DOMESTIC HOT WATER ENERGY SAVINGS IN MULTIFAMILY BUILDINGS

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ABSTRACT

Field studies and energy consumption analyses of domestic hot water (DHW) system retrofits were performed on seven multifamily building complexes in Trenton and Asbury Park, New Jersey. The retrofits all involved substitution of separate gas-fired water heating equipment for existing systems, all of which used central space-heating boilers to heat water. Only one of the new systems consists of water heaters in each apartment; the rest are centrally based. The measurement of energy savings from these retrofits posed special problems which precluded the direct use of a standard scorekeeping methodology such as PRISM (The PRInceton Scorekeeping Method). Some of the problems were: oil-heated buildings where tanks are not filled during deliveries, oil to gas equipment conversion, lack of DHW fuel submetering, concurrent heating system retrofits, seasonal changes in DHW heating equipment, and changes in gas meter configuration before and after retrofits. Since some of these situations are quite common, the methodology developed to handle them will have broad applicability. The results show great variation in savings across buildings, ranging from -15% to +7% for the five buildings for which annual savings were determined. The three buildings with positive savings also report an inadequate supply of hot water following the retrofit. The lack of savings is a surprising result, since the installation of a water heater separate from the heating system is a popular measure generally believed to have significant energy savings potential.

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INTRODUCTION

Domestic hot water (DHW) comprises the second largest use of energy in houses next to space heating, and can be an even greater part of the total in multifamily buildings. DHW heating equipment in multifamily buildings is often mechanically quite different from that in houses, and may involve continuously circulating distribution loops, long runs of underground piping, and higher storage temperatures. DHW system retrofits are becoming common and range from piping repair and reinsulation to complete replacement of DHW heating equipment.

The purpose of our study is to quantify the energy savings due to major DHW system retrofits in seven multifamily buildings, and in the process, to develop methods for analysis which have broad applicability. Data of this type should improve decision making for managers of modernization programs in multifamily buildings.

The buildings in our study are all New Jersey public housing projects, five in Trenton and two in Asbury Park. Building characteristics are summarized in Table I. The buildings range in construction date from 1939 to 1963, and in style from multi-building walk-up to single building high-rise. They range in size from 60 to 376 units. All are family housing with the exception of Lumley Homes, which is for senior citizens.

The five Trenton properties are heated with paired, oil-fired steam boilers which, before the retrofits, also provided DHW by means of heat exchangers. DHW and steam are distributed among the buildings by underground piping. The boilers have modulating burners which fire to maintain steam pressure in the mains; zone valves are controlled by simple controllers with offset and gain adjustments, and outdoor temperature sensors as inputs. The retrofits made in these properties were fairly conventional and virtually identical. Each consisted of removal of the existing heat exchangers and the installation of atmospheric-combustion commercial water heaters, storage tanks, mixing valves, and controls (see Figure 1). The number of heaters installed varied by property from two to four, and either one or two storage tanks were installed.

The control systems on the new units are fairly straightforward. Water is circulated through the heaters and tank(s) by a pump which is controlled according to a temperature sensor in the top of the tank. The burners are each on or off independently according to the outlet temperature at each heater (although observations indicate that they operate more or less simultaneously. As in the old systems, a thermostatically controlled pump circulates hot water so that it is available at all locations without delay. Water from the return line enters at the bottom of the tank(s) and leaves at the top where it is mixed with cold water in a three-way valve which operates to maintain a fixed hot water supply temperature. The loop circulator is actuated by a temperature sensor on the return line, as it was before the retrofit. All of the temperature setpoints are adjustable and have about a 10°F dead-band.

The Trenton systems were installed from October 1985 to January 1986, and ranged in cost from $190 to $340 per apartment.

Hot water at Asbury Park Village (APV) and Lumley Homes (also in Asbury Park) was previously provided by centrally-located gas-fired steam boilers, heating water storage tanks (1000 gal. at APV, 865 gal. at Lumley) with heat exchangers. The distribution systems were similar to those in Trenton. At Asbury Park Village, individual gas-fired water heaters along with furnaces were installed in each apartment, in September 1983 at a cost of $700/apt[1] (December 1985 dollars) (Dutt et al., 1986). At Lumley homes, a separate steam boiler for summertime water heating was installed in May 1982 at a cost of $191/apt (December 1985 $) (DeCicco and Dutt, 1986).

METHOD FOR ENERGY ANALYSIS

In this section, we discuss briefly the circumstances which precluded the direct use of a standard scorekeeping method such as PRISM (Fels, 1986) in estimating DHW retrofit energy savings. Some of the problems were: oil heated buildings where tanks are not filled during deliveries, oil to gas equipment conversion, lack of DHW fuel submetering, concurrent heating system retrofits, seasonal changes in DHW heating equipment, and changes in gas metering configuration before and after retrofits. The models developed to handle these cases are explained below.

PRISM

PRISM, the PRInceton Scorekeeping Method, uses utility bills to determine a weather-adjusted index of annual energy use called normalized annual consumption (NAC) (Fels, 1986). The weather in the normal year is characterized by the annual heating degree-days, computed at a reference temperature, τ, which is estimated by PRISM for a particular set of consumption data. NAC is given by PRISM as:

$$NAC = 365\alpha + \beta H_o(\tau) \qquad (1)$$

where

α = base level (MBtu/day)

β = heating rate (MBtu/°F-day)

$H_o(\tau)$ = average annual heating degree-days for approximately ten year period, to base temperature[2] τ.

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[1]This includes labor and installation for the water heaters, plus a portion of the new gas piping, which also provides gas for space heating.

[2]The parameter τ is found as that value which maximizes the R^2 statistic (Fels, 1986).

Changes in energy consumption from one period to the next (preferably one-year periods, with complete heating seasons) are calculated as the difference between values of NAC determined for each period.

New methods

Oil tanks not filled. The five Trenton buildings are heated with No. 4 fuel oil. Deliveries are generally made by the truckload, ranging in volume from about 4500 to 6000 gallons. The horizontal, underground tanks are never filled, but the boiler operators usually take dipstick measurements of the oil level in the tank at the time of delivery and also at regular weekly intervals. These depth readings are converted to volume with the use of a chart from the tank manufacturer. The depth, volume, and date, along with deliveries, are recorded on a log which is turned in to the housing authority accounting office every month. These records contain a great deal of data on oil consumption, but extracting the information is a challenge, for several reasons. Data quality varies tremendously from one boiler operator to another. It is not always clear whether dipstick measurements preceded or followed a delivery, except when the boiler operator has recorded both measurements. Sometimes readings are clearly wrong, so data points are lost if they cannot be reconciled. Occasionally volumes listed do not agree with depths. On rare occasions, deliveries are not recorded, although these can usually be found by comparison with invoices, if available. These problems, as well as the large quantity of data, demand a computerized means of systematically processing raw data into a form suitable for further analysis. A spreadsheet-based procedure that we developed has several functions[3]:

- Enables easy data entry and the use of calendar-related functions.
- Checks for consistency between tank depth and volume data and flags periods showing negative consumption, giving the user additional information with which to correct the data point or eliminate it from analysis.
- Enables the user to specify conditions for aggregating consumption to regular intervals of any length. This eliminates some of the noise associated with one- or two-day intervals, and provides periods of approximately equal length, avoiding disproportionate weighting of short periods[4].
- Results in a file of "clean" data that can then be used as input to PRISM or another model.

