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Instrumentation for Monitoring Energy Usage in Buildings at Twin Rivers

DAVID T. HARRJE

Center for Environmental Studies and Dept. of Aerospace and Mechanical Sciences, Princeton University, Princeton, N.J. 08540 (U.S.A.)

RICHARD A. GROT

Center for Building Technology, National Bureau of Standards, Washington, D.C. 20234 (U.S.A.)

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The measurement systems used at Twin Rivers for determining energy usage are described. These include a weather station, three different systems for the measurement of temperatures and energy-related events in a house, automated devices to measure the air infiltration rate, and infrared thermography. Each of these systems played a role in assessing the actual usage of energy in individual buildings, in identifying the factors that determine energy consumption, and in checking the accuracy of theoretical models for predicting the energy performance of dwellings.

INTRODUCTION

Early in the project at Twin Rivers it became evident that there was little actual data on many of the important factors that affect the energy consumption of an occupied dwelling. Though it was well recognized that air infiltration was one of the major sources of heat losses in buildings, very little actual measurement of air infiltration had been made and the instrumentation to make this measurement in a non-obtrusive manner such that normal dwelling usage could continue during the test did not exist at the beginning of the project. Within a house the occupant can perform many actions, such as opening doors and windows, turning on vent fans, adjusting the thermostat, and operating appliances, which can significantly affect the energy requirements of the family.

The performance of the heating and cooling system is usually given by laboratory tests at steady-state conditions, and there has always been some question as to the actual performance of this equipment, especially under partial loads and transient operation. The assessment of energy conservation strategies, such as increasing the amount of insulation in a dwelling, adding storm windows, caulking, or night set back of the temperature, usually assumes an understanding of the heat loss mechanisms existent in built dwellings, and very little had been done to verify the nature of the losses and their relative importance.

The systems described in this article consist of a remote weather station, a data acquisition system, sensors for determining the detailed response of three townhouses, an event-activated rapid scan system for determining the real time response of the dwelling and its mechanical system, a data system that was deployed in a sample of thirty-one dwellings in order to obtain a more detailed statistical pattern of the important parameters affecting energy consumption, a tracer-gas-based air infiltration measurement system capable of operating unattended for a period of a week, and infrared thermography for localizing heat losses in the building envelope in a rapid, non-contact manner. We will not describe the considerable laboratory instrumentation and field checkout instrumentation that we have also used. It is to be understood that such instruments as hot wire anemometer probes and heat flux probes added directly to our knowledge of the houses and the systems under investigation, and that special oscilloscopes, counters, and checkout circuits were used to insure that the field equipment was operating properly and to diagnose difficulties when they occurred.

TABLE 1

Channels Monitored in the Weather Station
(data recorded hourly)

Outside humidity — dewpoint
Outside temperature
Wind speed averaged
Wind speed instantaneous
Wind direction
Solar flux — total
Solar flux — shaded
Solar flux — west*
Solar flux — east*
Rainfall
Ground temperature*
Barometric pressure
System voltages

*Obtained for limited time periods.

TABLE 2

63 Channels monitored in the three highly-instrumented townhouses*

(scan every 20 minutes onto magnetic tape in Energy Laboratory at Princeton)

1	Thermostat setting
2	Basement temperature
3	First floor temperatures — 6 total
4a	Second floor temperatures — 3 total
4b	Attic temperature
5a	Furnace gas consumption or air conditioner electricity consumption
5b	Furnace fan on-time
5c	Duct flow rates — 9 total
5d	Supply and return flow rates — 4 total
5e	Register temperatures — 9 total
5f	Supply and return temperatures — 4 total
5g	Supply and return humidity — 2 total
6a	Water heater electricity consumption
6b	Electric range electricity consumption
6c	Electric dryer on-time
6d	Electric refrigerator on-time
7a	Front door open-time
7b	Front living room window open-time
7c	Front bedroom window open-time
8a	Back door open-time
8b	Back bedroom No. 1 window open-time
8c	Back bedroom No. 2 window open-time
8d	Basement door open-time
8e	Bathroom vents open-time — 3 total
9a	Total electricity consumption from lighting and 110 V appliances
9b	Voltage level, townhouse and system — 4 total
10	Hot and cold water temperature

*Numbering system conforms to Table 3, and indicates roughly how we have "collapsed" channels in the Omnibus houses.

