CONVERSION FROM CENTRAL TO APARTMENT-LEVEL HEATING IN MULTIFAMILY BUILDINGS: THE ASBURY PARK VILLAGE CASE STUDY

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ABSTRACT

Asbury Park Village is a 126-unit public housing project in Asbury Park, New Jersey. This twelve-building complex was heated by a central gas-fired space and water heating system until 1983, when the central system was replaced by atmospheric gas-fired furnaces and water heaters located in each apartment. Total gas use fell by 53% at a simple payback period of about five years, not counting reduced maintenance costs. Engineering estimates of building heat loss agree with estimates derived from billing data analysis. The low efficiency of the old heating and hot water system appears to be the result of leakage from the distribution network, poor apartment temperature control, and possibly faulty steam trap or high off-cycle boiler losses. Conduction losses from distribution piping and condensate leaks could not have accounted for the poor efficiency. A comparison with alternative high-efficiency decentralized heating options indicates that fuel savings could have been about 65% with comparable payback periods. Of the alternatives, a somewhat novel approach involving three direct-vent space heaters and a high-efficiency water heater per apartment appears to be particularly attractive.

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INTRODUCTION

Asbury Park Village is a 126-unit public housing complex in Asbury Park, New Jersey. Energy consumption in this building complex was studied as part of Princeton's research program on energy conservation in multifamily buildings. This building is of particular interest because of a major retrofit in 1983 when its central gas-fired space and water heating system was replaced by separate gas-fired furnaces and water heaters located in each apartment.

Energy use in Asbury Park Village (APV) was studied on the basis of its physical characteristics, engineering heat loss analysis, and billing data analysis.

Energy billing data was used to estimate fuel savings and to estimate the original heating system efficiency by comparison with the efficiencies of the replacement furnaces and water heaters.

Economics of the conversion were evaluated using actual costs and measured savings. The conversion was compared with other decentralized heating and water heating options for APV, using estimated costs and AFUE ratings.

BUILDING AND SYSTEM DESCRIPTION

Asbury Park Village (APV) consists of 12 two-story, brick apartment buildings operated by the Asbury Park Housing Authority. Each building consists of one efficiency, two one-bedroom and eight two-bedroom apartments, with a gross floor area of 89,176 ft^2. Prior to the heating system conversion, space and water heating were provided by a gas-fired Superior steam boiler, Model 7112-12S24 with an input rating of 8.4 MBtu/h; a second identical boiler served as a backup. Domestic hot water was provided by the steam boiler using a steam coil in a 1000-gallon storage tank in the boiler house. Supply lines connected the boiler to a two-pipe steam distribution system located in crawlspaces and in underground tunnels, along with a pipe loop that circulated domestic hot water to the apartments. The Housing Authority decided to replace the space and water heating system because of leaks in the distribution lines, degenerated vacuum pumps, and high maintenance costs (Sangillo, 1985).

HEATING SYSTEM CONVERSION

The equipment conversion occurred in the fall of 1983, and included installation of furnaces, water heaters, vents, ducts, thermostats, and gas and water piping. A typical installation is shown in Figure 2. In the new heating system, a Heat Controller Inc. Model GHJ-80-DH upflow gas furnace provides heat in each apartment. With a standing pilot, atmospheric burners and 80,000 Btu/h input, the furnaces have an AFUE rating of about 64% (GAMA, 1984). Uninsulated and exposed ducts distribute the warm air to the different rooms of each apartment, and a locked, but not tamper-proof thermostat in each apartment controls the furnace. A thirty or forty gallon gas water heater, with a service efficiency of about 44% (70% recovery efficiency, 6%/hr. standby losses) (GAMA, 1985) provides hot water in each apartment. The furnace and water heaters are vented through the roof with type B sheet metal vents. A new underground gas piping system was also installed and in this new arrangement, each of the twelve buildings has its own gas meter.

ENGINEERING ANALYSIS OF HEAT LOSSES

Natural gas is used in this building complex for space heating, water heating, and cooking. None of these are separately metered, either before or after the conversion.

Space heating energy use is determined by the building heat loss rate and the heating system efficiency. Water heating energy use depends on the hot water used and the efficiency of water heating. Cooking gas use depends on the pilot gas consumption rate, cooking practices, and possible space heating with cooking equipment. Of these factors, only building transmission loss (by conduction and radiation) can be calculated using engineering analysis. The remaining components can be estimated by analyzing utility billing data and by using data from other buildings where these components were independently measured.