Oil to gas equipment conversion. The five Trenton properties changed from heating DHW using the oil-fired space-heating boiler(s) to using two to four gas-fired domestic water heaters. Before the retrofit, the boilers

[3]This procedure is discussed in greater detail in Appendix A.

[4]A recent version of PRISM, still in the testing phase, will allow automatic weighting of points according to period length (Hurvich, 1986).

were on all year, and the heating steam header was opened in the fall and closed in the spring. Now, the boilers are shut down in the spring, and turned on again in the fall. Figure 2 shows a plot of oil consumption against mean outside temperature for one of these buildings. Before the retrofit, the boiler was operating on the "elbow" of the line during mild weather. After the retrofit, consumption is strictly a linear function of outdoor temperature with no temperature threshold. PRISM relates consumption to degree days calculated from a specific base temperature, and is not directly applicable. In the post-retrofit case, NAC also depends on the boiler on/off dates, which are to some extent arbitrary. We have developed a calendar-based model which gives NAC as a function of two regression parameters related to building characteristics, normal daily outside temperatures, and boiler on/off dates. Here NAC is expressed as E_{hd} (MBtu/yr), the sum of a normal-year heating component E_h and a normal-year DHW component, E_d:

$$E_{hd} = E_h + E_d \tag{2}$$

where

$$E_h = \sum_{i=m}^{i=n} [a + bT_i] \tag{3}$$

a = parameter determined by regression (MBtu/day)

b = heating slope determined by regression (MBtu/°F-day)

T_i = normal daily average temperature for day i (°F)

m = boiler on date

n = boiler off date

E_d = DHW energy consumption, post-retrofit (MBtu/yr)

The calculated change in consumption between the pre-retrofit period and any given post-retrofit period will thus depend on when the boiler is turned on and off. In our analysis, we have calculated E_{hd} for several combinations of boiler season endpoints.

If, following the retrofit, the DHW gas is separately metered, E_d (post-retrofit) is determined as follows. DHW gas use depends on outside temperature, decreasing at higher temperatures. If we assume a linear dependence, with no temperature threshold, E_d is given by:

$$E_d = 365c + d\sum_{i=u}^{i=v} N_i(T_i)T_i \tag{4}$$

where

T_i = ith integer temperature for a distribution of daily average temperatures for a normal year (°F)

N_i = number of days in a normal year with temperature T_i

u = lowest integer temperature

v = highest integer temperature

c,d = intercept at T = 0°F, and slope determined by regression of monthly DHW gas use vs. outside temperature (MBtu/day)

The quantity

$$\sum_{i=u}^{i=v} N_i(T_i)T_i$$

turns out to be the normal-year cooling degree-days at base 0°F[5]. So Equation 4 reduces to

$$E_d = 365[c + dC(0°F)] \tag{5}$$

where

C(0°F) = normal cooling degree-days *per day* taken at base 0°F (°F-days/day)

DHW fuel not submetered. We encountered a problem with two of the Trenton properties--Kerney Homes and Campbell Homes--where the natural gas supply for the new water heaters was taken off the existing (cooking) gas meters. As a result, post-retrofit gas meter readings include consumption by both uses. In an effort to separate the two, we analyzed pre-retrofit cooking gas consumption patterns in these and other multifamily buildings. (Englander, 1986). Figure 3 shows monthly-average cooking gas consumption per day plotted against average outside temperature for each metering period. A weather dependence can be seen clearly in these data, with the exception of one outlier which occurs in mild weather. The weather dependence could be due to the temperature dependence of cooking--more cooking at lower temperatures--and use of gas ranges for supplementary space heating. The outlier also has physical significance--this occurred during the period in the fall before the heating header had been opened (and heat was not available to the occupants), yet temperatures were starting to get low. We model cooking gas consumption as a linear function of outdoor temperature, with a correction for the outlier.

Pre-retrofit *annual* cooking gas consumption, E_c (MBtu/yr), is given by:

$$E_c = 365[e + fC(0°F)] + N\delta \tag{6}$$

where

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[5]This quantity is also the normal-year average temperature in areas where the normal daily temperature never goes below 0°F.

N = number of days in the period associated with the outlier

δ = excess gas use per day due to the outlier (MBtu/day)[6]

and the parameters e and f are analogous to c and d in Equations 4 and 5, and are determined by regression of pre-retrofit monthly gas use with outside temperature[7]. We assume E_c remains unchanged before and after the retrofit. The post-retrofit annual DHW energy consumption is then computed as the difference between the post-retrofit annual gas use for cooking plus DHW (E_{cd}), determined by meter readings, and the pre-retrofit gas use for cooking (E_c):

$$E_d = E_{cd} - E_c \tag{7}$$

E_{cd} is given by:

$$E_{cd} = 365[g + hC(0°F)] \tag{8}$$

where the parameters g and h are analogous to c and d in Equation 5, and are determined by regression of post-retrofit monthly gas use vs. outside temperature. The normalized annual consumption for heat and DHW in the post-retrofit period, E_{hd}, is then computed using Equation 2.

Concurrent heating system retrofits. This is one of the more difficult complications that can arise in estimations of retrofit savings, especially when cooking, DHW, and space heating gas use are not separately sub-metered. The case-in-point is Asbury Park Village, a 12-building public housing complex in Asbury Park, New Jersey. A central boiler originally providing both space heat and DHW was replaced with separate furnaces and water heaters located in each apartment. Gas meters combine the usage for space heating, DHW, and cooking in the post-retrofit period. A detailed study of the retrofits was done (Dutt et al., 1986); only the results are summarized here.

PRISM was used to determine the pre-retrofit base-level gas use, which typically corresponds to average summertime consumption (Fels et al., 1984). Energy used for summertime water heating was estimated by subtracting summer cooking gas use, which in turn was estimated using data from studies of national residential energy use (Meyers, 1981) and submetered data in other New Jersey public housing projects (Englander, 1986). The energy savings due to the DHW retrofit were thus based on summer use only, and probably underestimate the actual savings because of losses, before the retrofit, from underground DHW distribution piping.

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[6]A first order estimate of this is obtained using the outlier in the pre-retrofit cooking gas consumption data. Although this correction will change from year to year, as it depends on the weather and boiler on/off dates, this estimate is probably adequate, since the outlier amounts to only about 6% of annual cooking gas consumption.

[7]The regression was performed *excluding* the outlier.

Seasonal changes in DHW heating equipment. In several properties operated by the Asbury Park Housing Authority, DHW is heated by the main gas-fired boiler during the winter, while during the summer this boiler is shut off, and a separate, smaller gas-fired boiler is used for water heating.

One building in particular, Lumley Homes, a senior citizen high-rise, has been studied in detail (DeCicco et al., 1986). Here, summer DHW gas use was estimated by summer gas meter readings and coincided with the PRISM base-level estimate. Since the retrofit was done in isolation and affects only summertime operation, the savings were therefore evaluated strictly on the basis of summer billing data, pre- and post-retrofit.

RESULTS

Figures 4a through 4e show energy use by component for each of the Trenton complexes: those with DHW gas submetering (Lincoln, Donnelly, and Wilson), and those without (Kerney and Campbell).

