Instrumenting Energy Audits

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ABSTRACT

This report is concerned with increasing the accuracy and thoroughness of energy audits of buildings by the use of specialized instruments and improved audit techniques. Although the emphasis is on the residential sector, certain of the evaluation methods directly apply to high-rise buildings. Air infiltration measurements are a key item in the audit procedures. Use of infrared scanning with pressurization techniques allows rapid discovery of major energy loss sites; bypasses involving both building envelope and interior structure. Portable equipment such as the blower door speed these procedures. Sensitive temperature measurement probes quantify information. An appliance consumption meter adds needed data together with heating/cooling efficiency evaluation. Emphasis throughout the audit is to make optimum use of past utility records. By adding questionnaires and simple air infiltration surveys (SF_6 plastic bottle sampling), the highest priorities for retrofitting may be quickly assessed.

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INTRODUCTION

The question of inspection and evaluation of both new and existing U.S. housing with regard to energy consumption becomes increasingly important as oil supplies are limited and energy costs soar. However, the complexity of the energy audit directly affects what methods can be economically employed. The fact that only 2% of the U.S. housing is constructed each year, places heavy emphasis on acquiring individual energy use data on the 98% of existing homes. These homes offer a different set of constraints to the energy audit process compared to new construction.

This report emphasizes energy audit techniques that can be employed to investigate both existing and new housing. At times the evaluation will fall short of defining the energy consumption precisely, however, the relative importance of each energy item will be emphasized in the test procedures. Application of the tests to more complex buildings will also be described.

The emphasis throughout the report will be on detection and evaluation of the energy consuming construction and building use shortcomings, with the goal of appropriately correcting these items.

Discussion of the level of training necessary to perform the testing will be addressed since we are considering roles for the homeowner as well as the professional in the energy audits.

The instrumentation of homes for studying energy utilization can be subdivided into two major types:

1. The "House Doctor Kit" type of instrumentation for generalized short-time surveys.
2. Data collection systems for highly-instrumented homes for detailed and for long-term surveys.

With the first goal in mind we have designed "House Doctor Kits."

1. The "Homeowner's Kit". This is a group of low-cost, semi-precision, simple instruments that can be used by the average homeowner. The kit would allow the owner to make a rough survey of the house over a period of a weekend or so, and the kit might possibly even be rented. The instruments should be simple, easy to operate, direct reading and of reasonable accuracy.
2. The "Expert's Kit". This is a group of more specialized, precision instruments of moderate cost requiring training to use. This kit would enable a team of "experts" to make a more detailed survey on a house in a fraction of a day.

SECTION I

ENERGY RECORDS OF PAST USE

In the study of energy consumption in residential housing we have employed measurements ranging from monthly utility data to information obtained from lightly- or highly-instrumented buildings.[1] The detailed information is necessary if one is to delve into the complex interactions of temperature, solar and wind components outside vs. room, system, and people interactions inside. Indeed, these studies have led the group to think in terms of such concepts as equivalent thermal parameters.[2] However, this report must, of necessity, avoid such detail and shall initially concentrate on parameters that may be derived from energy consumption data and prevailing weather conditions.

A starting point in the energy audit process is making proper use of past utility billing data. From such energy consumption records for heating, together with local weather records, an energy-temperature plot can be constructed as shown in Fig. 1. The plot provides an "energy signature" for the house.[1, 3-5] The higher the slope the greater the energy loss per degree of temperature change. The reference temperature is that temperature below which energy other than free heat is required to heat the house. The excess energy immediately beneath the inside temperature point is the free heat generated by solar, lights and appliances, and the occupants. Comparisons between houses or between houses and standards are aided if the energy is plotted per area of house floor so as to provide a more common denominator. House type will also alter the slope because of such factors as surface to volume ratio.

Use of monthly energy data tends to average out the effects of sun and wind, often making these data more desireable than daily energy records. The heating component must be separated from other uses of energy in the home. Use of monthly energy data between the heating and cooling seasons provides the base usage which then must be subtracted from the winter energy records to provide "heating alone" information. Better than $r^2 = .9$ data fits are the norm for such energy signature plots.[6]

Well conceived retrofits will lower the slope of the energy signature. This lower energy requirement per degree temperature change will result in a lower reference temperature (since the free heat is unchanged) thus minimizing or eliminating the need for heat in the "shoulder months" at the beginning and end of the heating season. We have seen this reference temperature as low as 52°F (11°C) in houses that were monitored.[1]

Lowering inside temperatures also reduces the reference temperature (Fig. 1 dotted line) but the slope remains unchanged. This approach to energy savings is limited by the comfort of the occupants. Night setback performs the same savings function but moves the interior temperature back to comfort levels at an appropriate morning hour. In plotting the graph for setback conditions, the average daily inside temperature would be used as T_{in}.

A final point as to the uses for such an "energy signature," one can match the losses to the energy produced at any given temperature.

So far we have discussed information which was available from the utility and weather bureau. The energy signature approach allows the house population to be culled for prime retrofit candidates using these limited data, a procedure that can be done for relatively low cost. For the energy signature to be a still more accurate tool, supplementary information from a household questionnaire is needed.[7] The questionnaire should provide:

- Information on the size and type of dwelling.
- Detail on interior temperature settings including night setback
- Location factors such as degree of protection from wind; proximity to neighbors, nearby tree cover and surrounding terrain.
- Window data - which would include the south facing and percentage of south facing glazing, winter window opening information and drape usage.
- Preliminary data on insulation levels.

SECTION II

ITEMS FOR ENERGY AUDIT

Unfortunately key items of information cannot be obtained from either the energy signature or the household questionnaire. One key item is the tightness of the house, what air infiltration levels are present? Another is how well is the insulation really performing? A third is what are the true house temperatures in the heating/cooling seasons? A fourth is what is the actual performance of heating/cooling equipment? The resolution of these and other vital questions is what makes an on-site energy audit necessary.

In the sections that follow key items for on-site audit will be discussed considering the level of complexity of the task. In concluding that the energy audit is essential, one is also confronted with the economic constraints of achieving these goals. As pointed out by Becker and Dutt[8] public interest wanes when the audit costs more than a few dollars. Thus one appropriate approach may be that of providing more than an audit, but rather an audit with immediate savings built in. Often such immediate savings can be achieved through air infiltration reduction and furnace tune-up.

Who performs the energy audit? The complexity of energy analysis can vary from installation of meters and detailed hour-to-hour measurements over a period of weeks or months[1] (which is appropriate for research and documentation) to a walk-through visit of an auditor with findings heavily influenced by the past experience of the individual. The instruments described in the following sections have been chosen with the principle in mind that the operator would require little or no training in taking the required measurements. This overall collection of instruments and measurement suggestions is referred to as a "house doctor kit."