DATA SYSTEMS FOR WEATHER AND FOR HIGHLY-INSTRUMENTED TOWNHOUSES

Similar data acquisition systems were used to process data from the weather station and from the first three townhouses instrumented in our program. One basic twenty-channel data acquisition system was used for the weather station, and another was expanded to 200 channels to accommodate the large number of channels desired in the three (adjacent) townhouses. Data from both systems were sent over telephone lines to our Energy Utilization Laboratory at Princeton University and were recorded on a magnetic tape recorder and a teletypewriter. The taped data were batch processed by computer, while the teletypewriter output was scanned several times a day for quality control. The importance of quick scanning cannot be overemphasized; without it one is certain to lose considerable data from local power interruption or other system malfunction.

The channels monitored in the weather station are listed in Table 1 and those monitored in the highly instrumented townhouses (HIT) are listed in Table 2. When both data systems were on line, the townhouse data were logged every 20 minutes, the weather station once an hour. When weather data alone were transmitted, a 20-minute interval was chosen to give further detail.

The data acquisition system provides channel sensitivity of either 0.1, 1.0, or 10 mV, with a range equal to about 2000 times the sensitivity. Thus, considerable latitude was possible in choosing individual sensors. Several sensors are shown in Fig. 1.

In both the weather system and the HIT system, temperatures were measured with

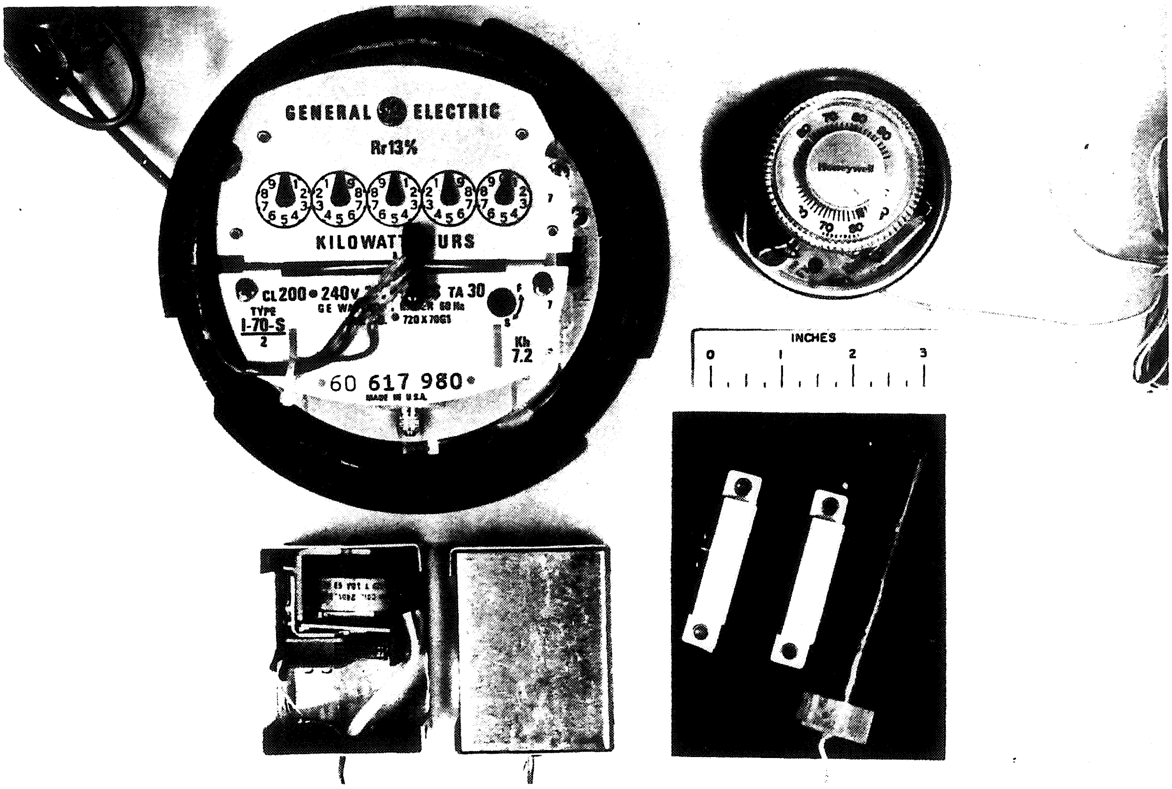

Fig. 1. Sensors. Clockwise from upper left: adapted Wh meter, adapted thermostat, thermistor, magnetic switches, dual water-heater relays.