The heating and DHW consumption, E_{hd}, is well determined for the Trenton buildings in the pre-retrofit period, and ranges from 115 MBtu/apt-year to 167 MBtu/apt-year (Table II)[8]. For this period, the DHW energy consumption, E_d, is not disaggregated from the total.

The post-retrofit DHW energy consumption, E_d, ranges from 30 to 47 MBtu/apt-year. The heating energy consumption, E_h, for this period depends on the dates the boiler is turned on and off. Table II shows values for this parameter obtained using the period October 15 to May 15, which is typical of the period for which the heating steam header was previously open in these buildings. Table III shows the sensitivity of E_h and savings to the choice of boiler-on period, using typical extremes as limits on the boiler on and off dates.

In the post-retrofit period, E_h, E_d, and E_{hd} are all well determined. Energy savings and percent savings are statistically significant in three of the five buildings. It is interesting that the choice of boiler-on period does not have a major effect on the results (less than 5% variation in E_{hd}), even though the longest and shortest periods chosen differ by 44 days.

For the period chosen in Table II, savings across buildings vary widely, from -17 ($\pm$ 4) to 10 ($\pm$ 3) MBtu/apt-yr, or -15% ($\pm$ 4%) to 7% ($\pm$ 4%).

Patterns of main boiler heating season oil consumption post-retrofit can be compared with pre-retrofit patterns for each of the building complexes in Figure 4. The three building complexes with positive savings, Kerney (b), Donnelly (c), and Wilson (d), show quite a decrease in heating-season oil consumption. In each case, the slope of the regression line is about the same, indicating a similar response of the systems to changes in outdoor temperature. However, the level of the line has dropped

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[8]Standard errors shown in Table II are derived in Appendix B.

considerably -- 0.1 to 0.2 MBtu/apt-day, an amount comparable to the post-retrofit gas use for water heating. By contrast, the building complexes with negative savings, Lincoln (a) and Campbell (e) show no reduction in heating season oil use after the retrofits. One possible explanation is that the boiler and heat distribution controls in these systems were not adjusted to account for the reduction in load after the retrofits. However, there is no evidence that such adjustments are required, as frequency and intensity of burner firing, controlled so as to maintain steam pressure, should change automatically with a change in load. We have not, in this study, attempted to determine the physical basis for the post-retrofit performance of the main boilers.

The three building complexes with positive savings in E_{hd} (Donnelly, Kerney, and Wilson) reported problems in meeting peak DHW demand after the retrofits, and therefore less hot water was being provided. However, the ASC in these complexes did not decrease with the retrofits, suggesting that the new systems are no more efficient than before. The addition of heaters to meet peak demand most likely increased post-retrofit energy use, although we have not analyzed data for the period after the additions.

A direct comparison of energy use for DHW before and after retrofits is not possible because in the pre-retrofit period, it was not separately metered. We may, however, compare summer consumption for water heating. The PRISM pre-retrofit base-level estimate α, based on a regression of all-year pre-retrofit data, is often not well-determined and may not be a good indicator of summertime use. Instead we estimate a value α_s from the consumption during the five non-heating months preceding the retrofit. Figure 4b presents a comparison of α and α_s for Kerney Homes. The α_s value is annualized simply as $365\alpha_s$. The corresponding post-retrofit estimate of annualized summertime DHW energy use can be determined by

$$E_{ds} = 365\ (c + dT_s)$$

where

c,d = regression parameters as given by Equations 4 and 5

T_s = average summertime outside temperature corresponding to the same summer months used in calculating α_s.

A comparison of $365\alpha_s$ with E_{ds} is presented in Table II. In three complexes, Lincoln, Kerney and Wilson, there is essentially no change in the annualized summer consumption (ASC) before and after the retrofits. Donnelly shows a substantial increase while Campbell shows a larger decrease in ASC. Curiously, positive ASC savings are not correlated with positive savings in E_{hd} (see Table II), further suggesting that changes in heating season boiler energy use patterns had a larger influence on energy savings.

The energy savings results calculated on the basis of E_{hd} before and after retrofits can be extended to cost savings, including the effect of price differences between natural gas and No. 4 oil. Table II shows the annual fuel cost savings per apartment, calculated using November 1985 and

April 1986 fuel prices[9]. Even at the higher November 1985 fuel oil prices, there is a significant increase in cost in one complex with positive savings, and very little change in the other two. Using April's lower prices yields a large cost increase all around. Of course, maintenance costs may be affected by the retrofit as well; we have not evaluated this effect here.

In contrast to the Trenton buildings, retrofits at APV and Lumley Homes both show positive energy savings. As discussed in the section above, the concurrent heating and DHW retrofits at APV without DHW submetering preclude an estimate of annual savings due to the DHW retrofits alone. Summertime fuel use data, adjusted for typical cooking gas use, suggest a reduction in summertime DHW energy use from 0.13 to 0.09 MBtu/apt-day (Dutt et al., 1986).

The Lumley Homes retrofit, involving a separate boiler for summertime water heating, showed spectacular savings. Average summer gas consumption fell from 0.13 to 0.07 MBtu/apt-day (DeCicco et al.,1986), saving 7 MBtu/apt-yr for 110 days of summertime operation. This straightforward comparison of summer consumption is an appropriate way to obtain a savings estimate in the case where there is a known, part-year change in system operation. Attempting savings analysis using PRISM with year-round billing data yields inconclusive results because the standard errors of parameter estimates are too large to detect this part-year change (even though the apparent reduction in normalized annual consumption agrees with the reduction in average summer gas use).

CONCLUSIONS

Problems of measurement of savings from DHW retrofits were resolved in most instances. Energy consumption in oil boilers can be measured where dipstick readings are recorded. Lack of DHW energy submetering requires an analysis of the combined energy use for space and water heating or water heating and cooking. Both required an extension of standard scorekeeping methodology and also led to weather-normalized indices of energy use. The effect of arbitrary start and end dates of boiler operation required an additional model using normal temperatures for each date in the period of operation.

Only in the case of simultaneous heating system retrofits was it impossible to separate the annual savings from DHW retrofits. In this case, however, change in summertime energy use is an indication of retrofit effectiveness.

In the five oil-heated Trenton building complexes where the DHW retrofit was a separate water heater, savings in annual energy use for space and water heating varied from -17 ($\pm$4) to 10 ($\pm$3) MBtu/apt-yr. The lack of savings seemed to be associated with an absence of apparent change in heating season oil consumption. Perhaps adjusting the heating system controls to match the reduced demand would reduce winter and annual energy

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[9]Each of the Trenton buildings receives natural gas service at one of two rates. This is accounted for in the cost savings calculations shown in Table 2.

use. A comparison of pre- and post-retrofit annualized summer consumption shows that the new water heating systems were no more efficient than before. This lack of substantial savings is a surprising result that has major implications, since the installation of a water heater separate from the heating system is generally believed to be a significant energy saving opportunity.

In Asbury Park Village the DHW retrofit (installation of water heaters in each apartment) could only be evaluated based on its effect on summertime consumption. Significant savings, about 28% of the pre-retrofit summertime gas use, were recorded in this case. Decentralized heating and water heating for apartment buildings with specific reference to Asbury Park Village, are discussed elsewhere (Dutt et al., 1986).