One approach we have considered as practical is that house doctor kits be made available for rental in the same way one rents lawn care equipment. Availability of the instruments in this way would allow the measurements to be taken over a day or two and thus provide sufficient time for a more thorough survey than what could be accomplished by an "expert" walk-through audit. The reasoning here is that the walk-through audit, to stay within reasonable economic bounds, must be limited to an hour or so in duration. A family audit on a weekend could probe more deeply into the problems of the home.

As for the walk-through "expert," one problem he must face is that vital items such as air infiltration losses can only be roughly estimated. Unless the house is riddled with openings, assuring high infiltration rates, estimates based on window and door fit can account for only a fraction of the air infiltration losses (order of 1/3, based upon a number of studies).[9,10,11] Thus it is strongly suggested that wherever possible the expert measure vital quantities if the overall analysis is to prove accurate.

Even large building energy audits tend to rely on walk-through techniques cataloging equipment and building layout details. Use of direct measurement of air infiltration and/or measurements of heat and air conditioning flow rates to balance floor-to-floor and area-to-area conditions are important factors in the building energy analysis.[12] The house doctor kit in revised, professional form should be applied to multistory buildings as well.

SECTION III

THE IMPORTANT QUESTION OF AIR INFILTRATION

One often used procedure to analyze the energy consumption in a home is to (a) carefully calculate conduction losses of walls, ceilings and floors and (b) add the conduction losses due to windows. Then one estimates the efficiency for the furnace, multiplies total energy used during the heating season by this efficiency to provide (c), the energy used to heat the dwelling. Then (a) and (b) are subtracted from (c) + (d) (the free heat), to arrive at (e), the air infiltration loss; (see Fig. 1 for graphical reference). However, often free heat is ignored and air infiltration is an even larger "catch all" in this calculation procedure. Another approach is to use the crack method to estimate air infiltration directly.[13] Unfortunately, as previously stated, much of the infiltration comes from sources other than windows and doors which are ignored in this method. Both approaches fail to treat air infiltration losses in a direct manner.

Because of the importance of air infiltration we will treat this subject first. We will confine our attention to two general instrumentation approaches. The pressurization method and the tracer gas method.

In the pressurization method one evaluates the building under an artificially imposed pressure difference. Rather than a wind pressure profile[14-18] the method uses a powerful fan to pressurize the building so as to cover a range of pressure differences.[9,10,14,15,19] These pressures are relatively uniform over the building envelope[9,10,14,18,19,20] (providing outside winds are low, less than 3 m/s (6 mph), as contrasted to the irregular wind pressure pattern imposed by nature. Two important house characteristics are gathered from such testing. First a profile of leakage rate (or leakage rate per surface area) versus pressure difference is established for the house as shown in Fig. 2. This profile can be compared with other houses to estimate relative leakiness. Second, the actual location of the leakage sites can be pinpointed using infrared scanning or smoke tracer techniques. This will be discussed in some detail later.

Location of such leakage sites often associated with flow bypasses[5, 21] means retrofitting need not be delayed until after the audit process, but rather can be performed immediately. Often these openings require inexpensive seals, such as wadded fiberglass. The potential savings defray the costs of the audit, possibly allowing the economics of audit to be feasible.[8] Fig. 2 shows the change in profile that take place.

The Blower Door

First a close examination of the pressurization method is necessary. The energy audit goal using this technique is to rapidly install the blower, measure the house pressure profile, check for leakage sites and then remove the equipment (research-oriented studies need not be as concerned with setup time nor time for equipment removal). With these audit goals in mind our approach has been to design a Blower Door with the following features:

- Blower placed in a common building component of a typical house so that it can be readily moved from house-to-house with minimum installation/removal time.
- Make the readout of flow rate as simple as possible retaining $\pm$ 5% accuracy.
- Provide controls that allow simple setting of blower speed so that tests may be quickly accomplished.
- Design the pressure differential readout system so that chance of error is minimized again retaining reasonable accuracy ($\pm 2°$).
- Provide an ability to both pressurize and depressurize the house
- Make the unit portable to the extent that two men might easily set up and remove the components, hopefully, advancing to a one man design.

Figure 3 illustrates the blower that has been used to meet these design goals. A complete list of the parts is to be found in Appendix A. The design consists of an 18 inch (54 cm) diameter fan and variable speed motor housed in a lower door panel of 3/4 inch plywood, not unlike a Dutch door. The panel itself consists of the fixed segment, and a smaller moveable sheet aluminum segment, which via two jackscrews is adjusted so as to fit the door jamb. The household door, in most cases, need only be opened rather than removed from its hinges. This technique allows the lower door portion with blower to be tightly squeezed into the available opening in a matter of ten minutes at most. Door size adjustment is between 30 and 36 inches (75 and 90 cm). A door unit was chosen over a window design because of the high degree of uniformity of the dimensions of this building component.

The upper half of the Dutch door makes use of the same jack screws and moveable segment design. As shown in Fig. 3 only an opening for the pressure probe is an added feature of this component (3/16 inch diameter hole). The upper door is mounted after the lower door is in place.

Between the two sections is an adjustable "bridge" which allows for variations in the vertical dimension. This component consists of two sliding aluminum plates which are expanded to the edges of the door opening. Three spin tight knobs are used to secure the bridge in place. Fully assembled the overall effect is not unlike a bank vault door. Should one desire to pressurize rather than depressurize the home, two techniques of testing are available. The first is merely to reverse the motor direction which allows for pressurization, but because of fan blade shape this requires the use of an entirely different flow calibration. If one wishes to use the same calibration the orientation of the lower door can be reversed, passing the cables through the bridge section and taping openings.

The ability to achieve a wide range of air volumes to conform to a variety of housing mandated a very sizeable blower, one that could provide flow rates of more than 3000 cubic feet per minute($\sim$ 85 m^3/min) at pressures of 0.3 inches of water (75 Pa) in a reasonable sized house. The blower chosen was a direct current motor driven axial fan. Using the speed control panel, speeds from a few hundred rpm to just under 3000 rpm are provided. The electrical consumption is up to 10 amperes allowing its use with any standard household circuit. The range of speed is uniformly varied such that the desired differential pressures can be achieved within a matter of seconds. Such pressures have normally been chosen as .05, .10, .15, .20, .25 and .30 inches of water (or 12.5, 25, 37.5, 50, 62.5 and 75 Pa). In the larger more leaky dwellings only half of this scale can be traversed.

Readout of flow rate has been achieved through the use of a flow calibration section in other studies[10, 15, 19] at the expense of portability and setup time. The approach taken in the design described here was to keep the unit compact (basic fan with the addition of two screens, 1/4 inch mesh, to meet OSHA safety requirements). We calibrate this door for a variety of pressure differential levels noting the rpm for each point. The readout of rpm can be achieved from the use of a strobe light.* This was the method used in initial calibration, however, it was felt that faster reading could be attained through the use of a magnetic pickup and dial-type readout. The magnetic pickup uses a six lobe ring on the motor drive shaft to supply the pulses. The drive to the blower used a timing belt to eliminate slippage (any slippage would make the calibration invalid). The electrical pulses are counted via a solid state circuit with a proportional voltage fed to a 0-1 milliamp gauge. The gauge is read as a fraction of 3000 rpm (i.e., 0.4 = 0.4 times 3000 or 1200 rpm).

