

IMPROVING DIAGNOSTICS AND ENERGY ANALYSIS FOR MULTIFAMILY BUILDINGS: A CASE STUDY

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ABSTRACT

Multifamily buildings are approximately one quarter of the U. S. housing stock, consuming over two quads of energy per year, and represent a considerable potential for energy conservation. This report describes a case study in multifamily retrofit research performed by Lawrence Berkeley Laboratory (LBL) in collaboration with the city energy office in Minneapolis, MN. The basis for the case study is a one-week experiment in a seven-unit brick apartment building in Minneapolis. The experiment was to use diagnostics that are not conventionally performed in multifamily buildings to evaluate some existing and potential retrofits. The project included a detailed energy balance on the building's brick-set steam boiler and an examination of the air leakage paths throughout the building. The boiler diagnostics involved determination of jacket heat loss from surface temperature measurements, and determination of off-cycle stack loss from tracer gas and stack gas temperature measurements. The off-cycle stack loss measurements showed that a vent damper, a retrofit that restricts the flow through the boiler flue when the boiler is not operating, reduced the energy consumption of the boiler by approximately 10%. The air leakage diagnostics involved blower door tests to measure the total external leakage area, (using six blower doors to pressurize the entire building), and tests to distinguish the leakage areas of different flow paths, made by testing individual apartments with and without simultaneous pressurization of adjacent apartments. These tests show that only 40% of the leakage area of the apartments is in the exterior envelope. These leakage areas are used in conjunction with a multizone air infiltration model to determine the flows between apartments and to the outside.

INTRODUCTION

Multifamily buildings represent 27% of the U.S. housing stock and use about 2.3 quads of energy. The Office of Technology Assessment (OTA) estimates that current cost-effective retrofit technology *could* save 1.0 quad (43%) per year by the year 2000, but because of numerous barriers (both technical and non technical) only 0.3 quads (13%) of savings are likely to occur. The Department of Energy (DOE) multi-year research plan for multifamily buildings identifies case studies among the research projects that can help reduce this gap between potential and actual savings — (DOE 1985).

The case study described in this report was a collaborative effort between Lawrence Berkeley Laboratory (LBL) and the Minneapolis Energy Office (MEO). It is based on one week of intensive measurements in a seven-unit multifamily building in Minneapolis, MN. This report presents the details of the project, including a description of the experimental diagnostics, the analytical techniques, and the results of the study.

DIAGNOSTIC PROCEDURE

Intensive measurements were made for approximately one week in the seven-unit, three-story Minneapolis building. This brick building was built in 1910 and is heated with single-pipe steam. Typical of buildings built at that time, it is not insulated and has a large glazing area that was previously retrofitted with storm windows (see Figure 1). The measurements were designed as potential diagnostics for choosing appropriate multifamily building retrofits. The diagnostic procedures included measurements of the surface heat loss of the original brick-set boiler, measurements of the air leakage of each of the apartments, and measurements of off-cycle airflow and air temperature in the boiler stack. The stack measurements were made with and without the vent damper in operation, and were used to evaluate the effectiveness of the vent damper in the boiler stack (a retrofit that had been previously installed).

Boiler Measurements

Like many early twentieth century buildings, this one is heated by a large brick boiler located in a basement mechanical room (see Figure 2). Boilers like these were originally designed to burn coal and have since been retrofitted to burn natural gas. They are usually significantly oversized and have larger off-cycle and on-cycle losses than modern boilers. Our demonstration project was designed to determine the operating efficiency of this type of boiler and to investigate potential retrofits, including complete boiler replacement.

Boiler surface heat losses (jacket losses) were monitored with both temperature sensors and heat flux meters. An easy-to-install data acquisition system developed at LBL (Szydlowski 1985), was used to monitor boiler surface temperatures, boilerroom and outdoor air temperatures, and boiler on-time. Measurements were made at two-minute intervals during two-day periods. To assure that the boiler surface temperatures were representative of the entire boiler, we used an infrared camera to examine the surface for temperature

irregularities or thermal gradients. Figure 3 shows ESM installed beside the boiler, as well as two surface temperature probes and one heat flux meter installed on the boiler wall.

The boiler heat flux was also monitored on both sidewalls of the boiler with heat flux meters, as was the heat flux on one of the boilerroom walls. We recorded the outputs of these sensors with a data acquisition computer. (This data acquisition computer was normally used by MEO to monitor apartment and radiator temperatures.) During the week-long tests, this device recorded the heat fluxes, the temperature underneath the boiler, and the apartment temperatures every two minutes. (The apartment temperature measurements are not discussed in this report.)

Air Leakage Measurements

The air-leakage measurements were made with the blower door test used extensively in single-family buildings (Diamond, et al. 1982). In a single-family building this test is used to determine the effective leakage area (or the sum of the effective areas) of the leaks in the external shell of the building. The test involves pressurizing and depressurizing the building to inside-outside pressure differences between 10 Pa (0.04 in H₂O) and 50 Pa (0.2 in H₂O), and measuring the flows required to maintain each pressure difference. These measurements are then used to calculate the effective leakage area of the building shell at 4 Pa (0.016 in H₂O).