The Lumley Homes result, in contrast to the Trenton retrofits, shows large (50%) savings in summertime gas use following the installation of a separate steam boiler for summertime water heating.

Additional measurements, such as those carried out at Lumley (DeCicco and Dutt, 1986), will need to be made in the Trenton buildings in order to understand the boiler, water heater flue and other heat losses. These studies should lead to the identification of energy conservation opportunities for these buildings as well as guidelines for improved specification of water heating retrofits in other buildings.

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Table I. Summary of building characteristics.

PROPERTY	Lincoln Homes	Donnelly Homes	Kerney Homes	Campbell Homes
BUILDING ID	5-1	5-2	5-4	5-5
CITY OR TOWN	Trenton	Trenton	Trenton	Trenton
OWNERSHIP	public	public	public	public
BLDG. CONFIGURATION	2s, 3s	2s dup/3s wk-up	3s	3s
GR. FLOOR AREA (ft^2)	86,744	252,033	72,629	59,184
CONSTRUCTION DATE	1939	1939	1953	1954
# UNITS	118	376	102	81
# BLDGS.	8	21	5	5
FAM/SEN/MIX	family	family	family	family
HEATING PLANT:				
TYPE	(2)Clvr Brks,stm	(3)Clvr Brks,stm	(2)H.B. Smith,stm	(2)H.B. Smith,stm
FUEL	#4 Oil	#4 OIL	#4 Oil	#4 Oil
INST. DATE	1973	1973	1980	1954
DISTRIB. SYS.	2-pipe steam	2-p steam	2-p steam	2-p steam
DHW SYS. CONFIG.	steam converters	steam converters	steam converters	steam converters
FUEL (IF SEPARATE)	n/a	n/a	n/a	n/a
DHW RETROFIT CONFIG.	(3) wtr htrs/tank	(4) wtr htrs/tank	(2) wtr htrs/tank	(2) wtr htrs/tank
FUEL (IF SEPARATE)	Nat. gas	Nat. gas	Nat. gas	Nat. gas

PROPERTY	Wilson Homes	Asbury Park Vill.	Lumley Homes
BUILDING ID	5-6	7-1	7-6
CITY OR TOWN	Trenton	Asbury Park	Asbury Park
OWNERSHIP	public	public	public
BLDG. CONFIGURATION	3s	2s	6s elev
GR. FLOOR AREA (ft^2)	167,878	89,176	39,200
CONSTRUCTION DATE	1954	1941	1963
# UNITS	219	126	60
# BLDGS.	9	12	2
FAM/SEN/MIX	family	family	senior
HEATING PLANT:			
TYPE	(2)H.B. Smith,stm	(2)Superior,stm	(2)Gibralter,stm
FUEL	#4 Oil	Nat. gas	Nat. gas
INST. DATE	1982	c. 1970 **	1963
DISTRIB. SYS.	2-p steam	2-p steam	2-p steam
DHW SYS. CONFIG.	boiler jacket wtr	main blr/coil/tnk	main blr/coil/tnk
FUEL (IF SEPARATE)	n/a	n/a	n/a
DHW RETROFIT CONFIG.	(3) wtr htrs/tank	apt. water heaters	dnkey blr/coil/tnk
FUEL (IF SEPARATE)	Nat. gas	Nat. gas	Nat. gas

** During the summer/fall of 1983, gas-fired, warm-air furnaces were also installed in each apartment, at the same time as the DHW retrofit.

Table II. Domestic hot water retrofit savings in five public housing complexes in Trenton, New Jersey (MBtu/apt-yr)[1].

Pre-Retrofit: 7/84-6/85					Post-Retrofit: 1985-86				Energy Savings		Savings ($/apt-yr)[2]		Inst.Cost
Building	E_{hd}	365α	$365\alpha_s$	Cook.	E_h	E_d	E_{ds}	E_{hd}	Sav.	%Sav.	11/85	4/86	$/apt
Lincoln	115(3)	29(6)	30	n/a	102(4)	30(1)	29	132(4)	-17(4)	-15(4)	-137	-157	313
Donnelly	138(3)	35(7)	36	n/a	84(4)	46(2)	44	130(4)	8(4)	6(4)	6	-62	187
Kerney	138(5)	9(25)	29	8(0)	97(3)	31(1)	28	128(3)	10(3)	7(4)	5	-54	322
Campbell	167(5)	41(12)	47	10(0)	136(8)	37(2)	33	172(8)	-5(8)	-3(6)	-85	-131	337
Wilson	157(5)	28(13)	38	n/a	97(16)	47(2)	40	145(17)	12(17)	8(11)	31	-45	187

[1]Standard errors shown in parentheses. Nomenclature: E_{hd}—energy used for space heating and water heating; 365α—PRISM base-level estimate; $365\alpha_s$ and E_{ds}—annualized summer consumption; E_h—energy used for space heating; E_d—energy used for water heating.

[2]Savings calculated using the following fuel prices in $/MBtu: Oil—5.32, Gas—6.06 and 6.87 (11/85); Oil—3.96, Gas—5.95 and 6.96 (4/86).

Table III. Sensitivity of post-retrofit heating energy consumption and energy savings to boiler-on period for five public housing complexes in Trenton, New Jersey (MBtu/apt-yr)[1].

Building	Units	Boiler on	E_h	E_{hd}	Savings	%Savings
Lincoln	118	10/15—5/ 1	101(3)	131(4)	-16(5)	-14(4)
		10/ 1—5/31	103(4)	133(5)	-18(5)	-16(5)
Donnelly	376	10/15—5/ 1	81(3)	128(4)	10(5)	7(3)
		10/ 1—5/31	89(5)	135(5)	3(6)	2(5)
Kerney	102	10/15—5/ 1	94(2)	126(3)	13(5)	9(4)
		10/ 1—5/31	101(3)	132(3)	6(4)	4(4)
Campbell	81	10/15—5/ 1	131(7)	168(8)	-1(9)	0(6)
		10/ 1—5/31	145(10)	181(10)	-14(10)	-9(7)
Wilson	219	10/15—5/ 1	96(14)	144(14)	14(15)	9(9)
		10/ 1—5/31	99(23)	147(24)	11(23)	7(15)

[1]Standard errors shown in parentheses. Nomenclature: E_h—energy used for space heating; E_{hd}—energy used for space heating and water heating;