linearly compensated thermistors, which were chosen because they give the desired voltage output and are small, accurate, and relatively inexpensive. (Figure 1 shows a mounted model.) In both systems, humidity was measured via dual-bobbin moisture sensors. This approach to measuring temperature and humidity required a well-regulated voltage source, whose level was also recorded.

Other approaches to measurement were closely parallel in the HIT system and the weather system. Both the average rate of air flow in ducts and the average wind velocity were measured using digital counters and digital-to-analog converters. The rotations of a cup anemometer were added over the counting interval, as were the rotations of a spinning disk mounted in the duct that chopped a light beam in an optical switch. This addition resulted in a proportional build-up of voltage on a counter card, with recycling each time the level reached 10 V. Similarly, both instantaneous flow rates in ducts and instantaneous wind velocity were measured by reading the anemometer output as a pulse rate on three-to-a-card tachometers. The instantaneous wind velocity (useful for detection of gusting) was obtained by having a three-cup anemometer drive a direct current generator. The methods of recording thermostat setting and wind direction were also closely related. We built an internal linear potentiometer into a standard home thermostat (see Fig. 1), so that output voltage was linearly related to temperature setting. The wind direction, similarly, determined a potentiometer setting through the rotation of a weathervane.

The remaining weather sensors were: (1) a rain gauge of the tipping bucket type, which sent a record of each tip to the counter card (the same approach was also used to measure air conditioner condensate); (2) solar flux meters for both total and shaded solar flux (either a temperature-compensated solarimeter or a pyranometer) whose millivolt output was stored over time on a digital volt–time integrator, and (3) a transducer for measuring barometric pressure.

A large number of sensors for the highly-instrumented townhouses measured the duration of specific events. To measure the "on-time" of appliances such as refrigerators and clothes dryers, switches were inserted at the power supply that were activated at a set level of current. (For example, the current demanded by the compressor was monitored at the refrigerator.) The switch energized a small synchronous motor within the instrument package, which turned a potentiometer at a constant rate so that voltage increased linearly with on-time. The potential difference from one reading to the next provided an accurate measure of appliance energy consumption in the interval, for those appliances whose energy use is dominated by a mode of operation that draws power at a constant level. This simple and inexpensive technique was trouble-free when care was taken to assure good contact at the wiper of the potentiometer. To measure the "open-time" of windows and doors, standard burglar alarm switches were used to energize motors similar to those used for the constant-power-output appliances (see Fig. 1).

To measure the energy consumption of appliances, like the range, that operate at variable power output, standard Wh meters were used, modified so that a switch was tripped as the Airy disk spun inside the meter. Optical switching was found to be preferable to mechanical switching, the latter becoming unreliable after many contact closures (see Fig. 1). Counting and digital-to-analog conversion were accomplished by methods similar to those used to record air flow rates. A bank of five standard Wh meters in each house permitted the monitoring of four appliances plus the total electric consumption for the house. A similar modification of the standard gas meter provided the measurement of gas consumption by the furnace.

Further details of these systems are found in early reports from our program [1, 2].

DATA SYSTEM FOR FAST READOUT IN HIGHLY-INSTRUMENTED TOWNHOUSES (RAPIDSCAN)

A second data acquisition system (Rapidscan) was installed in one of the three highly-instrumented townhouses, (and, subsequently, in other townhouses) that had two additional capabilities not present in the system described in the previous section. First, it was much faster, capable of sampling 20 data points per second; its 100-channel capacity was matched to the 63 sensors in the highly-instrumented townhouse (see Table 2, above) and could therefore acquire a complete townhouse profile in about five seconds.

