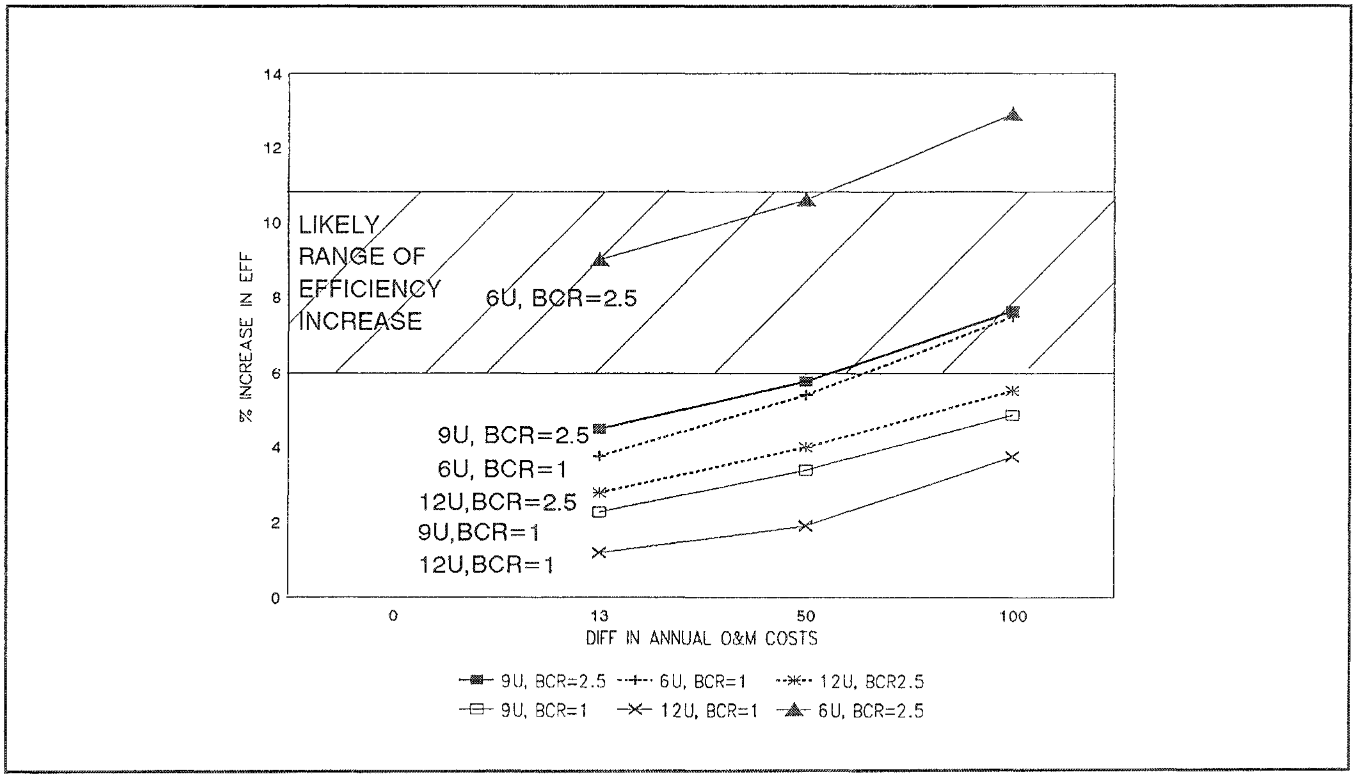

Figure 4. Boiler-Cost-Effectiveness as a Function of Change in Efficiency and O&M Costs

3. Conduct a study of the long-term efficiency of various replacement boilers. Test the steady-state efficiency two years and four years after installation and document the type and cost of operation & maintenance during this time.

4. Assess the sensitivity of the netBCR results to variations in component replacement lifetime and cost. Depending on the results, it may be appropriate to survey vendors and contractors who have extensive experience with both replacement boiler types to document the nature, cost and frequency of major component replacements.

5. Recommend the higher efficiency power burner boilers for all building sizes except perhaps in the 6 to 9 unit buildings that are in DSM programs subject to the Total Resource Cost evaluation procedure as presently applied in Illinois.

6. As part of the payout inspections in retrofit programs, measure the steady-state efficiency of new boilers and boilers that received a clean & tune measure or draft-reduction measure to verify that the expected efficiency was achieved.

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