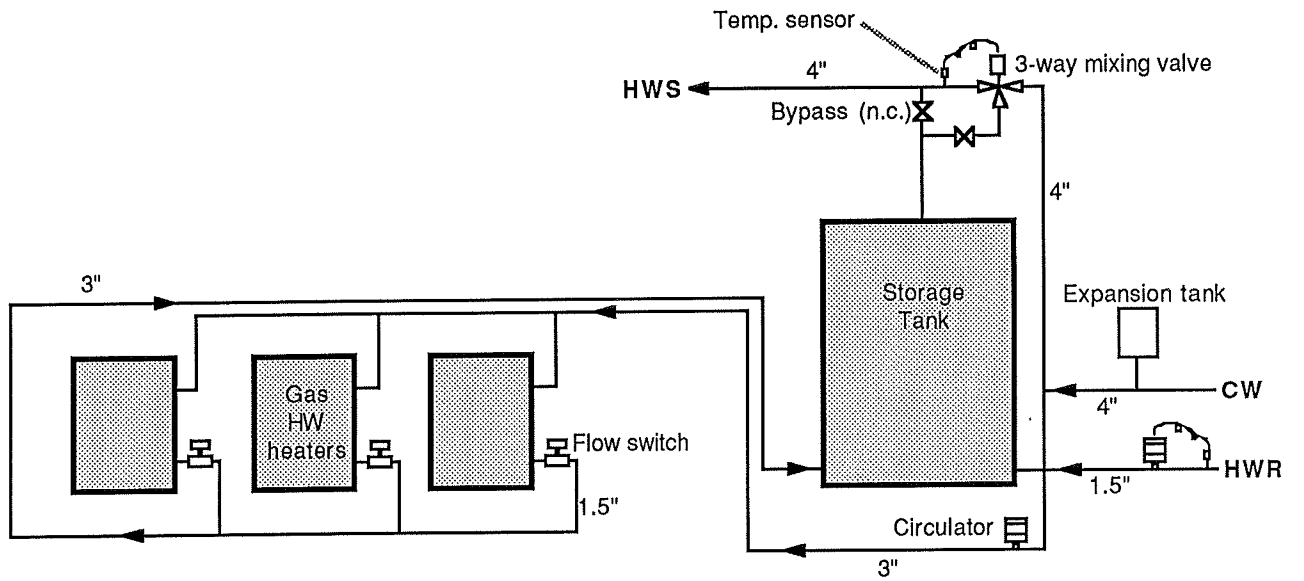


Figure 1. *Diagram of typical Trenton domestic hot water retrofit. Water was previously heated by the main boiler. Water is circulated between the tank and the heaters when the tank temperature falls within a set range. Each flow switch turns a burner on when flow is detected. The distribution loop circulator is on when the return temperature falls within a set range. The 3-way mixing valve operates to maintain a fixed temperature in the hot water supply pipe.*

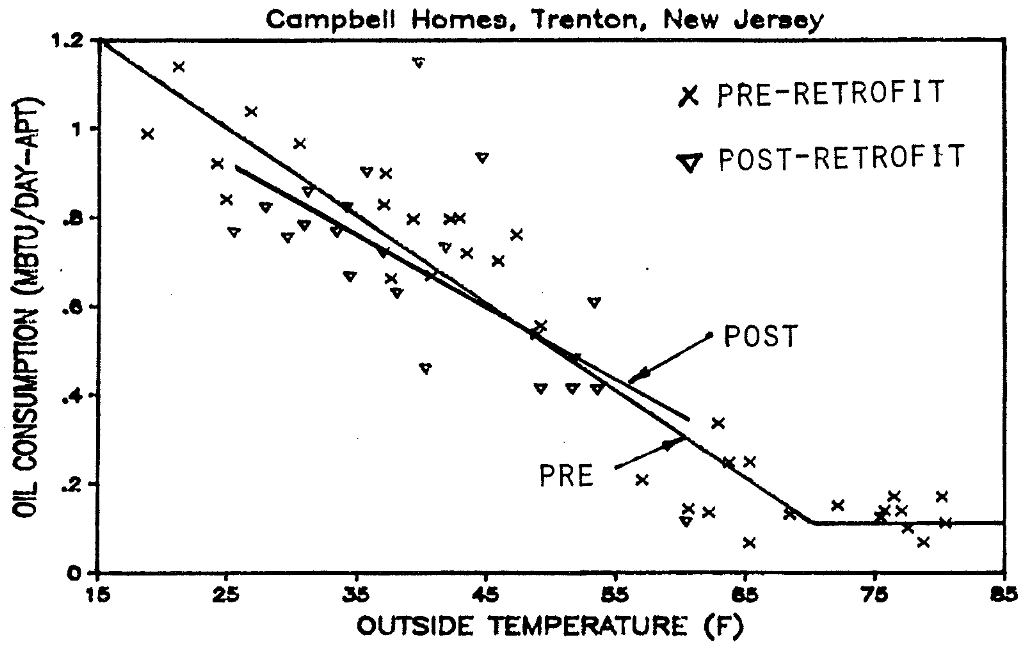


Figure 2. Pre- and post-retrofit oil consumption versus mean outside temperature.