Secondly, the signal conditioning package allowed data collection in both an event-activated mode and at a definite interval. Up to 16 distinct events were able to activate a read-out from the townhouse sensors; events used at Twin Rivers included changes in front door position (open or closed), changes in refrigerator operation (compressor on or off), and changes in furnace operation (main gas valve open or closed). The event was identified through dedication of two eight-bit channels and binary encoding. A record of the day, hour, minute, and second was also stored. The interval for standard data acquisition was adjustable from 5 seconds to 1 hour, but it was normally set at 1 minute. Output was recorded on seven-track magnetic tape in the townhouse.

A fast-readout system has been particularly useful in understanding the furnace operation, which is characterized by a firing cycle of 3 to 10 minutes *on* and 40 to 10 minutes *off*, depending on the weather. The cycles of duct temperatures and room air temperatures are remarkably stable over time, until one either changes the mode of furnace operation (for example, from intermittent to continuous fan), or adds insulation to the ducts, or otherwise retrofits the house [3].

DATA SYSTEM FOR LIGHTLY-INSTRUMENTED (OMNIBUS) TOWNHOUSES

A less sophisticated data acquisition system was required, once we decided to monitor a larger number of townhouses before and after retrofitting. The Omnibus instrumentation packages shown in Fig. 2 were developed to meet this need, based on a few sensors similar to those deployed in the highly-instrumented townhouses discussed above, but recording output as pulses on a slowly moving magnetic tape. The recorder was the four-channel Westinghouse WR-4C demand meter widely used by utilities, one channel of which is used to mark 15-minute intervals. The data processing facilities of Public Service Electric and Gas Company were used to count the pulses on the three data channels contained in every 15-minute interval, with output (number of counts) recorded on magnetic tape.

a thermal switch was placed in the flue that activated with heating; for the gas furnace and electric air conditioner, the switch responded to a signal from the control transformer. The temperature setting on the thermostat was monitored using the built-in potentiometer described above.

Further details of the Omnibus data acquisition system are found in an early report [2].

MEASUREMENT OF AIR INFILTRATION

In collaboration with the National Bureau of Standards, we have brought an automated unit for the measurement of the air infiltration rate in houses through successive stages of development. The device is based on standard methods of leak detection. We inject a tracer gas (sulfur hexafluoride, SF_6) into the house and sample its concentration periodically. The detection method is based on the electron absorption properties of SF_6, and a gas chromatographic column is located upstream from the electron absorption measurement to separate SF_6 from oxygen, which is also an electron absorber. The output, therefore, is two temporally separated sharp dips (negative spikes) in current across the absorber; the dip due to oxygen saturates the system but the device is calibrated so that the falling SF_6 concentration shows up as dips of