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*Strobe measurements are prone to error when using a multibladed fan as reference.

Deployment in a number of homes has shown the ability to set up the blower door in ten minutes and dismantle it in less. The tests at various pressure levels take only a few minutes to perform. If various sub tests are made, such as closing off the basement and closing other interior doors, this testing still lasts only about 15 minutes. Care must be taken with fireplaces that high flow rates and an open flue does not result in ashes being moved out from the hearth. Fireplaces, all windows and outside doors should be closed before testing. Tests run in conjunction with the infrared camera require 10 to 15 minutes to cool down house structure and up to 5 minutes in each room are required for infrared scanning noting problem areas and infiltration sites.

The Tracer Gas Method

Much has been written on this method of measuring air infiltration. The discussion here will be abbreviated to cover special techniques and new approaches to tracer gas measurement. More elaborate studies require more than one tracer gas to be used. For example, one can use sulphur hexafluoride to measure the overall house rate of infiltration and ethane to monitor one room or one ventilation component of that house.[22]

Confining our discussion to a single tracer gas, SF_6, the research at Princeton has required completely automated systems to be designed and field tested as well as simple grab sample approaches to checking rates of air infiltration.[23]

The automated system allows measurements to be made for extended periods over a range of weather conditions. The unit developed at Princeton in collaboration with the National Bureau of Standards[24] automatically either injects SF_6 into the house periodically or only at those times when the concentration falls below a chosen level. See schematic in Fig. 4. Measurements are taken from two sample locations (although a dozen such locations can be readily measured if additional valving is added) at time intervals from two minutes to 15 minutes. Analysis is made with a gas chromatograph and electron capture detector which is sensitive to SF_6 concentrations $<$ 1ppb. Using a five minute interval between samples, a standard 60 minute tape cassette lasts for one week, recording the SF_6 concentrations digitally. The high purity argon and tracer gas bottles are sized to last for the same one week period. Details on the components of this automated unit are listed in Appendix A.

How may tracer gas techniques be used in energy audit situations? One way is to simplify the approach, striving for testing under specific weather conditions and with limited equipment on site. With the SF_6 detector located in the lab one can bring the samples to the equipment using bag or bottle samples.[23] This approach has been followed by Grot in his nationwide studies of retrofitted homes.[25] We have used this approach in the LBL study of various tracer gases.[27] A west coast home was seeded with SF_6, bag samples were taken at half hour intervals and the analysis was made on the east coast. What could be simpler? We think that plastic bottle sampling is even an easier and less expensive way to measure infiltration. Later in this report the method will be applied to a high-rise building.

The method used in the case of bottle sampling is almost identical to that used with the bag samples. One variation is that the SF_6 is also provided in bottle form together with six empty sample bottles. Loosening the cap on the SF_6 bottle one need only walk around the house squeezing the bottle to achieve seeding of the SF_6.* With a warm air system one can use the furnace blower to finish the mixing process. If the ducting system does not couple with the outside air (e.g., ducting entirely within the living space), the furnace blower may be used throughout the test period. If such coupling is suspected a measurement with furnace blower on intermittantly or on over the test period will immediately reveal such coupling by registering an elevated air infiltration rate. The normal on cycles (say, 20 minutes out of the hour) of the furnace have proven to be adequate to maintain uniform gas concentrations in the house. Floor fans are required with hydronic heating. Following the initial mixing period sample bottles are filled every half hour (six numbered bottles over 2 1/2 hours with times noted) with house air. Squeezing the bottle first from one side and then 90° away, for ten squeezes, fills the bottle with room air, one central location in the house has proven adequate. Returning the bottles to the lab, by mail if necessary, (they fit in a small box) we are ready for analysis using the equipment as shown in Fig. 5. Each of the bottles has a natural rubber gasket and the plastic cap has been drilled so that the SF_6 detector probe, which is adapted

*Evening hours are normally chosen for the test since wind speed is down (< 3 m/s or 6 mph), outside and inside temperatures are recorded.

to a hypodermic needle, can be inserted into the bottle (the gasket acts as a septum with many reuses possible). As air is withdrawn from the bottle at a controlled rate measured by a sensitive flow meter, pressure must be exerted on the bottle to avoid injestion of room air. This is achieved by a weighted clamp. SF_6 concentrations are recorded for each of the six sample bottles (double or triple readings can also be taken as a check on possible error) together with the previously noted time and temperature data. A simple hand calculator program provides the infiltration rates over the five periods. Again as with the other instruments these components are listed in Appendix A.

This method allows one to sample a number of homes prior to any retrofitting program. Post retrofit sampling is also simple and inexpensive. Complementing the "energy signature" such data provides an inexpensive way to survey homes as to leakiness. The entire transaction can be conducted by mail if necessary.

SECTION IV

INSULATION AND INFRARED SCANNING

The use of infrared scanning to uncover faults in construction and insulation is a well known technique. Thermography can be used in a number of ways to observe surface temperature and surface emissivity variations. Viewing the home from above in overflight scans one must be able to separate effects of attic conditions from insulation levels as well as to discriminate between a variety of roofing materials and roof configurations. Residual effects from solar heating places the flight window in the early hours of the morning. Since the outer surface air film resistance is nominally listed as 0.17[13] and the inner wall as 0.64 there is almost a four to one sensitivity factor in favor of scanning inside rather than outside. Stated another way, the temperature difference inside-to-outside would have to be four times as great in the case of outside scan for the same temperature resolution. With these factors in mind our evaluation of retrofits at Twin Rivers concentrated on <u>inside infrared measurements</u> to evaluate improved insulation or effective sealing.[29]

What can be done to enhance the temperature contrast? One method pioneered in Sweden combines pressurization and infrared scanning to uncover problem areas.[30] Because coupling between attics and living space and/or basements has proven to be so important[21] (bypass routes) we have used the blower door to slightly pressurize the house while viewing the attic floor with the infrared scanner as an early step in energy audit. Rather than an expensive, $40,000 or more scanner, we have used a $6,000 hand-held unit that provides essentially the same sensitivity. The unit has added conveniences of improved portability and only a few seconds are required to warm up the equipment (cool down is actually more accurate).

The energy audit procedure continues with the house depressurized (25 PA, or 0.1 inch of water), following the pressure profile measurement. Then we use room-to-room scanning looking for inadequate or poorly installed insulation as well as infiltration sites. In the attic viewing we were looking for hot spots often resembling a "bed of coals". In the inside scanning we are looking for cold spots* -- dark areas on the viewing screen. Fig. 6a and 6b illustrate the details seen in the IR scanning. As in the other sections, the actual house doctors kit components are listed in Appendix A.