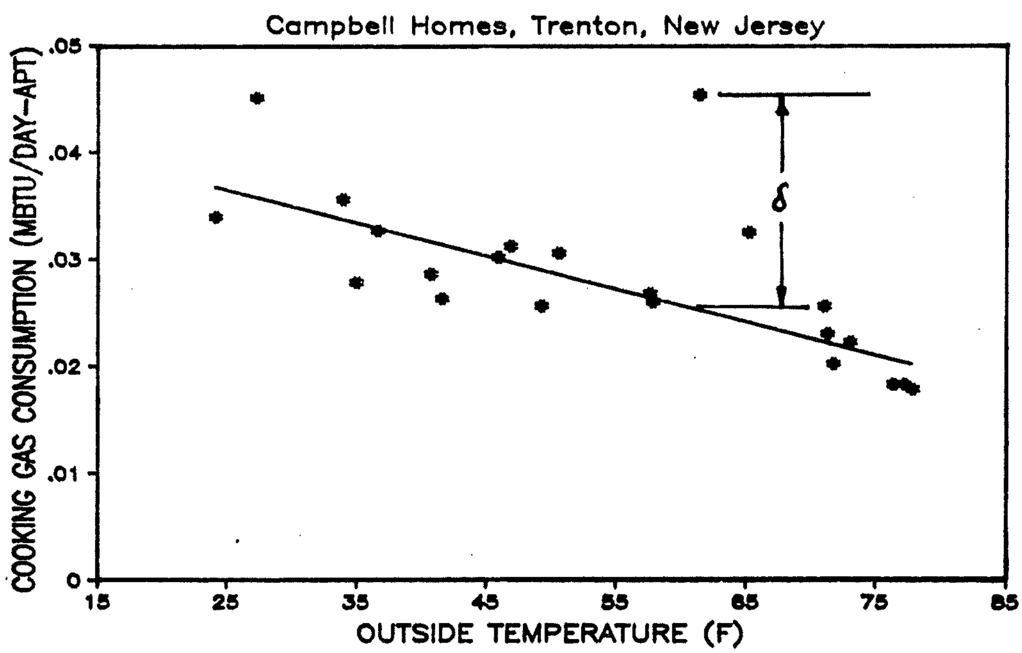
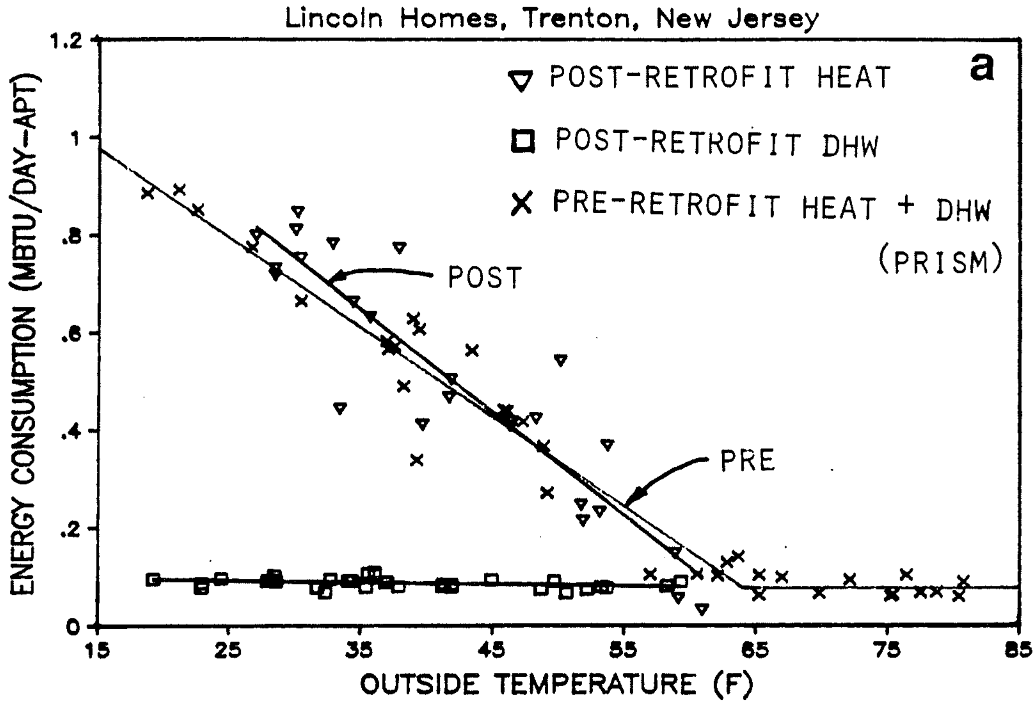
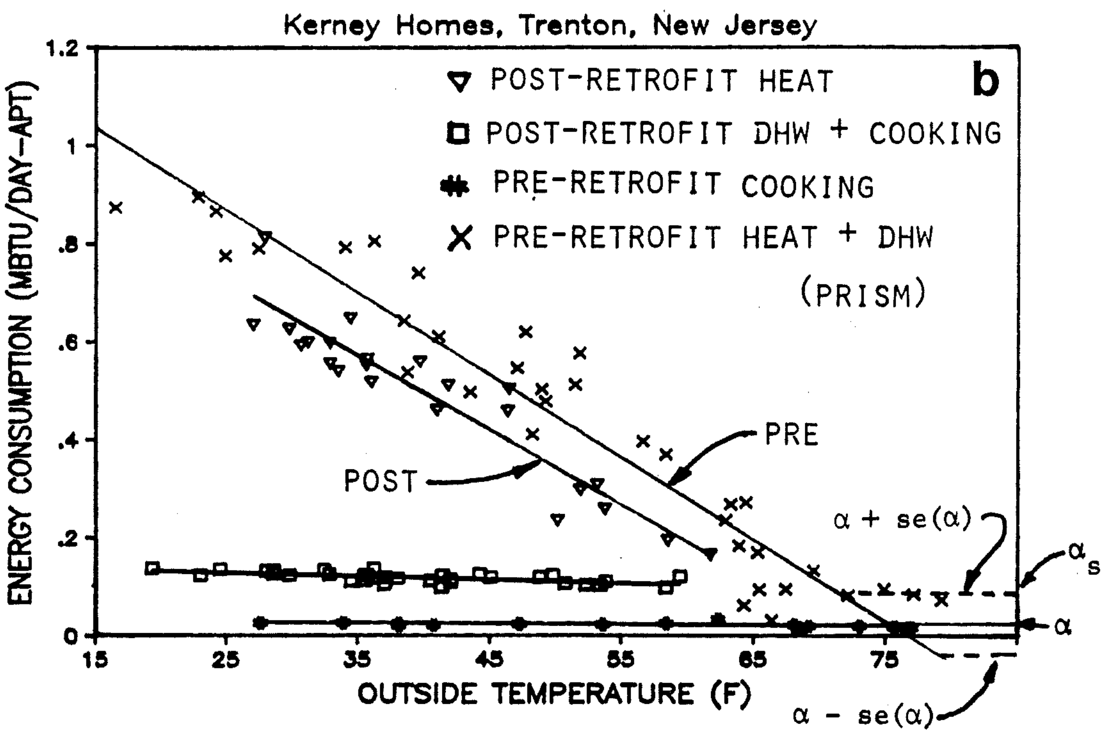
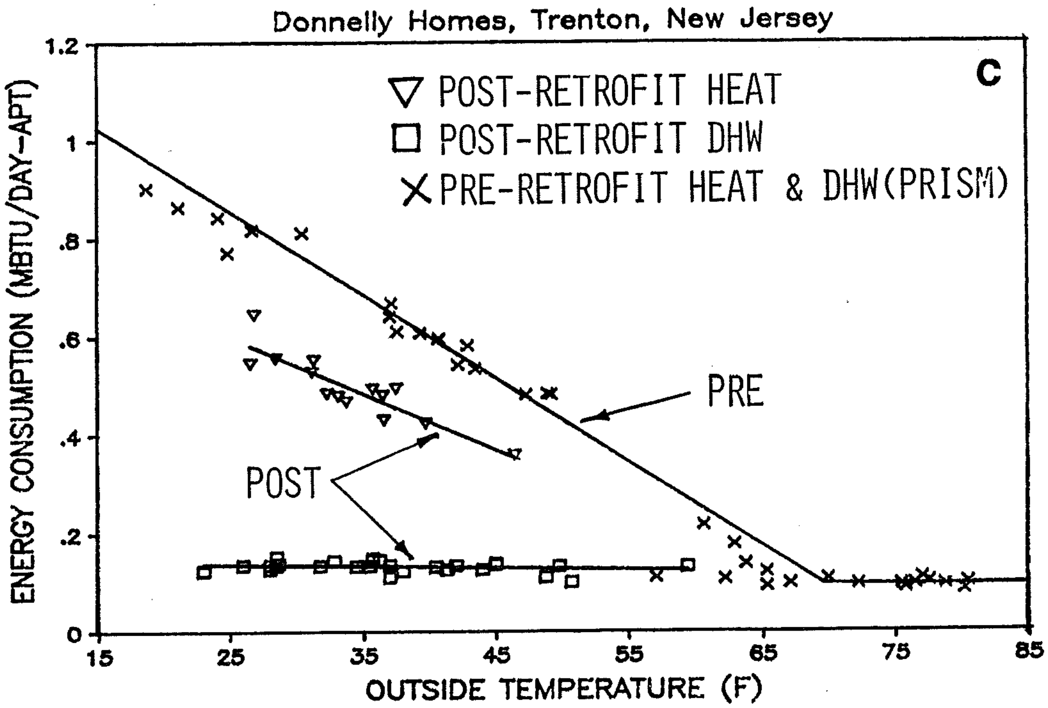


Figure 3. Pre-retrofit cooking gas use versus mean outside temperature; outlier represents use of gas ranges for space heating.