Building transmission loss calculations are shown in Table I. The total transmission loss is 0.86 MBtu/°F-day. The average air infiltration rate is assumed to be 0.75 ($\pm$0.25) air changes per hour (ACH), the additional heat loss rate would be 0.25($\pm$0.08) MBtu/°F-day. The total heat loss rate would thus be 1.11 ($\pm$0.08) MBtu/°F-day, or 8.8 ($\pm$0.6) kBtu/°F-apt-day.

BILLING DATA ANALYSIS AND ENERGY SAVINGS

The Princeton Scorekeeping Method, PRISM, was used to analyze the gas consumption data. PRISM 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)

$H_o(\tau)$ = annual heating degree days averaged over a ten year period, to base temperature[1] τ.

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.

After the heating system conversion, there were separate gas meters for each of the twelve buildings, in contrast to the single meter used earlier. For the post-conversion period, we analyzed the data by first adding the consumption from each meter, since all meters were read on the same day. Figure 3 shows PRISM estimates of NAC, α, β, and τ for successive twelve-month periods from June 1982 to May 1986. The NAC, determined with relatively small standard errors, shows a large decrease at the time of the conversion and a slight downward trend thereafter. Energy savings are thus retained for the two-and-one-half years following conversion.

As is typical, the other PRISM parameters τ, α, and β are less well determined, especially after the conversions (Fels, 1986). Estimates become somewhat better defined, with smaller standard errors, for the data period ending in 1986. Table I shows PRISM estimates for the pre- and post-conversion periods 6/82 to 6/83 and 5/85 to 5/86. The normalized annual consumption (NAC) was 211 (±7) MBtu/apt-yr, of which 58 (±13) was base level consumption, with the reference temperature estimated to be 62.0 (±2.6) °F. Following the conversion, NAC fell by 53% to 99 MBtu/apt-yr. Other apartment complexes managed by APHA use[2] from 89 to 245 MBtu/apt-yr. When normalized for floor area and local weather, (represented by degree days to base 65°F), the total pre- and post-conversion gas use of 61 and 29 Btu/ft^2-DD(65), respectively; in contrast, a typical single family gas heated home in the Middle Atlantic region uses about 14 Btu/ft^2-DD(65) of

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

[2]Based on unpublished PRISM analysis of utility billing data from July 21, 1982 to September 19, 1984, for all Asbury Park Housing Authority buildings.

gas for heat and other uses, and a typical gas-heated apartment in this region, about 19 Btu/ft^2-DD(65) (EIA, 1984a and 1984b)[3].

PHYSICAL INTERPRETATION OF SAVINGS

Heating system efficiency

We estimated the efficiency of the old central space and water heating system as follows. The heating efficiency, η, may be defined as

$$\eta = \frac{\text{building heat loss}}{\text{space heating fuel use}} \qquad (2)$$

The building heat loss can be calculated from manufacturers' estimates of furnace efficiency (GAMA, 1984) and PRISM estimates of normalized annual heating fuel use, E_h, (Table II). GAMA reports the annual fuel utilization efficiency (AFUE) of the furnace, an indicator that does not include distribution losses. However, since the ducts are contained within the apartment, these losses are negligible and we may assume that η equals AFUE, 64% for these furnaces. E_h = 57.1 ($\pm$9.6) MBtu/apt-yr. The annual building loss is then 0.64 x 57.1, or 36.6 ($\pm$6.2) MBtu/apt-yr. Assuming that the building heat loss was the same before the conversion, we estimate η for the central boiler using Equation 2, and pre-conversion heating fuel use (Table I).

$$\eta = \frac{36.6\ (\pm 6.2)}{152.5\ (\pm 10.7)} = 0.24\ (\pm 0.04)$$

This estimate of boiler efficiency is far lower than that of the furnaces, 64%. The reasons for this large difference include:

- misallocation of heating component by PRISM
- differences in boiler and furnace losses
- heat losses from steam and condensate lines (leakage and conduction to ground, as well as faulty steam traps);
- differences in building heat loss rates (due to improper control).

PRISM estimates the heating component by subtracting a base-level estimate from the normalized annual consumption. PRISM'S base-level estimate is essentially the annualized summertime rate of fuel usage and underestimates annual-average usage for hot water and cooking (DeCicco et

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[3]Average for multifamily gas-heated apartments is for households paying their own bill--not centrally-metered buildings. Average floor area for single-family houses is 2011 ft^2, and for multifamily units, 902 ft^2.

al., 1986). If the annual baseload were 25% higher than the PRISM estimate (73 MBtu/apt-yr instead of 58 MBtu/apt-yr), the heating estimate would decrease to 138 MBtu/apt-yr. Using the same heating loss of 36.6 MBtu/apt-yr, the efficiency of the old heating system would increase to 0.27 from 0.24 calculated earlier. Thus even a 25% increase in base level energy use would only result in a slight increase in heating system efficiency, within one standard error of the PRISM-based estimate, 0.24 ($\pm$ 0.04).