*Winter scanning is assumed here with 20°F (12°C) lower outside temperatures.

SECTION V

TEMPERATURE PROBING

We have just discussed thermographic surveys of walls, ceilings and floors looking for cold or hot spots. The question remains, how cold or how hot? In addition to these building surfaces there are a number of other temperatures to be measured quickly and accurately throughout any building. The details of our approaches to such temperature measurements is the subject of this section.

First, a partial list of the features to be measured:

a. Surfaces (walls, ceilings and floors):
   inside (55 to 85°F, 13 to 30°C)
   outside (0 to 150°F, -12 to 65°C)

b. Air: inside (50 to 90°F, 10 - 32°C)
   outside (-30 to 120°F, -55 to 70°C)

c. Hot water heater:
   inlet (40 to 70°F, 5 to 21°C)
   outlet (110 to 160°F, 43 to 71°C)

d. Air ducts:
   Inlet same as room temperature
   Outlets and supplies (50 to 150°F, 10 to 65°C)

e. Furnace stack temperature:
   (115 - 700°F, 45 to 370°C)

An instrument to provide these measurements requires the following characteristics to fit House Doctor needs:

1. Easily portable with battery supply for 8 hours.

2. Use leaves one hand free, the other for the probe. This dictates it be light enough for use on a neck strap.
3. Direct Reading. This dictates a digital readout visible both inside and outdoors.
4. An overall accuracy (sensor + readout) of better than ± 1°F (± 0.5°C) with 0.1°F (0.05°C) resolution.
5. An operating temperature range of at least 32 - 122°F (0 - 50°C) (for the a, b application) while maintaining the required accuracy.
6. Maintain a required accuracy during thermal shock anywhere within the operating temperature range.
7. Use commercially available sensors that do not require special calibration and will be interchangeable.
8. As wide as possible storage temperature range. In the case of the professional "House Doctor" the equipment will probably be stored in a van parked in an unheated garage or outdoors.
9. Minimum warm-up time.
10. Ability to "hold" the reading. That way the probe can be set down and the reading copied, so as to avoid human memory errors.

These requirements in part have been a result of hindsight following the development of the AC powered temperature probe shown in Fig. 7, and then the construction of a battery powered system as shown in Fig. 8. The details of these two units and the guidelines such development testing has established for proposed new units are described in Appendix B. In this section we will concentrate on the applications of the temperature probe.

Following the infrared scans that were described in the previous section, one has an option of whether or not to gather further detail on the wall cavity. The two cases of heavily insulated or non-insulated wall sections are normally quite obvious. However, because the retrofit procedure to insulate outside walls such as by filling them with cellulose, fiberglass or foam is quite expensive (approaching one dollar per square foot) one wants to be certain of the insulation status of the wall. In lightly-insulated walls this knowledge becomes even more important in the retrofit decision. We have found the use of a sensitive temperature probe can prove extremely helpful in such data gathering.

The measurement procedure is as follows: select a North or West facing wall in the morning to eliminate solar heating effects.* Carefully select the wall location to be free from ducts or radiators again to eliminate heat sources. Measure and average the wall surface temperature, T_{wall} at a half dozen locations staying between the studs (slight movement of the low mass surface temperature probe will insure elimination of any error because of heat removal from the local spot to the probe. Wave the probe in the room air 6 inches (15 cm) or so from the wall and record temperature, T_{in}. Repeat the air temperature measurement outside the same wall, T_{out}. Now we can make use of the relationship that the thermal resistance of the inside air layer[13] is $R = .64 \frac{ft^2hr}{Btu}$ and that:

$$R_{wall} = .64 \frac{T_{in} - T_{out}}{T_{in} - T_{wall}} \text{ (inside surface)}$$

*Solar effects may last for periods of more than four hours therefore care must be taken to avoid solar confusion.

Using this procedure on known resistance walls of R = 4.0, 6.5, and 9.0 predictions of R to $\pm 1 \frac{ft^2 hr}{Btu}$ accuracy were indicated. Often there is no access to the wall interior and this approach is very useful. Surface temperature measurements of insulation on hot water tanks and refrigerators using the same equation can prove useful in deciding whether insulation need be added.

Thermostat adjustments often provide temperatures far from the dial indications. Temperature information within the house (prior to any blower door test) will reveal the true house temperature and aid in the establishment of a more accurate energy signature plot.

Surface temperature measurements on the outlet line of the water heater reveal how accurate that thermostat is maintaining temperature. Adjustment of the temperature to 120°F (∿50°C) (or to 140°F [60°C] where higher temperatures are required for dishwashers) is one of the fastest retrofit payback items in the home. Increasing insulation on this same water tank also provides rapid payback.

Another area of interest in air or surface temperature measurements is associated with the heat distribution system. Register or radiator temperature measurements reveal whether sufficient heat is reaching remote areas of the house. The decision of whether or not to insulate the duct or pipe runs should be aided by such measurements. In addition temperature measurements at the flue or on the furnace surface reveal information associated with furnace performance, the topic of Section VII.

SECTION VI

APPLIANCE ENERGY CONSUMPTION

One important aspect often underrated in the evaluation of the energy consumption in the home, is the appliance consumption. It is particularly necessary to monitor the electric consumption of the larger usage appliances such as refrigerators, freezers, window air conditioners, heaters, some kitchen appliances, etc. For this task it would be desirable to employ an inexpensive semi-automated instrument on a short term basis to estimate the monthly energy consumption.

General Design Considerations: Such a device should preferably have a digital readout, directly calibrated in units such as 1.0 kWh per month or 0.1 kWh per day. It should also be compact, self-contained, free from both susceptibility to and the generation of electromagnetic interference (EMI). It should also not interrupt or interfere with the operation of the device under test. An outlet and line cord should be provided so that the device under test can be plugged into the instrument and the instrument plugged in a wall outlet.

Method of Measurement: The majority of home appliances contain motors and these operate at power factors in the 0.6 to 0.8 range. This precludes a simple voltmeter-ammeter measurement. Also, the presence of harmonics in the line current (caused by the iron in the motors) can introduduce additional error in all but the root mean square (RMS) reading ammeters. Therefore, the use of an AC wattmeter or watthour meter is indicated. However, a simple wattmeter measurement is inadequate, as most of these appliances are operated on a cyclic basis (usually automatic) and/or have use-dependent load factors. For instance, a refrigerator's consumption will increase noticeably after a family's weekly shopping trip as compared to middle of the night usage. This increase can be attributed both to the introduction of a quantity of "warm" foods that must be chilled and the associated amount and duration of door openings. Thus, an energy usage must be recorded over a suitable time period to enable the confident prediction of the appliance's monthly power consumption. The final form of the meter, therefore, should be a watthour meter with a time-operated digital readout.