The procedure for measuring leakage areas in a multifamily (i.e. multizone) building is considerably less developed than the single-zone procedure (Shaw 1980). Because leaks from an apartment to other apartments, to the central stairwell, to the basement, as well as to the outside each have a different effect on the airflow through that apartment, they must be individually measured. In addition, even if all the apartment doors were opened to the central stairwell (approximating a single zone) to measure the total leakage of the building shell, one blower door is probably incapable of supplying the required flows.

To determine the total external leakage area of the building, we pressurized all six apartments simultaneously, using six individual blower doors, one in each apartment except the basement apartment. The doors from each apartment to the interior stairwell were opened, and the blower doors were installed in the doors to an external stairwell at the rear of the building. Because of the interaction between blower door flows, measurements had to be made simultaneously, which was accomplished with one person directing the measurements from the backyard (see Figure 4). By equalizing the pressures in all of the apartments, we could measure the flows going directly to the outside. We computed the external leakage area from the sums of flows at each pressure difference.

On an individual apartment basis, the conventional blower door test cannot distinguish between leaks in the external shell and leaks between apartments. To distinguish the leakage areas of different flow paths, we performed tests with and without simultaneous pressurization of adjacent apartments. Each apartment was pressurized by itself, with one adjacent apartment pressurized, with two adjacent apartments pressurized,

and with three adjacent apartments pressurized. The differences between the leakage areas measured for various configurations could then be used to separate the leakage areas of different paths.

Vent Damper Measurements

We used constant-flow tracer gas measurements of airflow up the stack, similar to those used to measure whole-building airflows, together with air temperature measurements, to quantify the effectiveness of the vent damper. For this test, we continuously injected Sulfur Hexafluoride (SF_6) tracer gas into the boiler air inlet while the boiler was not firing, and measured the concentration of that gas in the boiler flue. The airflows are computed directly from the measured SF_6 flow and the concentration. By measuring the concentration both with and without the vent damper closed, we determined the vent damper's effect on airflow through the boiler. In addition to measuring SF_6 concentration, we measured the temperature of the flue gas for the two vent damper positions, so we could calculate the heat loss from the boiler. By also measuring the concentration downstream of the barometric damper (which controls the flow of air from the boiler room), we determined the effect of the vent damper on airflow through the boiler room.

BOILER ENERGY BALANCE

One possible retrofit in buildings with old single-pipe steam heating systems is replacement of the existing brick-set steam boiler. These boilers are usually significantly oversized, have large standby losses, and thus have low seasonal heating efficiencies. Because of the difficulties associated with separating envelope and distribution system performance from boiler performance, energy bill analysis is not adequate for evaluating boiler replacement as an option. However, boiler surface-temperature measurements, heat-flux measurements, and stack heat-loss measurements can be used to make a detailed energy balance the boiler. Such a detailed energy balance contains the information required to evaluate both boiler retrofits and complete boiler replacement.

We used the measurements made during our week-long experiment to make a detailed energy balance on the boiler. The surface temperature measurements, along with the boiler room air temperature were used to calculate the convective and radiative heat losses from the surface of the boiler during both on- and off-cycle periods. The heat losses from the steam pipes in the boiler room were estimated from short-term measurements of their surface temperatures. We used the temperature measured on the ground underneath the boiler, along with estimates of outdoor air temperature and the groundwater temperature to determine the conductive heat losses from the bottom of the boiler. The off-cycle stack heat losses were determined from the tracer gas measurements used in the vent damper tests, and the on-cycle losses were determined from steady-state efficiency measurements made by the MEO staff.

The heat losses from the boiler surfaces were determined using simplified models of radiative and convective heat transfer, and assuming that the wall surface temperatures were equal to the boilerroom air temperature.

We found that most of the convective heat transfer occurred in the turbulent regime, so that the convective heat transfer coefficient could be expressed as (Modera 1984):

$$\bar{h}_c = K \frac{(T_s - T_a)^{\frac{1}{3}}}{\left(\frac{T_s + T_a}{2}\right)^{0.41}} \quad (1)$$

where

\bar{h}_c = the turbulent convective heat transfer coefficient [$W/m^2 K$ ($Btu/h ft^2 R$)]

T_s = the surface temperature [$^{\circ}K$ ($^{\circ}R$)]

T_a = the ambient air temperature [$^{\circ}K$ ($^{\circ}R$)]

K = a dimensional constant [$15.9 W/m^2 K^{0.92}$ ($2.94 Btu/h ft^2 R^{0.92}$)].

For several pipes, including the boiler flue, the flow is laminar. For these surfaces the convective heat transfer coefficient is (Kreith 1973):

$$\bar{h}_c = K' \left(\frac{T_s - T_a}{D}\right)^{\frac{1}{4}} \quad (2)$$

where

\bar{h}_c = the laminar convective heat transfer coefficient [$W/m^2 K$ ($Btu/h ft^2 R$)]

T_s = the surface temperature [$^{\circ}K$ ($^{\circ}R$)]

T_a = the ambient air temperature [$^{\circ}K$ ($^{\circ}R$)]

D = the characteristic length [m (ft)]

K' = a dimensional constant, [$1.14 W/m^{7/4} K^{5/4}$ ($0.27 Btu/h ft^{7/4} R^{5/4}$)].