The PRISM estimate of building heat loss may also be compared with engineering estimates. PRISM estimates a heating slope of 10.8 ($\pm$1.8) kBtu/apt-°F-day (Table I) or 1.36 ($\pm$0.23) MBtu/°F-day for the whole building. Again, assuming a furnace efficiency of 64%, the building heat loss rate is 0.87 ($\pm$0.15) MBtu/°F-day. The corresponding engineering estimate is 1.11 ($\pm$0.08) MBtu/F-day. The estimates are barely overlapping--the lower bound of the engineering estimate (corresponding to an average air infiltration rate of 0.5 ACH) equals the upper bound of the PRISM estimate. If we use the engineering estimate of building heat loss, the boiler efficiency, as given by Equation 2 is

$$\eta = \frac{1.11\ (+0.08)}{4.54\ (\pm 0.49)} = 0.24\ (\pm 0.03)$$

The estimate is the same as that obtained earlier, in spite of a discrepancy between engineering and PRISM estimates of building heat loss rate, 1.11 ($\pm$0.08) vs. 0.87 ($\pm$0.15) MBtu/°F-day. The reason is that the reference temperature (τ) estimates are different for the pre- and post-conversion periods, and the engineering estimate of annual heat loss (4698 MBtu/yr) at the pre-conversion τ of 62 °F is virtually identical to the PRISM estimate of post-conversion heating use (4605 MBtu/yr).

The steady state efficiencies of both the old boiler (reported to be operating properly at the time of the conversion) and the new furnaces would be in the 70 to 80% range. Thus the on-cycle losses of the boiler and furnaces should be comparable. The off-cycle losses of the existing steam boiler were probably much higher than those of the gas-fired furnaces, although we have no way of quantifying them.

The losses from the underground and crawlspace distribution system is a major additional loss for the old boiler. There are four types of losses--by conduction (to the ground and ambient air), by steam leaks, by condensate leaks, and by flashed steam resulting from steam traps which have failed open. The heat and hot water pipes run in the same tunnels; the steam pipes are off in the summer months. We estimate the annual heat loss from the steam and hot water pipes to be 775 MBtu/yr. Assuming a 75% steady-state efficiency for the boiler, the additional fuel use due to distribution losses could be 1,033 MBtu/yr or 8.2 MBtu/apt-yr, less than 4% of the pre-conversion NAC. Thus, heat losses through the insulated piping cannot account for the much higher energy use of the old heating system. We have no data on the condition of the steam traps prior to the conversion and thus cannot quantify loss of steam from leaky traps.

One reason the housing authority notes for replacing the old system was leaking condensate pipes. However, even if all the condensate leaked out before returning to the boiler, the resulting losses of about 19.8 MBtu/apt-yr[4] would be less than a fifth of the observed savings in NAC of 112 MBtu/apt-yr (Table II). Steam leaks, on the other hand, could account for very large heat losses, but cannot be estimated retroactively.

Our PRISM-based estimate of efficiency for the old heating system presumes that the building heat loss was unchanged by the conversion--a situation not strictly correct. Air infiltration is increased by the conversion because of penetration of the building envelope by the chimney. The increase in apartment air infiltration by the air leakage through the chimney itself is captured in our assumed efficiency of 0.64 which takes into account off-cycle losses.

The increase in building heat loss due to the conversion is likely to be small compared to its reduction by better temperature control. In the old system, the heating controls lacked apartment temperature feedback, and the boiler was probably operated to minimize cold complaints, keeping many apartments overheated. This would increase building heat loss in two ways--by higher average indoor temperatures and by increased air infiltration through windows, opened by residents to regulate overheating. The reference temperature, τ, could not be used to estimate interior temperature because (a) the building was operated without an interior-temperature thermostat before the conversion, and (b) τ was poorly determined after the conversion (67$\pm$6F, Table II).

In summary, the low estimate of boiler efficiency appears to be due to high interior temperatures (though improper control) and resulting window openings, and possibly from steam leaks and higher boiler off-cycle losses as well. Condensate leaks and conduction losses from distribution piping cannot account for a significant part of the losses.