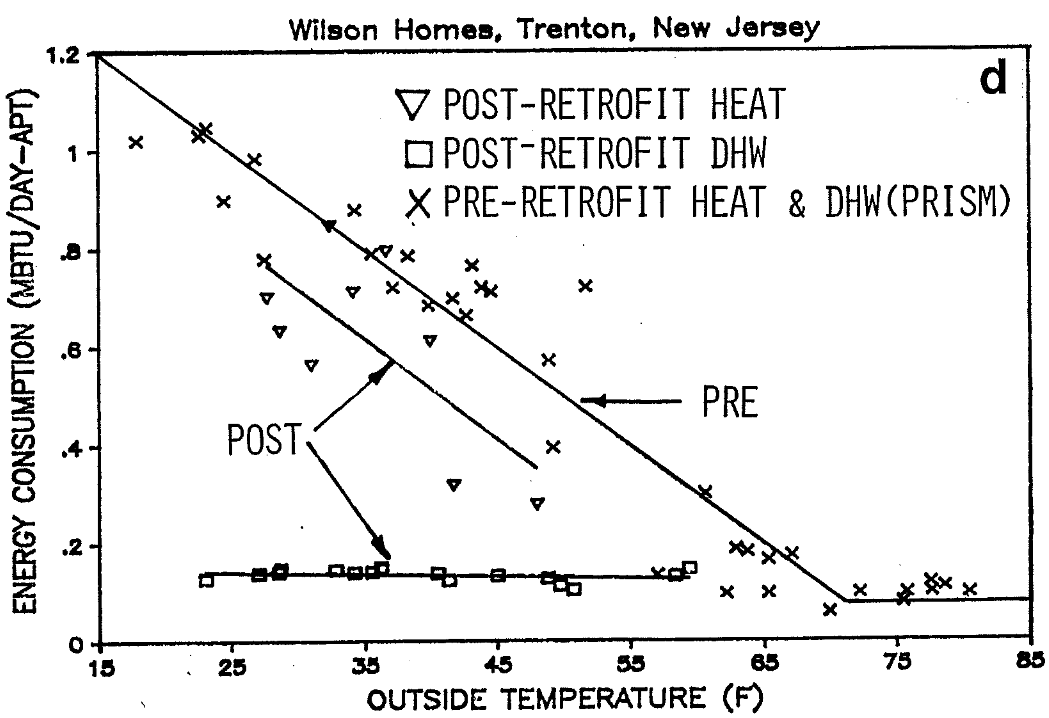




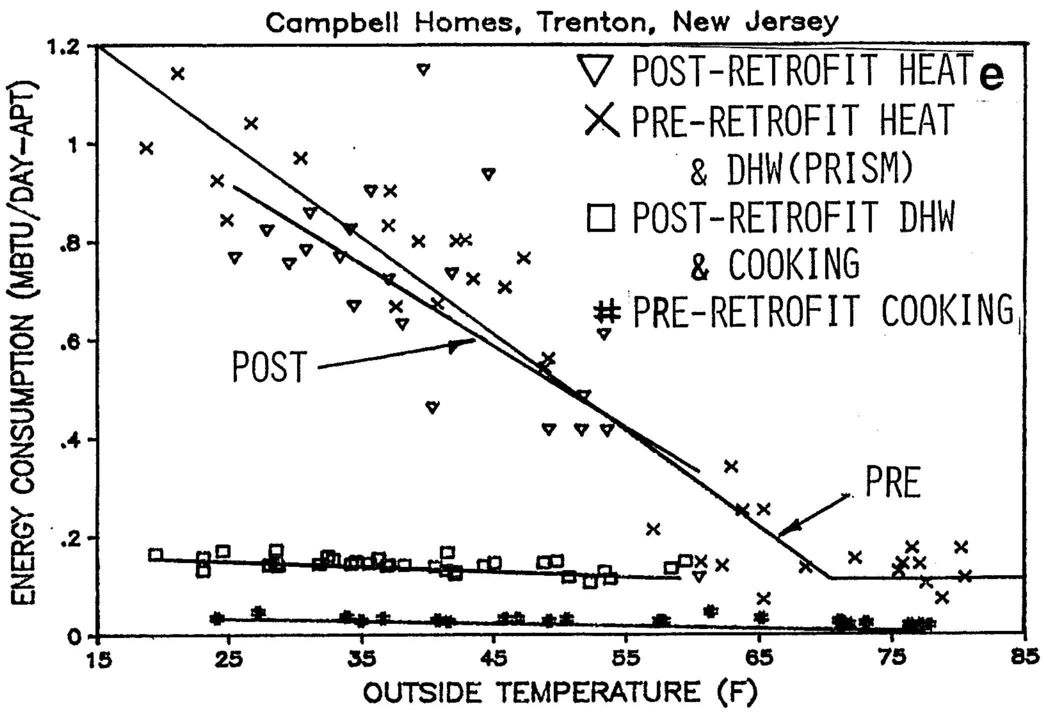
Figures 4a - e. Energy use by component versus mean outside temperature for five public housing projects in Trenton, New Jersey, before and after a retrofit.



Donnelly Homes, Trenton, New Jersey
c
POST-RETROFIT HEAT
POST-RETROFIT DHW
PRE-RETROFIT HEAT & DHW(PRISM)
PRE
POST
ENERGY CONSUMPTION (MBTU/DAY-APT)
OUTSIDE TEMPERATURE (F)
1.2
1
.8
.6
.4
.2
0
15
25
35
45
55
65
75
85



Wilson Homes, Trenton, New Jersey
d
POST-RETROFIT HEAT
POST-RETROFIT DHW
PRE-RETROFIT HEAT & DHW(PRISM)
PRE
POST
ENERGY CONSUMPTION (MBTU/DAY-APT)
OUTSIDE TEMPERATURE (F)
1.2
1
.8
.6
.4
.2
0
15
25
35
45
55
65
75
85


Campbell Homes, Trenton, New Jersey
POST-RETROFIT HEATe
PRE-RETROFIT HEAT & DHW(PRISM)
POST-RETROFIT DHW & COOKING
PRE-RETROFIT COOKING
POST
PRE
ENERGY CONSUMPTION (MBTU/DAY-APT)
OUTSIDE TEMPERATURE (F)
1.2
1
.8
.6
.4
.2
0
15
25
35
45
55
65
75
85

APPENDIX A: OIL CONSUMPTION DATA REDUCTION PROCEDURE

As described in the methods section, we have developed a spreadsheet-based procedure which is used to process raw fuel oil consumption data.

The inputs required from boiler room logs, are:

1. Date of oil depth measurement or delivery (delivery dates are compared with oil company invoices)

2. Measurement of oil depth in tank

3. Volume corresponding to depth measurement as recorded in log.

4. Volume of delivery, checked against invoices

Item 2 is not essential, but it is necessary to perform a check on volume data, which in our experience, are more often in error than are depth data. (Figure A.1 shows an excerpt from the data entry section of a spreadsheet for a building with two oil tanks.)

In addition to these, the total tank volume and radius are needed. If unknown, these can often be estimated from the highest dipstick readings shown and confirmed by successive iteration of the program.

The volume of oil in the tank is verified using the following equation, based on a cylindrical tank oriented with its axis horizontal:

$$V = L\left[r^2\left(\sin \frac{H-r}{r} + \frac{\pi}{2} \right) + (H-r)\left[r^2 - (H-r)^2\right]^{1/2} \right]$$

where

L = length of the tank, calculated by the program from total volume and radius

r = radius of the tank

H = oil level measured from the bottom of the tank

Occasionally, the consumption calculated for an interval is negative. This is most often due to entry of a volume measurement before a delivery that actually preceded it. The program flags such points, enabling the user to correct them.