The heat loss from the bottom of the boiler was estimated with a finite-element heat-conduction simulation program (ANSYS 1983). We made simulations using an average soil conductivity value of $1.7 W/m^{\circ}K$ ($1.0 Btu/h ft F$) which is appropriate for soils such as those in Minneapolis (MacDonald et al. 1985). The deep groundwater temperature in Minneapolis is approximately $10^{\circ}C$, and calculations were made based on an outdoor air temperature of $0^{\circ}C$ and a boiler floor temperature of $105^{\circ}C$. We also assumed that the water table was approximately 6 m (20 ft) below ground*. The simulations showed that the heat loss was rather insensitive to the outdoor air temperature, as more than 80% of the heat was lost to the groundwater.

The heat fluxes from the various surface elements of the boiler, including the steam pipes, are summarized in Table 1 for on-cycle periods and in Table 2 for off-cycle periods.

* Personal communication, Martha Hewett, Minneapolis Energy Office, Minneapolis, MN.

The results in Tables 1 and 2 indicate that the boiler surface heat losses remain relatively constant whether or not the boiler is firing. Only the temperatures of the steel plates, the boiler access, and the breeching vary significantly. The temperature variations are plotted in Figures 5 and 6 for the boiler walls, plates, and flue. However, the magnitude of the total boiler surface heat loss is rather large. When the boiler is firing it consumes approximately 375 kW (1,280,000 Btu/h), but it only fires approximately 13% of the time (from submetered data for the winter of 1982-83). This corresponds to an average energy consumption of 48.8 kW (167,000 Btu/h). The 8.2 kW (28,000 Btu/h) average boiler surface heat loss thus translates to approximately 17% of the boiler's energy consumption.

A comparison of the heat flux measured on the boiler walls and the heat flux calculated from the surface temperature measurements shows that the temperature-based calculations underestimate the heat loss in comparison with the heat flux meters. The temperature measurements determine the average heat flux to be approximately 115 W/m^2 (36 Btu/h ft^2), whereas the heat flux meters determine the average heat flux to be approximately 150 W/m^2 (48 Btu/h ft^2). This difference could result from poor thermal contact between the temperature sensors and the boiler brick, calibration errors for the heat flux meters, or inaccuracies in the simplified heat transfer models. The most likely cause for the 23% underprediction of the heat flux is poor thermal contact of the temperature sensors, as the sensors were rather large and not designed for surface mounting. Because of the underprediction, we can conclude that the heat losses determined from the temperature measurements are conservative estimates of the surface heat losses.

Steady-state efficiency measurements made by the MEO staff yielded a value of 84%, which indicates that 16% of the energy consumed by the boiler is lost directly up the stack during combustion. This is equivalent to a 60 kW (200,000 Btu/h) loss during boiler firing. As this boiler fires approximately 13% of the time during the winter season, this corresponds to an average heat loss due to on-cycle stack losses of 7.8 kW (27,000 Btu/h).

The off-cycle stack heat losses were determined from the tracer gas measurements. For this boiler operating without a vent damper, the airflow during off-cycle periods is approximately $510 \text{ m}^3/\text{h}$ (300 cfm) at approximately 94°C (201°F). This translates to a heat loss of approximately 9.5 kW (32,000 Btu/h) during off-cycle periods, or an average heat loss of 8.3 kW (28,000 Btu/h). Thus, if this boiler was not retrofitted with a vent damper, the off-cycle stack loss would be larger than the on-cycle stack loss. The stack losses, including the heat lost from the boiler room through the barometric damper, are summarized in Table 3.

The boiler's energy balance can be used to determine its overall efficiency, and to quantify the importance of the different heat loss mechanisms. The energy balance is summarized, in pie-chart form, in Figure 7. Approximately 50% of the energy consumed by the boiler is used to heat the apartments; the other 50% is lost by convection up the stack and conduction from the boiler walls. Combustion inefficiencies account for 16% of the energy consumption (on-cycle stack losses), whereas heat loss during the periods when the boiler is not supplying steam account for 34% of the energy consumption (the jacket losses represent conduction

from the boiler walls and pipes, and the off-cycle stack losses represent the heat lost by convection through the boiler and up the stack). We can compare these individual heat losses with those for modern boilers for greater certainty when comparing retrofit options.

AIR LEAKAGE AND INFILTRATION

Both the magnitude and distribution of leakage area for each apartment were determined from the multiple blower door tests. The average leakage area for each apartment was approximately 1600 cm^2 (250 in^2). The distribution of leakage for each of the apartments is shown in pie-chart form in Figure 8. The pie chart indicates that only 40% of each individual apartment's leakage was in the exterior envelope.

Although only 40% of the leakage area of the apartments was in the exterior envelope, the exterior envelope leakage was still larger than that normally found in single-family buildings in cold climates. The specific leakage area, which is the envelope leakage area normalized by the floor area, was $5.3 \text{ cm}^2/\text{m}^2$. The specific leakage area for single-family houses in cold climates normally varies between 2 and $4 \text{ cm}^2/\text{m}^2$, although it should be noted that, even in these climates, older construction tends to be leakier (Sherman et al. 1984; Lipschutz et al. 1982).