Water heating efficiency

As noted above, the PRISM estimates of base level energy use is strictly a measure of summertime gas use. Summertime water heating can be determined by subtracting cooking gas use from the base level consumption. We estimate cooking gas use from two sources--from an analysis of US residential energy use (Meyers, 1981) and from data on cooking gas use in New Jersey public housing where it was separately metered (Englander, 1986).

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[4]For this calculation, we assume that (a) steam is raised at a boiler steady-state efficiency of 75%, so that an NAC of 211 MBtu/yr-apt corresponds to $0.75 \times 211 \times 10^3$ or 158,250 lb of steam a year; (b) the heat lost by the condensate leakage would be equivalent to raising this quantity of make up water from 55°F (cold water temperature) to 180°F, the presumed condensate temperature.

Using an estimate of cooking gas use at APV of 30 ($\pm$9) kBtu/apt-day, the summertime water heating gas use after the conversion is 86 ($\pm$30) kBtu/apt-day. With a 44% service efficiency of the new water heating system (GAMA, 1985), the post-conversion water heating load is 38 ($\pm$13) kBtu/apt-day.[5] For the same pre-conversion cooking and water heating load, and a PRISM-estimated base-level consumption of 159 ($\pm$35) kBtu/apt-day, the implied pre-conversion summertime water heating efficiency would be

$$\frac{38}{159 - 30} \quad \text{or} \quad 0.29$$

with a standard error of 0.13.

We estimate a summertime heat loss from underground piping of 8.9 kBtu/apt-day, which is only 7% of the gas used for summertime water heating and leaves a large part of the losses unexplained. Hot water leaks and boiler off-cycle losses could account for the poor efficiency. Since no measurements were made while the old system was in place, we cannot pinpoint the culprits.

Our estimates of space and water heating efficiency before and after the conversions are shown in Table III.

ECONOMICS OF THE SYSTEM CONVERSION

The reduction in normalized annual consumption, derived using PRISM is both substantial and well determined, 112 ($\pm$9) MBtu/apt-yr (Table II). The total cost of the conversion (in 1983$) was $401,054, or $3200 per apartment. Of the total, 60% was for furnaces, ducts, vents, and their installation. Plumbing which included underground gas piping, excavation, and indoor gas and hot water piping accounted for another 37%. The water heater capital cost was only 3% of the total.

At $5.60 per MBtu, the annual savings is $627/apt and the simple payback period is 5.1 years. If the lower operation and maintenance costs of the new system are considered, total cost savings are higher, making the conversion an even better investment.

ALTERNATIVE SYSTEMS

The heating and DHW systems installed at APV are some of the lowest in first cost; however, other systems have higher efficiencies. The six systems analyzed are all gas-fired and can be divided into forced air and wet systems. The forced air systems comprise (a) the <u>new</u> system actually installed, (b) a condensing furnace together with a high-efficiency

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[5]This implies a hot water consumption of about 51 gallons/day-apt, heated to 140°F from 55°F.

submerged-combustion-chamber water heater, and (c) three separate wall-mounted direct-vent space heaters and a submerged-combustion-chamber water heater. The wet systems are (a) the old central system, (b) a direct-vent high-efficiency wall-mounted boiler with baseboard convectors, and (c) an integrated space and water heating system in a package unit, with baseboard convectors. Capital costs and efficiencies of the various systems are shown in Table IV, where they are listed as "NEW", "CONDEN", "SPACE", "OLD", "WALL", AND "INTEGR" respectively.

The four alternatives to the system actually installed are quite comparable in overall efficiency[6] (0.77 to 0.82) each substantially higher than either the old system (0.25) or the new system (0.57). The costs vary significantly, however, from about $3400 for the space heater option to about $4600 for the condensing furnace option. If the space heater alternative had been installed at the time of the conversion the extra system cost of $234 per apartment would have demonstrated a 1.8-year simple payback (Table IV). Although the condensing furnace would save slightly more energy, the additional cost of $1140 per apartment relative to the space heater option would have almost a 50-year simple payback. Within the uncertainties of our analysis, the options are all equally cost effective relative to the existing system, with simple payback periods of 4.5 to 5.8 years (Table IV).

Of the alternative systems, the system actually installed has a low first cost while providing significant savings (53%) over the old system and uses conventional technology. The space heater option uses three strategically-located heaters in each apartment and enjoys a first cost advantage of $1100 to $1200 per apartment because no heat distribution is needed. With an induced-draft direct-vent design, it has a heating efficiency of about 85%. In the proposed configuration the space heaters are accompanied by submerged-combustion-chamber, storage-type water heaters with a service efficiency of 61%.