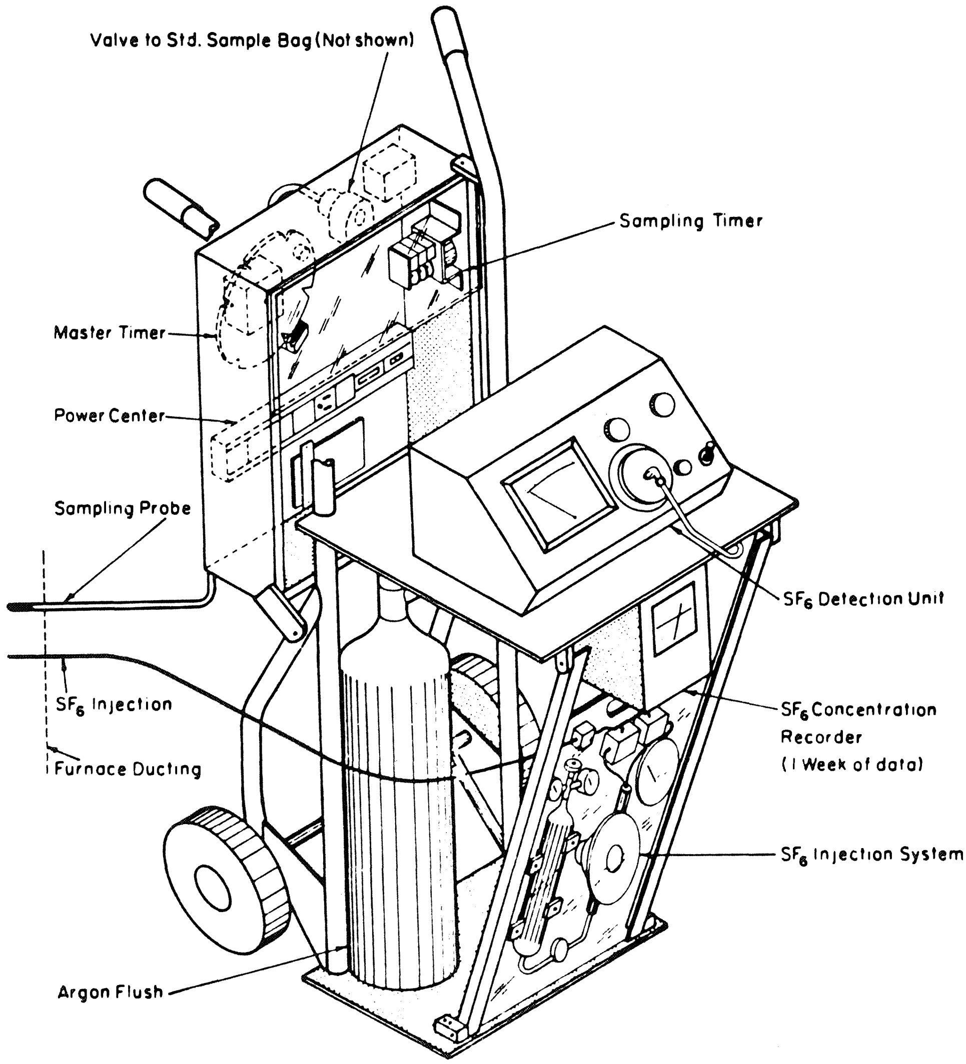

Fig. 4. Automated air infiltration unit — Mark II.

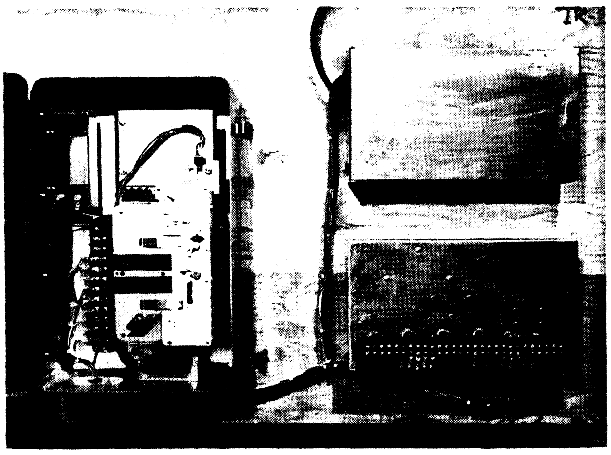

Fig. 2. Omnibus instrumentation package.

TABLE 3

Channels monitored in the lightly-instrumented (Omnibus) townhouses

Channels 1 - 8 are recorded hourly, and channel 9 is recorded at 15 minute intervals.

1	Thermostat setting
2	Basement temperature
3	First-floor temperature
4	Second-floor temperature
5	Furnace on-time or air conditioner on-time
6	Electric water heater on-time
*7	Front door or front window open-time
*8	Back door or back window open-time
**9	Total electricity consumption

*The measurements of channels 7 and 8 were combined to channel 7, and the free channel 8 was assigned to attic temperature just prior to the 1976 winter.

**As the study progressed the need for additional attic temperatures and/or flow measurements became evident in certain homes. Four measurements then replaced the total electric consumption channel.

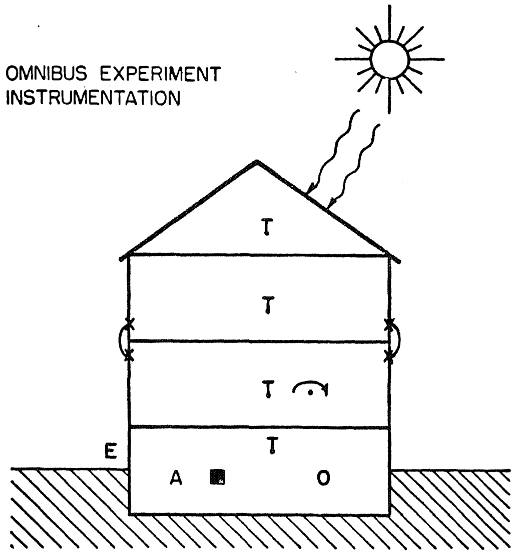

Fig. 3. Location of Omnibus instrumentation.