The large leakage areas *between* apartments, approximately 950 cm^2 (150 in^2), indicate that there is very little resistance to flow between apartments. To examine the effects of these inter-apartment leaks, we used the measured leakage areas as input to a multizone air infiltration model (Feustel and Kendon 1985). The model was used to simulate the airflows for different outdoor temperatures, wind speeds, and wind directions. An important subset of the flows determined by the simulations is the set of outdoor airflows into each apartment. These flows can be used to determine (1) the overall energy loss due to air infiltration, (2) the nonuniformity of infiltration heat losses and resultant uneven heating loads of apartments, and (3) the total fresh airflow through each apartment and degree of contamination between apartments, both of which affect indoor air quality.

Figure 9 shows the outdoor air infiltration for apartments on the first, second, and third floors as a function of windspeed, for wind coming from the east (i.e., the rear of the building). It shows that at low windspeeds the upper story apartments receive very little cold air and would thus have lower heating loads unless the occupants react to the lack of fresh air by opening windows. This would not be the case if these apartments were well sealed from the lower stories, as each apartment would then have its own stack effect. Under the present leaky conditions the individual apartment stack effects are dominated by the stack effect of the entire building.

Figure 10 shows outdoor air infiltration for wind from the north (i.e., the side of the building). In this case, because of resistance to flow through the building on each story, the windward and leeward apartments have very different fresh airflow rates. The leeward apartments on the upper stories receive almost no fresh air,

independent of wind speed. It should also be noted that for windspeeds above 1 m/s (2 mph), the total fresh airflow (infiltration) through the entire building is always lower for wind from the north compared with wind from the east.

The blower door tests were accompanied by inspections of the leakage sites within the building. There were many leaks between the basement and the apartments via long vertical cavities within the building. These cavities occurred in the stairwell, around steam pipes, around water and drain pipes, and inside the exterior wall cavity. Smoke sticks were used to locate leaks and assure that they did not lead into sealed cavities. As part of the demonstration project, some house doctoring was performed on the basement. We spent four hours plugging large leaks with insulation and injecting expanding foam into small cracks. This effort reduced the leakage area of the basement by approximately 20%.

VENT DAMPER PERFORMANCE

The one-week study performed in this building included a short-term test to measure the effect of the vent damper. A vent damper restricts the flow through the boiler flue when the boiler is not operating. By measuring the stack airflows and temperatures with and without the vent damper operating, we can estimate the energy impact of the vent damper.

The stack heat losses were computed for the boiler operating both with and without the vent damper. The losses without the vent damper are summarized in Table 3, and the losses with the vent damper installed are summarized in Table 4.

A comparison of Tables 3 and 4 shows that the vent damper decreases the off-cycle stack heat losses from the boiler by approximately 25% and decreases the stack heat loss from the boiler room by approximately 35%. The pie-chart representation of the boiler energy balance with a vent damper (see Figure 11) shows that the vent damper increases the useful energy delivered by the boiler from 50% to 55% of the energy consumed (compare with Figure 7). This corresponds to an approximate 9% reduction in the heating energy bill for this building. These energy savings can be compared directly with the price of installing the damper to determine its cost effectiveness.

The staff at MEO has made conventional measurements of the performance of the vent damper installed in this building (Hewett and Koehler 1985). Their measurements involved a flip-flop experiment, recording the energy consumption of the boiler with and without the vent damper in operation. The vent damper was operated on and off for one week periods, and the energy consumption of the boiler was recorded for each one-week period. After the boiler consumption was corrected for the weekly degree-days, it was found that the vent damper reduced the energy consumption by 10%. Based on the 10% energy consumption savings, MEO, computed a \$707/year savings, which, when compared with the \$850 installation cost, yields a 1.2 year payback (Hewett and Koehler 1985).

CONCLUSION

The most important conclusion to be drawn from this case study is that the diagnostics performed in this building provided a picture of the energy consumption of the building that could not be obtained by simply examining the energy bills. The boiler measurements determined the net operating efficiency, as well as pinpointing and quantifying the magnitude of each of the heat loss mechanisms. The blower door tests gave a picture of the airflow through the building, which aids in evaluating air leakage retrofits, balancing the steam distribution system, and evaluating possible indoor air quality problems that could lead to occupant actions such as opening windows. In addition, the stack-flow measurements determined in four hours the effectiveness of the vent damper; this effectiveness was confirmed with long-term conventional measuring techniques.

As far as the blower door measurements are concerned, we needed over 400 individual data points to determine *all* the multizone leakages. Even under ideal circumstances this procedure requires several researchers and takes all day. In this demonstration project, the occupants were very cooperative; such cooperation cannot generally be expected. Although our test provided the desired result, the manpower requirement pointed out the need for better leakage diagnostics for multifamily buildings.

Essentially equal savings from the vent damper were measured by two independent test methods. This result is encouraging because it increases our confidence in both measuring techniques. However, the most encouraging conclusion to be drawn from this comparison is that the short-term measurement, which took approximately four hours from start to finish, reproduced the results of the two-month study of vent damper performance.