Technology under development today holds the promise of further energy savings. Pulse combustion space heaters developed by the Gas Research Institute (GRI) have demonstrated efficiencies of 92% in field tests (Thrasher and West, 1984). The best stand-alone gas water heater in our comparison has a recovery efficiency of 81% with 3.2% per hour standby losses, resulting in a service efficiency of 61% (GAMA, 1985). GRI design goals for its pulse combustion water heater calls for a recovery efficiency of 92% and 0.8% per hour standby losses, i.e. a service efficiency of 83% (Johnson, 1985), substantially better than what is available today.

CONCLUSIONS

The conversion from a central boiler to furnaces and water heaters located in each apartment saved 53% of the total gas used in the buildings,

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[6] Overall efficiency is defined in footnote i of Table IV.

at a simple payback period of about five years, not counting reduced maintenance costs. The savings appear to be the result of reduced leakage from the old heat and hot water distribution network, improved control of apartment temperatures and perhaps, reduced off-cycle losses from the heating systems.

Less-conventional high-efficiency gas equipment alternatives are economically comparable to the system installed, within the errors of the estimates. A set of three induced-draft, direct-vent space heaters together with a high efficiency water heater located in each apartment--a somewhat novel alternative--may be the most economical among currently available alternatives.

ACKNOWLEDGEMENTS

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Table I. Building transmission load calculation, Asbury Park Village.

COMPONENT	AREA (*LENGTH) ft^2 (*ft)	U-VALUE Btu / h-°F-ft^2	UA Btu / h-°F	UA*24 MBtu / °F-day
Door	3275	.33	1,091	.026
Glass				
w/storms	7029	.55	3866	.093
no storms	7029	1.10	7732	.186
Wall				
Floors 1 & 2	52909	.20	10,317	.248
Fndtn abv grd	7746	.51	3,935	.094
Fndtn blw grd*	4225	.12	493	.012
Floor	44588	.06	2,497	.060
Roof	44588	.13	5,886	.141
TOTAL			35,816	.860

Table II. Prism analysis of energy savings from system conversion

	PRE	POST	SAVINGS	% SAVINGS
Period	6/82 - 6/83	5/85 - 5/86		
No. of obs.	11	12	-	-
R^2	0.977	0.923	-	-
Reference temperature, F	62 (3)	67 (6)	-	-
Heating slope, kBtu/ F-apt-day	36 (4)	11 (2)	25 (4)	70 (14)
Base level use, kBtu/day	159 (35)	116 (30)	43 (46)	27 (29)
Normalized annual consumption, MBtu/apt-yr	211 (7)	99 (5)	112 (9)	53 (5)
Normalized heating use, MBtu/apt-yr	153 (11)	57 (10)	96 (14)	63 (5)
Base level use, MBtu/apt-yr	58 (13)	42 (11)	16 (17)	28 (30)

(standard errors shown in parentheses)

Table III. Estimates of space and water heating efficiency, before and after conversion

	PRE	POST
space heating	0.24 (0.04)	0.64
summer water heating	0.29 (0.13)	0.44

TABLE IV. Comparison of alternative systems at APV[a]

	OLD	NEW	WALL	INTEGR	CONDEN	SPACE
<u>Capital costs per apartment ($)</u>						
Heating equip.[b]	0	400	766	1374	1200	1160
DHW equip.[b]	0	100	400	0	280	280
Heating Instal.[c]	0	406	766	800	800	900
Heating distrib.	0	1200	1100	1100	1200[d]	0
DHW instal.	0	176	400[f]	100[e]	176[d]	176[d]
Gas piping	0	900	900	900	900	900
TOTAL ($)	0	3182	4332	4274	4556	3416
<u>Relative efficiencies</u>						
Heat output (kBtu/hr-apt.)	53	53	72	??	56	54
Heating efficiency[g]	0.24	0.64	0.80	0.82	0.93	0.85
DHW efficiency[h]	0.32	0.44	0.68	0.70	0.61	0.61
Overall efficiency[i]	0.26	0.57	0.77	0.79	0.82	0.77
Fuel savings[j] fraction	0	0.53	0.63	0.64	0.65	0.63
<u>Economics relative to old system</u>						
Simple payback(yrs)[k]	-	5.1	5.7	5.4	5.8	4.5
<u>Economics relative to new system</u>						
Capital cost increment ($/apt)	-	-	1150	1092	1374	234
Simple payback (yrs)	-	-	9.0	8.0	9.0	1.8