The Meter Design and Operation: The details of the design approaches used to develop this meter are covered in Appendix C. The resulting meter is shown in Figs. 9 and 10. The choice was an all-electromechanical unit to achieve low cost. The readout of the meter has three scales depending upon the time interval of the reading which are 6, 12 or 18 hours. This allows one to estimate daily or monthly usage again, (see Appendix C for details).

Two sets of typical data are shown in the following table to illustrate the readings taken with the appliance consumption meter. When compared with actual meter readings over the period in question, it is clear that this is a 10% accuracy device in its ability to predict monthly usage. Care must be taken to avoid the shopping day as a basis for the monthly consumpt. Discriminating between high and low energy consuming units is achieved with the first meter reading. We have seen refrigerator-freezers whose monthly consumption was as low as 42 kWh and others with electrical use well over 100 kWh.

Appliance Meter Data Sets

Appliance meter used over 18 hour period to estimate monthly usage of appliance.

Unit #1 15 ft^3 Coldspot Refrigerator Over Freezer

		Start	Monthly Estimate
1)	7/1/77	09:30	76
2)	7/2/77	19:00	69
3)	7/3/77	16:30	71
4)	7/5/77	07:00	78

Unit #2 19 ft^3 Coldspot Freezer Over Refrigerator

1)	7/6/77	19:15	80
2)	7/7/77	15:30	81
3)	7/8/77	10:00	104 (shopping day)
4)	7/9/77	04:45	83
5)	7/9/77	23:15	83

SECTION VII

HEATING/COOLING PERFORMANCE

The heating/cooling equipment in the home and associated distribution system must never be overlooked in an energy audit. Unfortunately, if one seeks seasonal performance numbers for the equipment rather elaborate tests are often required. For example, in the case with a warm air system, where furnaces are located in the basement, one is dealing with the following complications. After each heating cycle, residual heat is left in the supply ducts. By natural convection that heat may continue to move upward through the house preferring the highest point in the system to deposit heat (i.e. condition for the greatest stack effect). On the other hand, if air infiltration rates are high in the basement much of this heat can be lost to the outside. If the duct system extends through the attic, the same stack effect that scavenged residual heat now works to leak that heat to the attic. In the basement itself there is the question of losses during the off cycle -- basement air escaping up the stack. Is this stack loss controlled by stack size or size of crack openings in the basement? The influence of the interior pressure of the house must also be considered.

With these and other factors influencing performance of the heating system what methods can be used to evaluate performance accurately? Perhaps the substitution of known output electrical heaters holds the most promise for quantifying the events as they take place. Several research groups have employed this technique[2, 31] and it was part of the EPRI study to evaluate heat pump performance.[32]

Limited to a visit of a few hours, substitution of electrical resistance heaters must be reserved for more detailed studies. In dealing with gas and oil furnaces the House Doctor Kit uses a Bacharach analysis approach. The process is simple: the furnace is brought up to steady-state temperature as measured with a dial thermometer with 12-inch reach placed into the flue immediately after the heat exchanger. Then from that same location samples are taken for analysis of CO_2 and O_2 content. These measurements are achieved by selectively absorbing the sample gas in individual containers filled with solutions. The process takes less than 15 minutes. The CO_2 and temperature readings translate directly to steady-state performance using an accompanying chart. The O_2 reading provides additional verification of performance and provides a warning (very low O_2 readings) that CO may be present. Multiburner gas furnaces will require this process to be repeated for each heat exchanger segment.

This steady-state reading is useful to see whether the burner is operating properly. Since a ten percent performance improvement on a 65 percent base translates to 15% overall, tuning burners to maximum performance has proven to be cost effective. In our retrofit studies we have been able to upgrade oil burner performance by proper adjustment, i.e. higher CO_2 and staying below the number two smoke number* (smoke number tests are part of the Bachrach analysis). Another variable besides adjustment, in the case of oil burners, is time from last cleaning.

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*DOE's latest regulations call for not greater than #1 smoke for new power burner testing.

Soot buildup can change the heat transfer by as much as 10%, thus degrading performance. New burner designs emphasizing blue flame rather than yellow flame operation should eliminate these seasonal performance variations. Newer oil burners tend toward higher pressure drop across the burner head thus off cycle air leakage is limited much like the inclusion of a flue damper.[33] Retrofitting new burners in old furnaces or boilers is one approach to upgrade performance. However, the situation must be carefully reviewed since often the higher performance demands a close match between how the burner releases heat and the location and design of the heat exchanger.

In the case of gas furnaces, beyond adjusting the primary air and rechecking the CO_2 and temperature, the situation becomes more complex. The furnace has been designed with a number of goals that must be achieved. Secondary air, that air freely passing into the combustion chamber without control at the burner itself, is controlled by baffles in the heat exchanger. Higher performance can be achieved if the burners are derated* but only if these baffles (or the exiting flue opening) are altered accordingly. In this process one must be careful that CO is not produced, this would require a CO sensor (a rather expensive addition to the house doctor kit). Also problems of cold spots in the heat exchanger, with resulting accelerated rust out, can easily develop in this adjustment procedure.

Rather than a set of samples of CO_2 and O_2 and separate temperature measurements one would desire an instrument that could perform such measurements almost instantly and simultaneously. Honeywell has been developing

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*The same size heat exchanger is then able to remove more heat from the reduced output burner.

such a combustion analysis meter and we were able to use it in certain of our field tests. The probe tip is placed in position at the exit of the heat exchanger as in the previously described tests. Efficiency is read directly on the dial and by switching the selector, temperature and O_2 levels can be read separately. The fast acting feature allows immediate adjustment of the burner to maximum performance. The meter also reveals such actions as slowly opening gas pressure regulators where efficiency is seen to decrease to the steady-state value. When marketed this meter will prove to be an important component of the house doctor kit for both the professional or the homeowner.

Neither the Honeywell probe nor the Bacharach analysis provides a seasonal performance number. This number may be approximated from computer techniques.[34] As previously stated individual house features may cause the actual performance to vary from that calculated. One of the largest factors is furnace location. If the furnace is within the living space, air infiltration losses between furnace operation will represent true infiltration loss. Located in the garage, the furnace losses will have no meaning but the temperature of air entering the furnace will vary with the season influencing furnace performance. A basement location will provide possibilities for reduced temperature air and infiltration loss. The significance of the later will depend upon the communication between house and basement.[14]

SECTION VIII

THE KIT AND PROCEDURES

In the preceding sections we have discussed many of the key components that make up the house doctor kit. In this section additional ingredients will be added together with a suggested procedure to follow in the residential audit. The full set of components to the suggested house doctor kit are shown in Fig. 11. Air infiltration equipment is not shown.

In the discussion of infrared scanning, surface temperature measurements were stressed. Section V Temperature Probing further described the actual temperature probe that we have used. However, when we talk about surfaces, area must be known as well as local temperature details. Detailed measurements of area are often very time consuming. Rather we have stressed using a series of "straight on" polaroid photographs with a calibration stick in the photograph. Using a fixed distance for such photographs allows a standard transparent grid to be used in surface estimation for walls and windows. Each photograph is marked as to the direction to which the wall faces so that if solar free heat is to be calculated the raw data is available. These components are shown at A, B in Fig. 11.