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TABLE 1 Boiler Surface Heat Loss (On-Cycle)			
Surface	Area [m ² (ft ²)]	Temperature [°C(F)]	Heat Loss [W (Btu/h)]
Boiler Sides (brick)	20(210)	36.5(98)	2300(7900)
Boiler Top (brick + concrete)	9(97)	37(99)	1100(3800)
Boiler Floor	8.2(88)	105(221)	940(3200)
Boiler-Top Access	0.96(10)	132(270)	1300(4400)
Breeching and Flue	4.0(43)	60(140)	1600(5500)
Steel Plates (e.g. doors)	3.6(39)	52(126)	1200(4100)
Steam Pipes	7.5(81)	44(111)	1600(5500)
Total	32(360)	n/a	10,000(34,000)

TABLE 2
Boiler Surface Heat Loss (Off-Cycle)

Surface	Area [m ² (ft ²)]	Temperature [°C(F)]	Heat Loss [W (Btu/h)]
Boiler Sides (brick)	20(210)	36.5(98)	2300(7900)
Boiler Top (brick + concrete)	9(97)	37(99)	1100(3800)
Boiler Floor	8.2(88)	105(221)	940(3200)
Boiler-Top Access	0.96(10)	60(140)	700(2400)
Breeching and Flue	4.0(43)	40(104)	600(2000)
Steel Plates (e.g. doors)	3.6(39)	41(106)	630(2200)
Steam Pipes	7.5(81)	44(111)	1600(5500)
Total	32(360)	n/a	7900(27,000)

TABLE 3
Stack Heat Losses (without Vent Damper)

Loss	Air Flow‡ [m ³ /h] (cfm)	Instantaneous Heat Loss [W] (Btu/h)	Average Heat Loss* [W] (Btu/h)
On-Cycle [Boiler]	n/a	60,000 (200,000)	7800 (27,000)
Off-Cycle [Boiler]	510 (300)	9500 (32,000)	8300 (28,000)
Off-Cycle↓ [Boiler Room]	1400 (830)	11,000 (37,000)	9400 (32,000)

* Assuming that boiler fires approximately 13% of the time during heating season.

↓ Heat required to bring outdoor air to boilerroom air temperature, assuming average heating-season temperature of 0°C (32F). Average outdoor temperature between October and April is -1.7°C (29°F), from NOAA 42-year averages.

‡ Volume flowrates at local temperatures.

TABLE 4
Stack Heat Losses (with Vent Damper)

Loss	Airflow‡ [m ³ /h] (cfm)	Instantaneous Heat Loss [W] (Btu/h)	Average Heat Loss* [W] (Btu/h)
On-Cycle [Boiler]	n/a	60,000 (200,000)	7800 (27,000)
Off-Cycle [Boiler]	340 (200)	7100 (24,000)	6200 (21,000)
Off-Cycle↓ [Boiler Room]	490 (290)	7300 (25,000)	6400 (22,000)

* Assuming that boiler fires approximately 13% of the time during heating season

↓ Heat required to bring outdoor air to boilerroom air temperature, assuming average heating-season temperature of 0°C (32F). Average outdoor temperature between October and April is -1.7°C (29F), from NOAA 42-year averages.

‡ Volume flowrates at local temperatures.