Notes (for Table IV)

(a) All costs are shown in 1983$, when the system was retrofitted.
(b) Actual costs for NEW system; for other systems, based on quoted wholesale prices when available or two-thirds list prices, and represent the estimated cost to APHA and to be installed by an outside contractor.
(c) Installation cost is assumed to equal wholesale heating unit cost.
(d) Assumed to be the same as in the NEW system.
(e) For integrated system, DHW installation is simpler and should be less expensive.
(f) Additional plumbing makes this more expensive.
(g) Based on manufacturer reported annual fuel utilization efficiency (AFUE) as listed in GAMA (1984).
(h) Service efficiencies as defined by the U.S. Department of Energy, from GAMA (1985) and ADL (1982).
(i) Average space and water heating efficiency, weighted by relative loads (36.6 and 13.9 MBtu/apt-yr) as determined in text; note that annual water heating load here is pro-rated summer value.
(j) Assumes unchanged cooking energy use of 1390 MBtu/year.
(k) Assumes gas at $5.60 per MBtu with no price escalation.

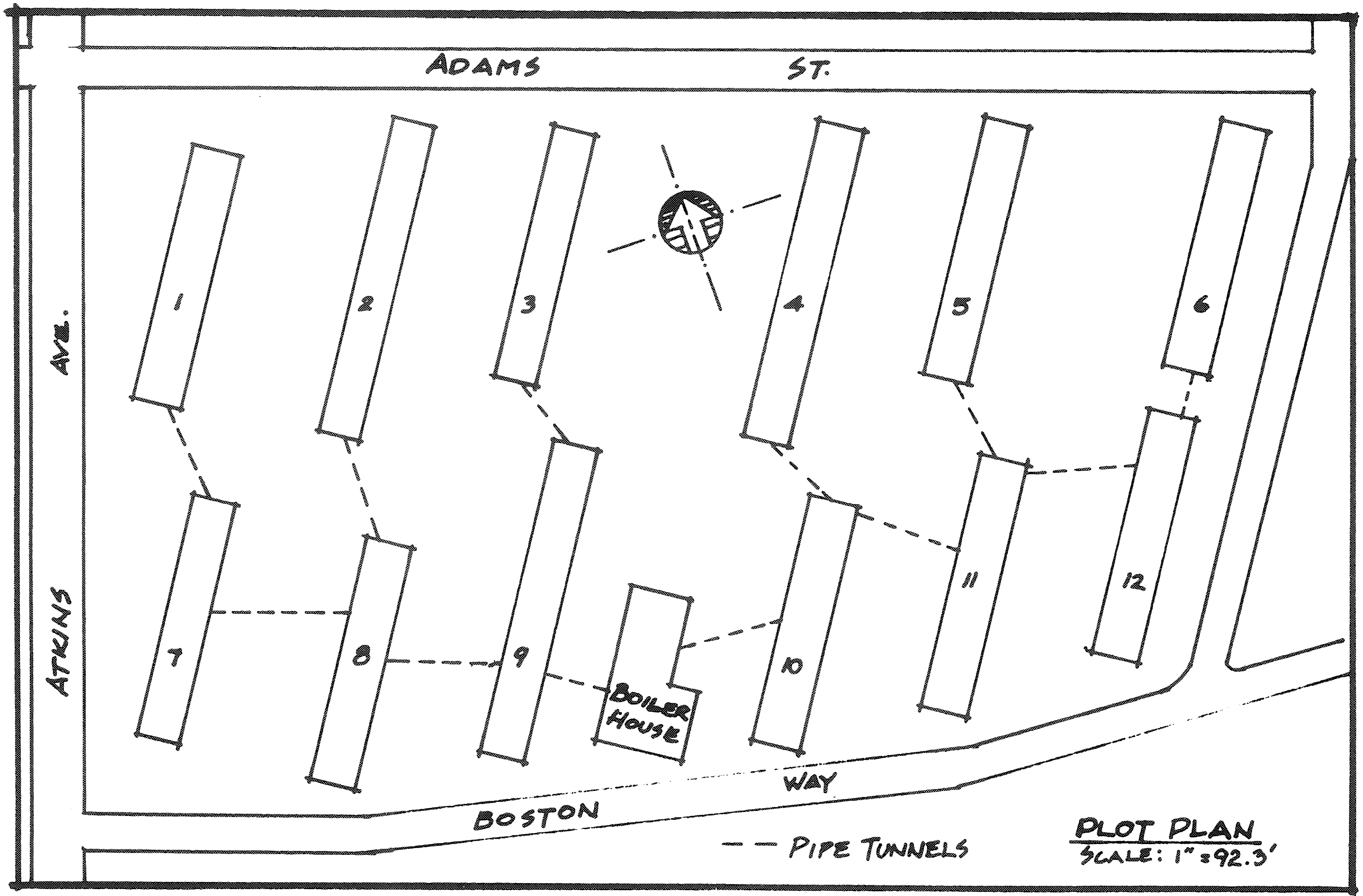
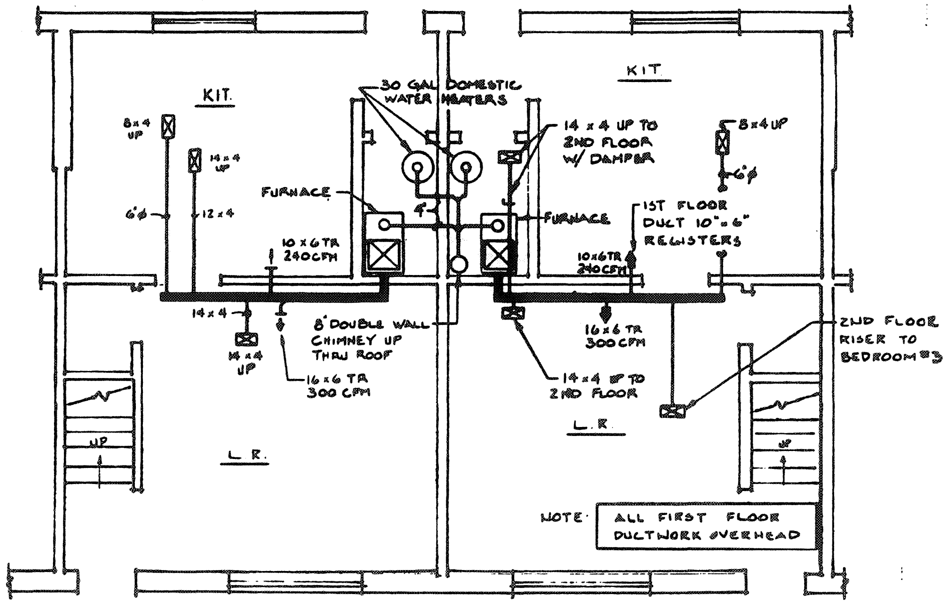
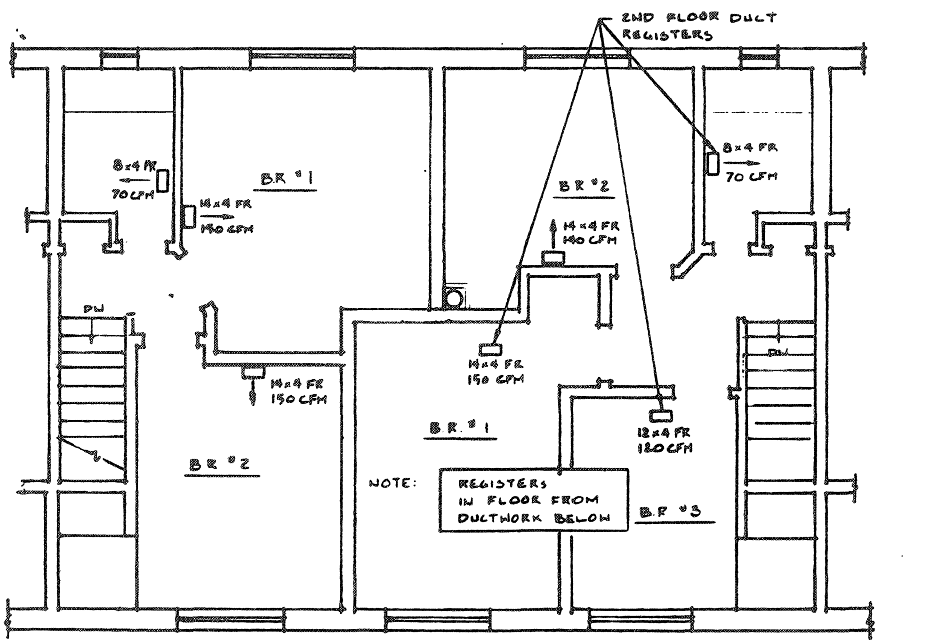


Figure 1. Plot plan of Asbury Park Village, showing pipe tunnels, through which steam, condensate return, DHW supply and DHW return lines run. Scale is actual.