Measurements of the perimeter of the building are made and used immediately on graph paper with carbons so that construction flaws, leak sites, missing insulation can be marked on the plan forms so as to facilitate follow-up retrofitting. These notes are taken on the clipboards shown at K.

Distances of surrounding trees and other residences can be quickly determined using a pocket rangefinder. Image matching establishes the distance to within a few percent. This device is handy for establishing the point for uniform distance photography as well (not shown in Fig. 11).

In the preceding sections the principle components of the house doctors kit have been described in detail. In this section these energy components are shown in Fig. 11. The appliance consumption meter is shown at D. A description of the sequence of how the consumption meter is used completes this section. At location E is the hand-held infrared scanner. Both the AC and battery-powered temperature probes are shown at location F. The blower door is shown in insert G with components at H and J.

In Fig. 11 item C is the standard Bachrach furnace efficiency measurement equipment including a smoke number analysis instrument. To the right of C is the prototype Honeywell furnace analyzer that provides almost instantaneous readout of furnace performance, temperature, and gas composition.

Although items in the kit for infiltration measurements via the tracer gas approach are not shown, this equipment can be seen in Figures 4 and 5. For the house audit the bottle sample technique can be used prior to the visit as explained in Section III. Where this is not possibl leaving a seven bottle kit with the homeowner with individual explanation and instructions will insure that this important item of base data is made available. Since appliance data using the appliance consumption meter D, requires leaving an instrument with the homeowner, the bottle samples can be picked up as well when the auditor returns.

Again, if the house doctor kit is rented, time constraints are relaxed in performing the various recommended tests.

House Doctor Energy Audit

1. Complete energy signature and homeowner questionnaire prior to visit if possible.
2. Check with homeowner prior to visit for fastest route to site, owner will be home for duration of audit. Answer any preaudit questions.
3. Proceed with outside polaroid photography and perimeter measurements as first item on site. Observe outside surface carefully to evaluate caulking, use binoculars for upstairs walls. Plot plan form.
4. Survey the house interior to determine true temperatures, pay special attention to thermostat settings and local temperatures.
5. Install blower door and <u>pressurize</u> house to ∿ 25 Pa (0.1 in. of water) using infrared camera to inspect attic area. Carefully note level and installation integrity of attic insulation. Inspect seal and insulation of entry. FURNACE MUST BE TURNED OFF PRIOR TO TEST.
6. <u>Depressurize</u> house with basement door open taking pressure data over range of pressures 10 - 75 Pa (.02 - 0.3 in. of water) thus establishing the leakage profile. Repeat test with basement door closed, upstairs door closed, etc. to isolate portions of house.

7. Infrared scan interior moving room-to-room with blower door providing 25 Pa (0.1 in. of water) negative pressure. One auditor scanning with camera, other taking notes and marking location on plan form graphs. Take care of easy plugable items to provide audit payoff. Recheck pressure profile following our infiltration reduction retrofits.
8. Bring house back up to temperature while at the same time measuring furnace performance. Adjust, on the spot, to the best setting.
9. Inventory major appliances and apply meters to refrigerator and freezer if more data is needed on these high consuming items.
10. Review with homeowner the preliminary findings.

SECTION IX

MORE COMPLEX BUILDINGS

Up to this point we have concentrated on residential dwellings of one to perhaps three stories. What follows is a series of tracer gas air infiltration measurements conducted on a nine floor office building located on the Princeton Campus. The purpose of the tests was to develop the procedures for conducting tracer-gas air infiltration measurements in large, multistory buildings. In particular, testing focused on the injection and sampling of tracer gas via a supply duct of the building's HVAC system, and on the use of small polyethylene bottles to conduct independent sampling studies of individual floors.

Furthermore, as a sub-task, the bottle tests were conducted with several objectives in mind.

- Use the results to calculate and compare infiltration rates for individual floors.
- Check tracer gas distribution problems due to stratification, stagnant areas and multichamber effects, all of which have been cited as possible sources of error in infiltration testing central ventilating systems.
- Obtain an approximate idea of the time between injection and the reaching of a "dynamic equilibrium" of tracer gas concentration throughout the building.*

Sequence of Experiments

The following is an outline of the preliminary trials that finally constituted the actual experiment. Previous tracer-gas infiltration tests have been performed in high-rise buildings by Hunt[12] Kelnhofer, Hunt and Didion[35] and Honma.[36] Only the first two have used the central ventilating systems to distribute tracer throughout the entire building. These and other studies have pointed up some problems with the inherent assumptions of tracer gas testing. Along with others Grimsrud[37] has noted that for the exponential-dilution law

$$C = C_o \exp\left(-\frac{L}{V}\, t\right)$$

to be a valid model for air infiltration, there must be: (i) perfect mixing of tracer gas with building air, and (ii) perfect mixing of

*In this sense, that point at which gas concentration, at a given instant, is relatively uniform throughout the building. Note: This state is one of the two criteria for use of exponential dilution law $C = C_o \exp\left(-\frac{L}{V}\, t\right)$ to calculate air infiltration, the other criterion being "perfect" mixing of infiltrating air with building air.

infiltrating air with the building air-tracer mixture. The recommendation is for sampling tracer concentrations throughout the experimental space in the course of a single test to detect problems of gas stratification and separation, or of multi-chamber effects (tracer gas movement resulting in higher or lower apparent infiltration rates). Dick[38] and Honma found that tracer concentrations in single rooms were relatively uniform if auxiliary fans were used, while Kelnhofer et al. performed spot checks during their infiltration trials and found minimal concentration variation throughout a building similar in many respects to the New South Building (NSB). Multichamber effects would hopefully be a small problem in NSB, given the lightness of many of the inter-office partitions; but the mixing efficiency of the perimeter/interior ventilating systems, and the "stabilization time" needed for a reasonably uniform tracer gas concentration to be established throughout the building, after injection, are questions that could be investigated before actual infiltration trials. Drivas et al [28] have described a multi-point sampling method was initiated using dry 250 ml. polyethylene bottles, a predecessor to the technique described in Section III of this report. The method would appear ideal for use in NSB, as it would allow easy and cheap sampling of localized tracer concentrations with very little modification of the SF_6 detection equipment.

Tracer gas concentration anomalies might be expected near ventilation duct louvers (initially), near suspected leakage sites in the exterior walls and internal shafts, and at the interfaces of HVAC zones. The sampling points marked by circles in Fig. 12 are placed so as to check these expectations. Samples would be taken at the corresponding points on three floors: the "A" basement (on the machine floor level), the third floor (typical of floors 2-5), and the seventh floor (where the interior-zone supply fan will be shut down during tests). The actual sampling schedule for these preliminary trials is outlined.