Figure 1. Exterior view of building

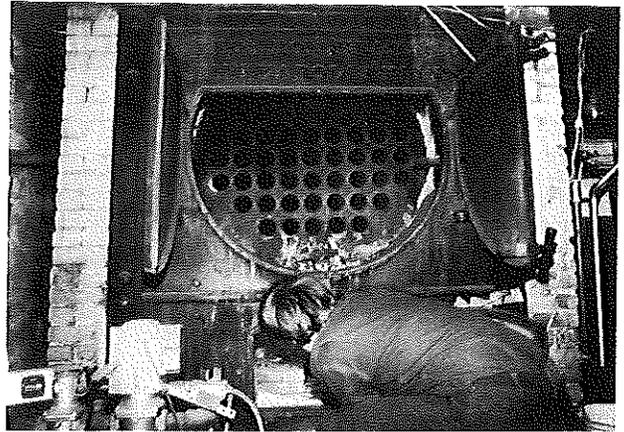


Figure 2. Large fire-tube boiler

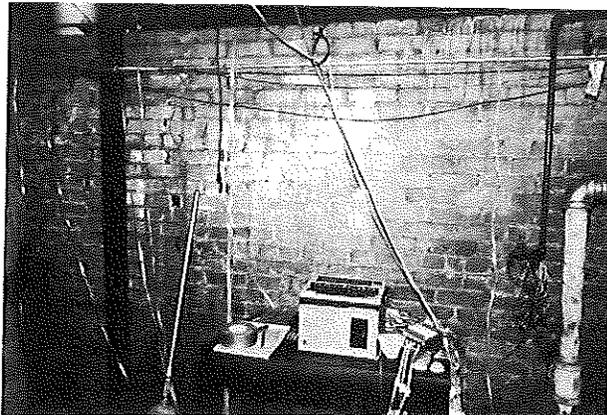


Figure 3. Energy signature monitor (ESM) installed beside boiler



Figure 4. Six blower doors used to depressurize entire building

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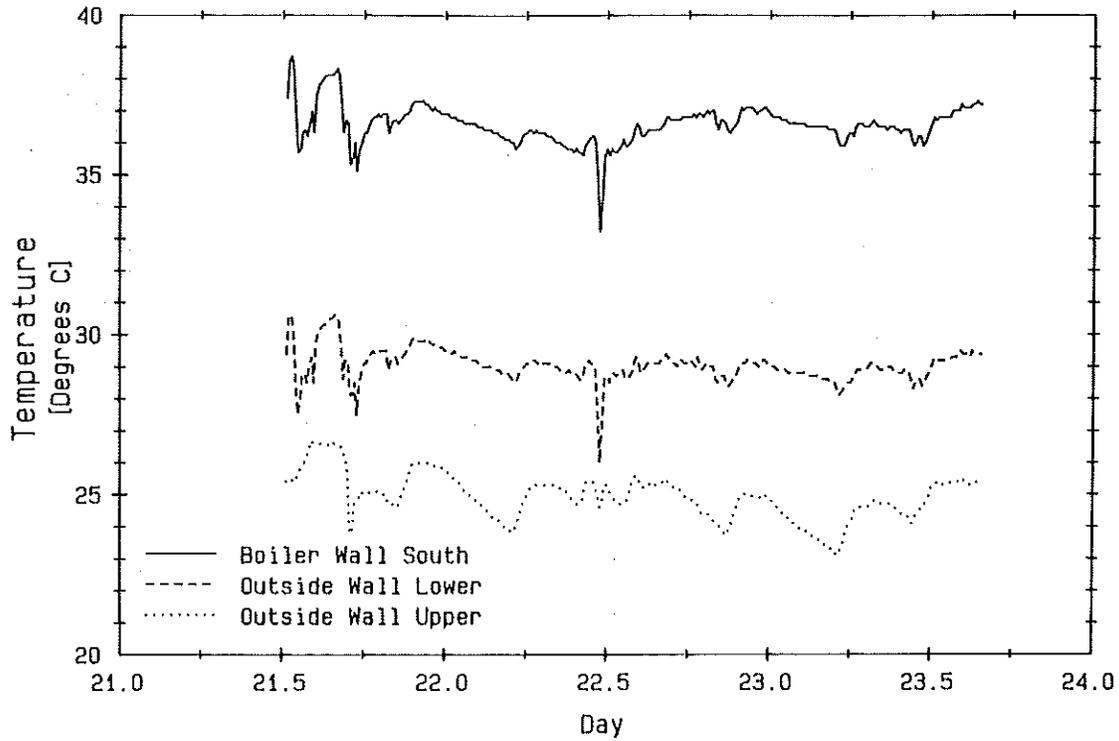


Figure 5. Variation in brick boiler wall temperatures

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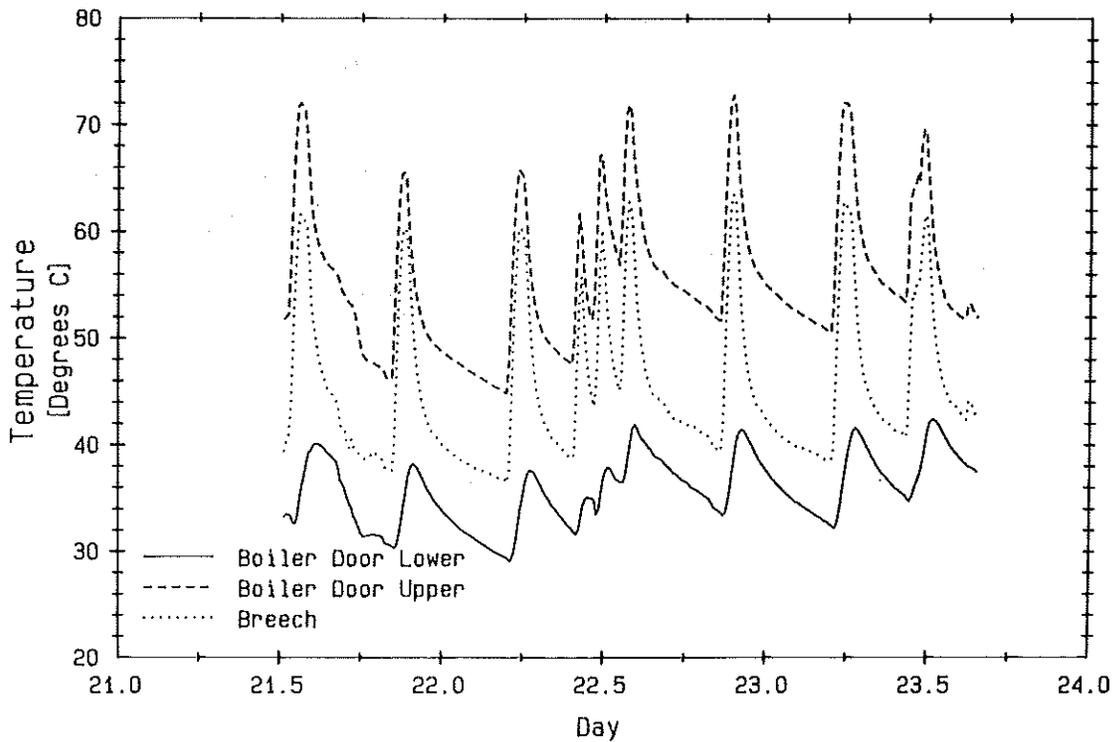