FIRST FLOOR PLAN
SCALE: 7/64" = 1'-0"



SECOND FLOOR PLAN
SCALE: 7/64" = 1'-0"

Figure 2. Floor plans of a typical furnace and water heater installation in a 2-story, 3-bedroom apartment at Asbury Park Village.

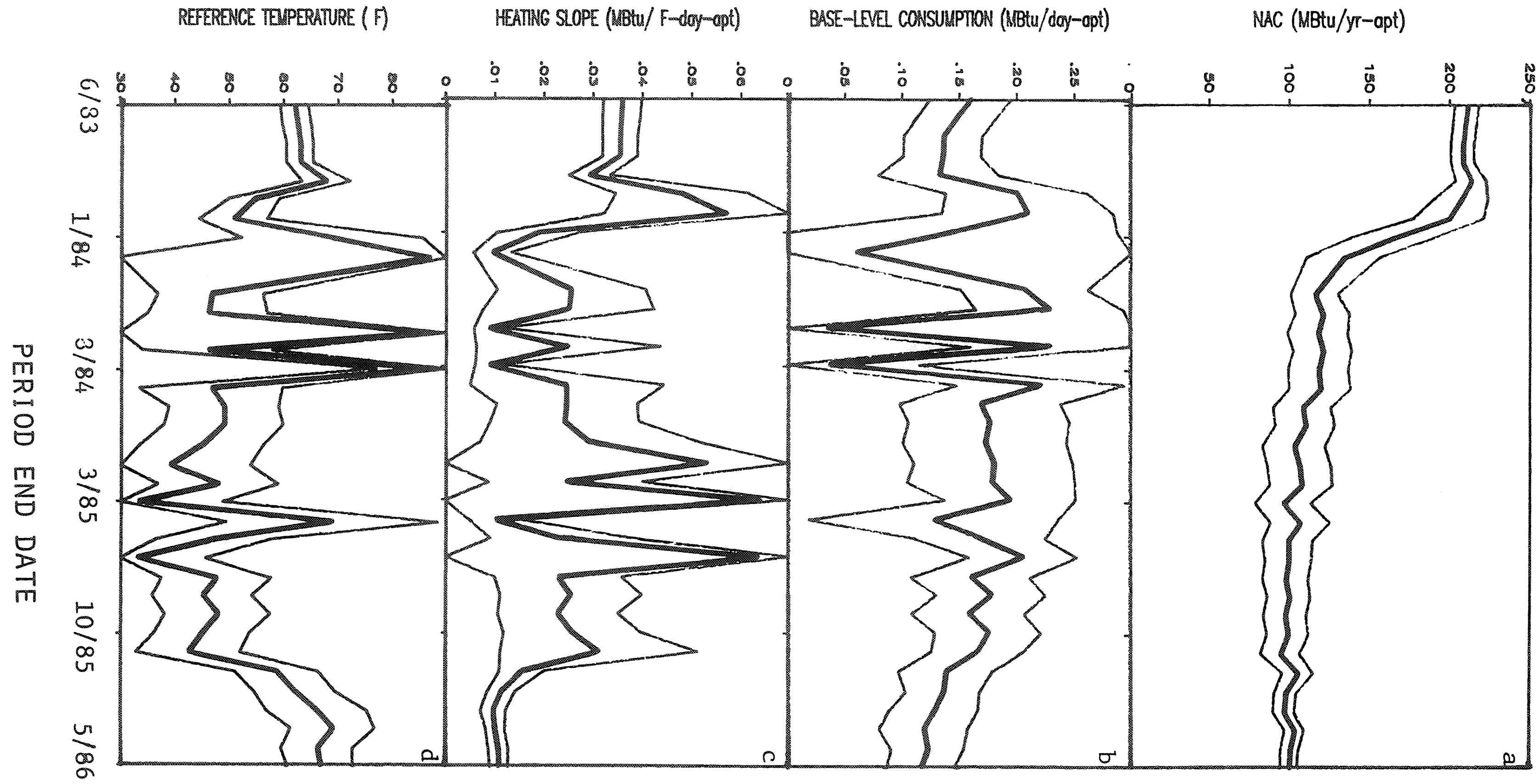


Figure 3. PRISM parameter estimate over sliding estimation periods: (a) normalized annual consumption; (b) base level consumption α; (c) heating slope β; (d) reference temperature τ. Lighter lines are standard error bounds.