Confronted with the requirement of 12 pieces of data per hour, we multiplexed the three data channels so that four different sensors could be read every hour. The channels monitored, listed in Table 3 and located spatially in Fig. 3, reflected a variety of considerations and compromises; one temperature measurement per floor was judged sufficient, based on readings in the highly-instrumented townhouses. Duct temperatures, duct flow rates, and appliance usage rates were abandoned, as of secondary importance — except for the water heater, whose direct and indirect role in total energy use stands out dramatically. Total "open-time" of doors and thermostat setting were retained in recognition of their interest to those studying resident behavior.

Outputs of the sensors that are shown in Fig. 1 were transformed into pulses through resistance-controlled oscillators contained in integrated circuit chips. Temperatures from basement to attic were measured using uncompensated thermistors whose resistance varies with temperature. Door "open-times" were recorded using the motor-potentiometer arrangement described previously. The energy consumption of furnace, water heater, and air conditioner was also recorded as an "on-time", thus departing from the approach of using modified utility meters, adopted in the highly-instrumented townhouses and described above. The measurement of "on-time" of the electric water heater was based on a relay (shown in Fig. 1) that snapped on when power was consumed; for the gas water heater, steadily decreasing magnitude over time. Between samplings, the device is continuously flushed with argon.

Initial concentrations of SF_6 of about 30 parts per billion are achieved through the injection of roughly 10 cm^3 of SF_6 into a central duct of the forced air distribution system of the house, the concentration within the house becoming uniform after not more than 15 minutes. Average house concentrations are measured by sampling from the return duct of the forced air system, with the fan kept in the mode of continuous operation throughout the experiment. Typical air exchange rates, λ, for a house run from 0.5 to 1.0 exchange per hour, where λ is defined by $dC/dt = -\lambda C$, C being the concentration at time t. A house exchanging air at $\lambda = 1.0$ exchange per hour, therefore, loses 95% of its SF_6 in three hours ($0.95 = 1 - e^{-3}$). Reinjection of SF_6 every three hours has been a standard mode of operation.

The Mark II device [4] is shown in Fig. 4. A mechanically activated timer accomplishes sampling every 15 minutes and injection every three hours. Output current is recorded on a roll of paper on a chart recorder. The Mark III device, in operation since 1975, has solid state timing, permitting both the injection interval and the sampling interval to be varied [5]. The output of the Mark III device is digitized and recorded on a magnetic tape cassette. The digital data are also displayed, permitting immediate data reduction in the field.

Both the Mark II and the Mark III devices normally operate for an entire week without attention. At the end of the week, the SF_6 and the argon are replenished and the cassette or chart paper is replaced. At such low SF_6 concentrations, accidental discharge of an entire week's supply of SF_6 presents no health hazard.

INFRARED THERMOGRAPHY

An infrared camera owned by the National Bureau of Standards has been used frequently at Twin Rivers both inside and outside the houses. The camera has a 25-degree angle lens and both a black-and-white and a ten-color monitor. When surfaces of uniform infrared emissivity are examined, the monitor gives immediate qualitative evidence of structural defects through its vivid display of cold and hot surfaces. Used in conjunction with contact probes of surface temperature, the infrared camera is on its way to becoming a quantitative tool as well.

Among the defects identified by infrared thermography have beem missing or poorly installed insulation, problems at corners, around windows and doors, around closets, and at the points between framing and masonry. The infrared cameras have also given useful information about heat losses from ducts in walls and from vents and flue, and about the degree of penetration of outside air into the space between the sheetrock side walls of the living area and the masonry fire wall between adjacent units. Some photographs in black and white are found in a recent summary report [3]. Color photographs that document the changes associated with retrofit in several townhouses are found in another report [6].

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