Figure 6. Variation in steel boiler surface and flue temperatures

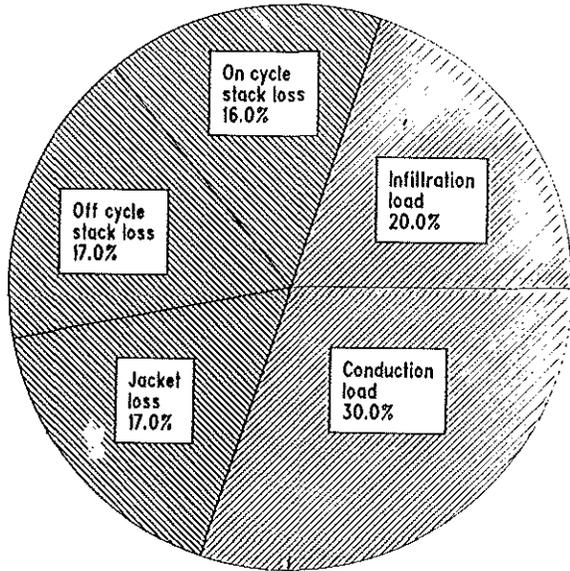


Figure 7. Boiler energy balance without vent damper

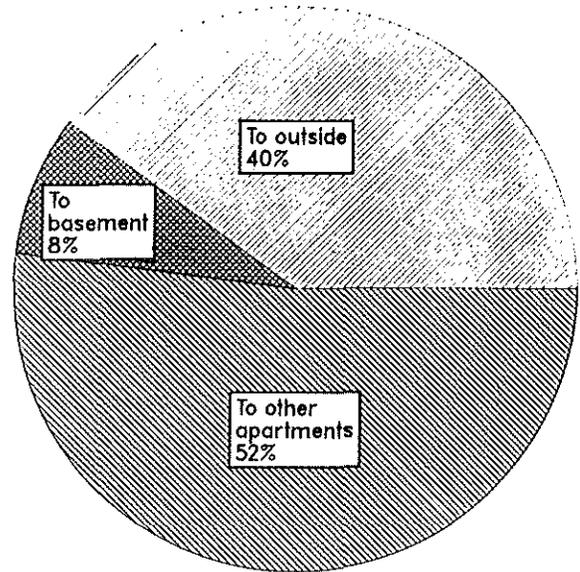


Figure 8. Leakage area of one apartment

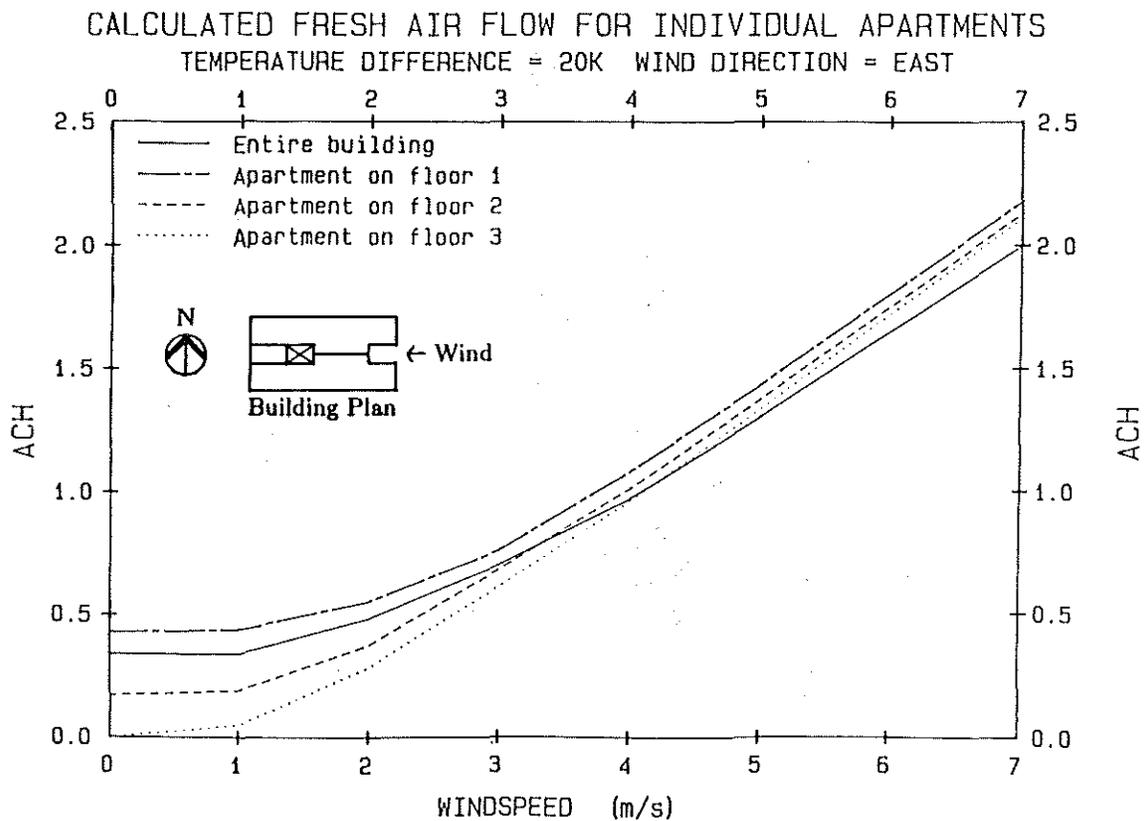


Figure 9. Outside airflow into each apartment as a function of windspeed for wind from the east