Outline of Preliminary Trial

(Designed for three researchers)

1. Inject SF_6 tracer gas into exhaust/return duct of system E-1.(Fig. 12). Set up detection equipment to monitor SF_6 concentration decay via sampling probe in duct, as proposed for normal infiltration testing.*
2. Twenty minutes after injection, initiate sample-gathering (using 250 ml plastic bottles) at 20-minute intervals, tentatively continuing for 1 2/3 hours after injection (5 sets of samples). Procedure for gathering one such set would have a researcher assigned to each floor, gathering and storing samples at synchronized intervals, at each of the four prescribed sample points. Procedure recommended by Drivas et al. for

*The entire sequence of building pressurization, etc., was not followed in these preliminary trials. Rather, to check the assumption of approach to a roughly uniform SF_6 concentration throughout the building at a given instant following injection, a "worst-case" approach was taken. We can make a crude analogy to two types of idealized chemical reactor vessels, of the building operating under the five "cases" suggested by Ross and Grimsrud.[39] Case 1 (100% recirculated air) is closer to the concept of a well-stirred batch (no feed, no effluent) vessel than is Case 4 (outside air dampers open, exhaust fans operating), which better approximates a CST (continuously-fed, stirred tank) vessel. The theoretical criterion of a CST -- that at steady actual sampling is to squeeze the bottle hard 10 times to inspire and mix sampled air with that left in the bottle. Since the test is only to detect local concentration gradients, absolute concentrations are not important. We can assume that surface adsorption/desorption of SF_6 onto the PE bottle wall will come to a constant equilibrium rate for all bottles.**

3. Record weather data via the weather station during the trial. This should be done a), as a check on the procedure for matching weather to air infiltration data, and b), to help explain any unexpected concentration irregularities that might have been brought about by high winds.
4. After all samples have been taken, they can be taken away and analyzed for SF_6 conc. This should be done using the techniques outlined in Section III -- slight bottle squeezing to avoid contamination. The results -- a three-dimensional profile of how tracer concentration in the building approaches a "dynamic equilibrium" with time -- can then be compared with the concentration readings obtained from the duct to check mixing assumptions and choose an appropriate concentration-stabilization time for normal infiltration testing.

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state, effluent concentration C is equal to that found throughout the vessel, or perfect mixing -- is also the premise of tracer-gas measurement of air infiltration in a building. The material balance assuming this criterion for a CST of volume V and volumetric feed rate Q is $QC_o = QC + V\frac{dC}{dt}$ which is simply a reexpression of the exponential-dilution law. A continuously-fed stirred tank vessel will approach the theoretical CST criterion as the macroscopic residence time $\Theta \rightarrow \infty$, where $\Theta = V/Q$: in other words, as the vessel approaches batch operation. Thus, of the two cases mentioned above, Case 4 is the "worst case" for expectation of an instantaneously-uniform SF_6 concentration after some stabilization time.

**Surface adsorption, reproducibility of sampling results, and other uncertainties of bottle sampling has been tested in the laboratory. No problems appear to be present in the testing to date.

One exception, use of supply duct S-1 (Fig. 12) instead of exhaust duct E-1 for injection and sampling, was found to be necessary after it proved impossible to obtain access to the latter. Kelnhofer, Hunt and Didion[35] in their infiltration measurements on a building very similar to the New South Building [the Union Plaza building in Washington, D.C.], also metered their SF_6 downstream rather than upstream of the exhaust fan. Further details of the actual tests included 1) supply/exhaust system S-3/E-3 was shutdown; 2) auxiliary exhaust systems (toilet, kitchen, mechanical rooms, dishwasher room, darkroom) OPERATING; 3) no fresh air (dampers closed); and 4) no covers on supply, exhaust dampers. Table I lists SF_6 readings.

Discussion and Conclusions

Checking some of the inherent assumptions of tracer gas testing revealed several things:

- The ranges of peak voltage PV below are an index of how SF_6 concentration varied throughout the New South building after the gas was metered into the ventilating system (standing current SC = 84):

Time	Range	ΔPV
18:20	65 - 73.5	8.5
18:40	72 - 77.5	5.5
19:00	76 - 79	3.0
19:20	79 - 82	3.0
19:40	81 - 82	1.0

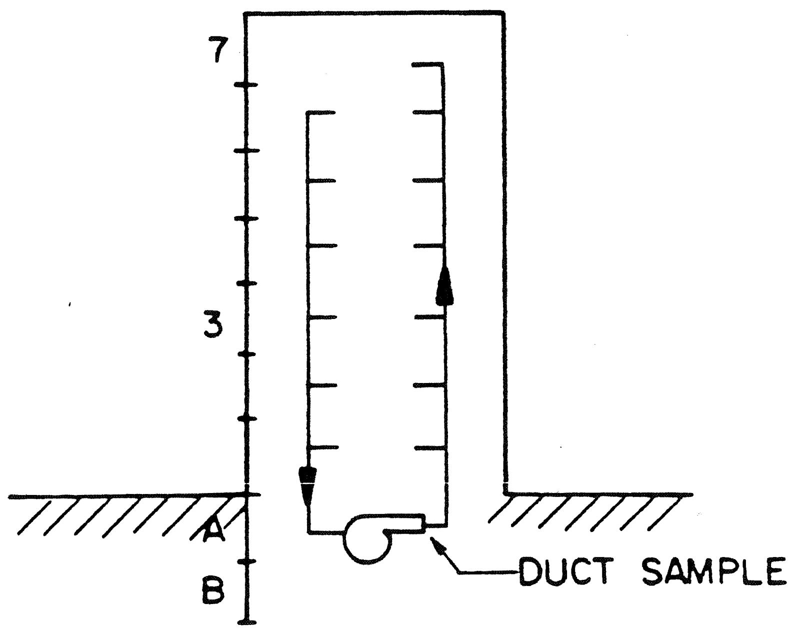
If we define a reasonably uniform concentration as that which falls within a 4 ppb band, this condition is not reached until ∿ 18:50, but SF_6 injection began at 17:45, this implies a "stabilization time" of over an hour. Hunt,[12] in tests on the Norris Cotton Building, waited one hour between injection and sampling; Kelnhofer, Hunt and Diolion[35] in the Union Plaza tests made spot checks of concentration and apparently waited "15 minutes or longer" for concentration stability. As was stated and proved in Ref. 40, the HVAC system setup noted above is close to a "worst-case" test of whether relatively uniform tracer gas concentrations can be achieved in the building (an even "worse case" would have been to have outside air dampers open, but this is not permissible in winter in NSB).

• Taking the 19:00-19:40 interval rather than the whole testing period (18:20-19:40) does not change the difference between the duct and bottle-sample results when air infiltration is calculated from concentration readings: the two test methods still differ in their predictions by about 0.07 exch. $hr.^{-1}$ However, both predictions are about 0.04 **exch** $\mathbf{hr}^{-1}$ higher for the shorter interval than for the longer. Reasons for this difference between intervals (if it be significant) are not clear: slightly higher winds were felt during the 19:00-19:40 interval, Table I, but whether this was the cause of the difference cannot be readily verified.