It is not uncommon for oil to be removed from a tank during cleaning or for transfer to another building in an emergency. The user can accommodate this by entering the volume removed as a negative delivery.

If data are collected several times a week, it is desirable to aggregate them to somewhat longer intervals, so as to eliminate some of the noise present in data with frequent intervals, since time of day is not recorded with the readings.

The program is able to aggregate readings according to inherent frequencies of measurement, so that as many points as possible will be preserved in the final data set. In order to aggregate the data in this manner, the program first searches the measurement intervals for a mode greater than or equal to a minimum acceptable mode specified by the user. It then tries to aggregate readings so that the resulting interval length approximates the mode. The data that we have worked with have a natural frequency of seven days, with occasional more frequent readings, and our procedure generally results in a set of weekly consumption data, which has proven to be satisfactory as input to PRISM or other models.

Output can be in two forms, as an option to the user: an ASCII file directly loadable by PRISM, consisting of dates and consumption, in MBtu, or a spreadsheet file which can be used in further analysis such as regression against outside temperature.

D A T E	O I L	O N	H A N D		
	|==== TANK 1	=====|	|==== TANK 2	=====|	
	DIP. RDG	VOLUME	DIP. RDG	VOLUME	DELIV
M D Y	(IN)	(GAL)	(IN)	(GAL)	(GAL)
1 2 85	75.0	12581	48.0	7505	
1 2 85					6500.0
1 4 85	75.0	12581	63.0	10441	
1 4 85					3500.0
1 8 85					6500.0
1 11 85	75.0	12581	44.0	6709	
1 11 85					6500.0
1 14 85					6500.0
1 17 85					6500.0
1 18 85	75.0	12581	67.0	11186	
1 22 85					6500.0
1 24 85					6500.0
1 25 85	61.0	10060	64.0	10630	
1 28 85					6500.0
1 31 85					6500.0
2 1 85	54.0	8696	63.0	10441	

Figure A.1. Sample oil data entry section for a building with two oil tanks.

APPENDIX B: CALCULATING STANDARD ERRORS OF ESTIMATES

The estimates of energy use before and after retrofit are based on a number of linear and non-linear regressions. Regression parameter estimates were used to calculate normal year estimates for energy use components. These component estimates were combined to yield other component estimates. The sequence of procedures required us to calculate standard errors for our parameter estimates to ensure that our estimates of energy use and savings were meaningful. This appendix describes the formulae used and assumptions behind our estimates of standard errors, corresponding to various equation numbers in the text. The equations are listed below in the natural order of their development.

Equation 1, $NAC = 365\alpha + \beta H_0(\tau)$

Standard errors of NAC, α, β, and τ are calculated by the PRISM model, using procedures based on work done by Goldberg (1982). Note that α, β, and τ are not independent estimates, and that PRISM accounts for this in the calculation of standard errors.

Equation 5, $E_d = 365[c + dC(0°F)]$

The coefficients c and d determined by ordinary linear regression, are again not independent estimates. The standard error of E_d, $se(E_d)$ is given by

$$se(E_d) = 365\{\sigma_c^2 + C(0°F)^2\sigma_d^2 + 2C(0°F)\sigma_{cd}\}^{1/2} \qquad (B.1)$$

where

σ_c^2 = variance of a $= \dfrac{s^2 \Sigma T_i^2}{\Delta}$

s^2 = residual variance $= \sigma_e^2$

σ_e^2 = variance of e $= \dfrac{\Sigma(e_i - c - dT_i)^2}{N - 2}$

$\Delta = N\Sigma T_i^2 - (\Sigma T_i)^2$

e_i = average daily DHW gas consumption for the ith metering period

N = number of data points = n - m + 1

$\sigma_d^2 = \dfrac{N\sigma_e^2}{\Delta}$

σ_{cd} = covariance of c and d $= -\dfrac{(\Sigma T_i)s^2}{\Delta}$

Equation 8, $E_{cd} = 365[g + hC(0°F)]$

This equation is similar in form to Equation 5, and the standard error of E_{cd} is given by

$$se(E_{cd}) = 365\{\sigma_g{}^2 + C(0°F)^2\sigma_h{}^2 + 2C(0°F)\sigma_{gh}\}^{1/2} \tag{B.2}$$

where $\sigma_g{}^2$, $\sigma_h{}^2$, and σ_{gh} are, respectively, the variance of g, the variance of h, and the covariance of g and h, calculated analogously to the similar parameters for Equation 5.

Equation 6, $E_c = 365[e + fC(0°F)] + N\delta$

The standard error of E_c is calculated like those for equations 5 and 8:

$$se(E_c) = 365\{\sigma_e{}^2 + C(0°F)^2\sigma_f{}^2 + 2C(0°F)\sigma_{ef}\}^{1/2} \tag{B.3}$$

The uncertainty in δ has been ignored here, as it is not clear what this should be, since δ is determined using one particular year's data. This is not of great significance, however, as $N\delta$ was less than 6% of E_c for the data we looked at.

Equation 7, $E_d = E_{cd} - E_c$

Here E_{cd} and E_c are calculated separately, and we assume that their estimates are independent. The standard error of E_d is

$$se(E_d) = [se^2(E_{cd}) + se^2(E_c)]^{1/2} \tag{B.4}$$

where the standard errors of E_{cd} and E_c are calculated as described above--see equations B.1 and B.2.

Equation 3, $$E_h = \sum_{i=m}^{i=n}[a + bT_i]$$

The standard error is

$$se(E_h) = [N^2\sigma_a{}^2 + (\Sigma T_i)^2\sigma_b{}^2 + 2N(\Sigma T_i)\sigma_{ab}]^{1/2} \tag{B.5}$$

where $\sigma_a{}^2$, $\sigma_b{}^2$, and σ_{ab} are the variance of a, the variance of b, and the covariance of a and b. See Equation B.1.

Equation 2, $E_{hd} = E_h + E_d$

Again E_h and E_d are estimated independently, and the standard error is

$$se(E_{hd}) = [se^2(E_h) + se^2(E_d)]^{1/2} \tag{B.6}$$

which is similar to Equation B.4.

Standard errors of energy savings and percent savings

Energy savings are calculated using

$$\text{savings} = (E_{hd})_{pre} - (E_{hd})_{post} \tag{B.7}$$

and since the pre and post estimates are independent, the standard error is

$$\text{se(savings)} = [se^2(E_{hd})_{post} + se^2(E_{hd})_{pre}]^{1/2} \tag{B.8}$$

The percent savings are

$$\%\ \text{savings} = 100\left[1 - \frac{(E_{hd})_{post}}{(E_{hd})_{pre}}\right] \tag{B.9}$$

and the standard error is

$$\text{se}(\%\ \text{savings}) = 100\left[\frac{(E_{hd})_{post}}{(E_{hd})_{pre}}\right]\left\{\left[\frac{se((E_{hd})_{post})}{(E_{hd})_{post}}\right]^2 + \left[\frac{se((E_{hd})_{pre}}{(E_{hd})_{pre}}\right]^2\right\}^{1/2} \tag{B.10}$$