CALCULATED FRESH AIR FLOW FOR INDIVIDUAL APARTMENTS
 TEMPERATURE DIFFERENCE = 20K WIND DIRECTION = NORTH

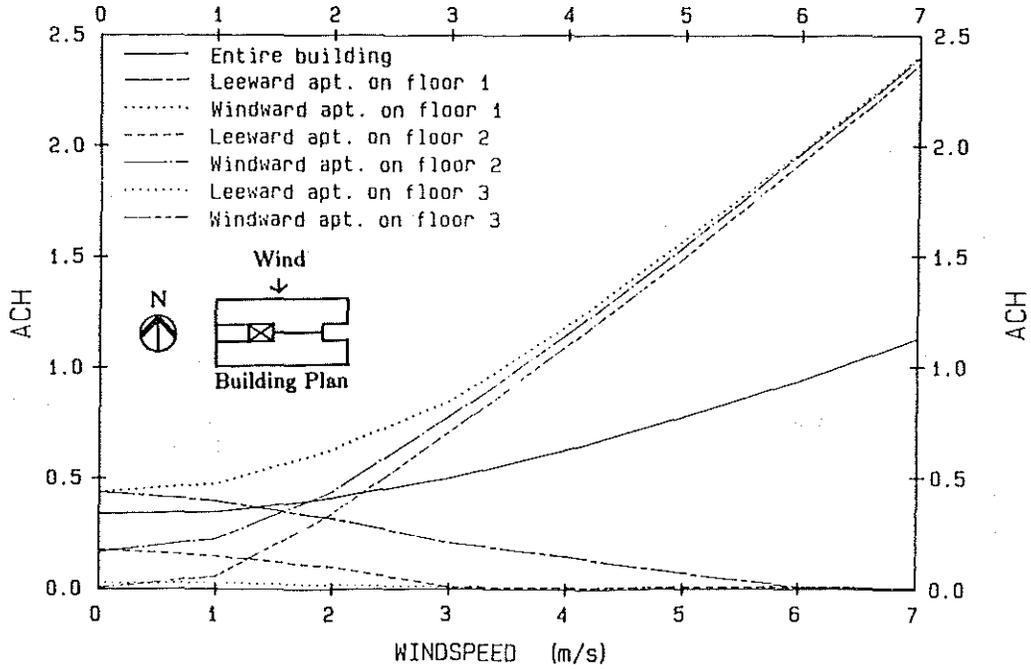


Figure 10. Outside airflow into each apartment as a function of windspeed for wind from the north

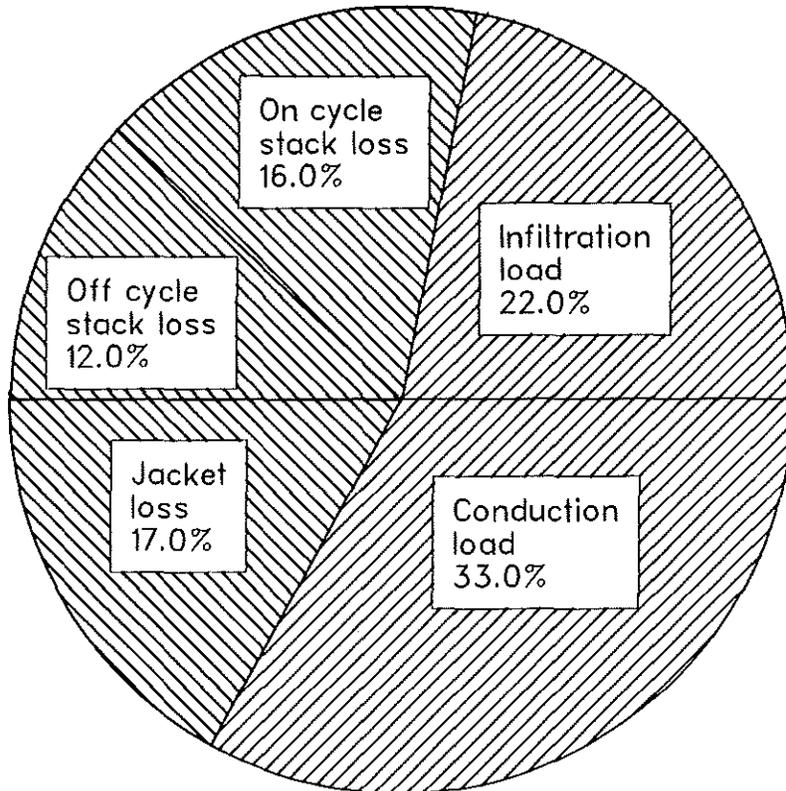


Figure 11. Boiler energy balance with vent damper