• Four sampling locations were chosen on each floor to check for suspected SF_6 concentration anomalies near ventilation duct louvers, exterior walls and internal (elevator and stair) shafts, and at the interfaces of New South's two ventilation systems (perimeter and interior). The concentration (SC/PV) readouts from the gas chromatograph -- one per bottle, for each location on the 20 minute interval -- are tabulated in Table II Marked concentration differences between the four locations are not really evident, though the readings near the windows, columns "A" and "D", seem (not surprisingly) to be generally more dilute than interior readings. The HVAC system thus seems to do a fairly good job of air distribution on a per-floor basis, at least.

• Fig. 13 shows the per-floor concentration readings averaged and plotted against time, to compare against themselves and with the air-leakage readings also obtained via the HVAC sampling duct. As the tabulated values for air infiltration in Table III bear out, the seventh and third floors averaged over the 80-minute test have the same air infiltration level, while floor "A" shows 12% lower AI levels. Activity on floors three and seven differed greatly (floor seven cafeteria was serving dinner to the University Madison Society throughout the test; while, besides the researcher and a lone office worker and his child, there was no other activity on floor three). Another point, floor seven's interior air supply/exhaust system (S-3/E-3) was shut down as mentioned, to maintain the validity of sampling from S-1 alone. This creation of a semi-"stagnant" interior region could have raised the fear of an SF_6 buildup as the test continued, which could have been seen at a "hung-up" concentration with correspondingly low leakage rates. Because of this air leakage out of floor seven may well have been higher than the 1.33 hr^{-1} averaged from the 20 minute readings -- it's impossible to tell whether SF_6 diffusion into stagnant air on this floor masked a higher

Q than floor three. (b) The below-average air-leakage levels for Floor "A" were predictable, part of the "floor's exterior walls are in fact underground. A simple solution to the problem of air infiltration energy loss, but not practical for all construction. (c) It is interesting to note how closely the basement-duct concentration readings follow those of the seventh floor. Since the basement duct air is drawn (via return system E-1) from the interiors of all New South Floors except the 7th, it begins to look like the 7th floor readings are less independent of the duct-sample readings, than are these readings obtained from the other two floors.



Comparison of bottle and duct samplings for predicting whole building air leakage shows promise of two compatible means for evaluating air-leakiness of buildings, if certain guidelines are followed, i.e. homogeneous multi-story building with central AC supply/exhaust systems, allowance of a reasonable tracer gas stabilization time, etc. In the final analysis, the duct sample produced air leakage Q undershoots the bottle-sample prediction by about .07 $hr.^{-1}$ Is this due to residual SF_6 in the duct after injection, i.e. to a weakness of the test procedure, or is it because the bottle-sample readings are less reflective of the whole-building behavior than is the "stirred average" represented by the duct measurements. In any case, the difference is less than 6% of either average; thus, the two methods of sampling would seem to give harmonious results -- either could be used.

SECTION X

MORE COMPLEX MONITORING

Often one is confronted with energy monitoring and analysis that goes beyond energy audit. Rather than a visit of hours, or even days, the monitoring must cover weeks or months and involves response of the building to changing weather patterns as well as the use of the building by the occupants. In those cases specialized energy monitoring equipment is necessary.

Submetering

Utility companies routinely survey their customers with metering that provides additional data on changing use patterns and as a predictor of appliance choices. Individual meters, submeters, may be added to either electrical or gas appliances and heating/cooling equipment. Such submetering is necessary for the utility to make reasonable estimates of future energy requirements. One example is submetering to determine the energy consumed by air conditioners, room-type or central, and extrapolating the effect on summer peak load.

The energy auditor in certain instances may wish to make use of submetering to determine the longer term usage of a questionable appliance or heating/cooling system. This approach was used at Twin Rivers[41] to monitor the individual large electrical users, air conditioning, water heating, electric clothes dryer, etc. In a more detailed study of appliances,[41, 42] individual gas meters were used as well, in a set of homes that provided gas hot water heating and gas clothes drying.

Instrument Packages

Beyond the submetering approach one can proceed to the installation of instrument packages. Several such packages have been developed in the course of the Twin Rivers program and are described in Reference 41. Only the latest advances in our approach will be covered in this section. However, a brief summary of what has been developed in the past should prove helpful.

HIT Package

The highly-instrumented townhouse package allowed 63 channels of energy-related data to be gathered every 20 minutes. This package relied upon a 200 channel Esterline-Angus data acquisition system (DAS) that interrogated the sensors in a sequential manner. Data was sent via telephone line to our lab and tape recorded there. The data were used to completely describe the energy functioning of the three houses. In addition, however, details on the air infiltration rate required a visit with the automated air infiltration unit (see Section 3). Complete details on the furnace and warm air supply system required the use of Rapidscan.

Rapidscan

Rapidscan was a second DAS which added the capability of sampling as often as 20 times per second if required: This Doric data system and associated 12 inch reel-to-reel magnetic tape recorder provided 100 channels of data and could rescan channels on 5 second to one hour intervals. Up to 16 distinct events were able to activate the readout. For example, turning on the air conditioner would initiate a scan of all sensors. This system was used to evaluate the detailed energy history of all major appliances in 16 additional homes at Twin Rivers.[42] Currently, the Rapidscan system is gathering selected data in the NBS-CSA national study of retrofitting lower income housing.[26]

Omnibus

A simpler instrument package was developed for monitoring before and after energy use in a group of 30 townhouses at Twin Rivers. This Omnibus package,[43] with modification, has also been used to monitor 10 heat-pump heated and cooled homes in central New Jersey.[44, 45] More recently Omnibus double packages have been used to monitor four older homes in the retrofit evaluation program. The Omnibus package makes use of a four-channel Westinghouse demand meter widely used by the utilities. Through the addition of a signal conditioning and multiplexing circuit the recorder can monitor 12 energy sensors once each hour. The double unit adds a second tape recorder to allow 24 sensor monitoring if needed.

A Computer as a Monitor

The perfection of the Microprocessor brought about the creation of the Microcomputer -- the inexpensive "Home Computer". One such home computer is the Commodore PET (2001 Series), based on the 6502 Microprocessor. However, unlike the KIM-1 or the VIM-1 (single card Micros), it has the following conveniences:

1. Built-in video monitor with interface monitor and screen memory.
2. Built-in keyboard with full ASCII character set and decoder.
3. 8K of BASIC on Read Only Memory (ROM).
4. 5K ROM Operating System, etc.
5. 8K of Random Access Memory (RAM) for program and memory.
6. Output ports for two audio cassette recorders (1-inboard, 1-outboard)
7. An IEEE-488 compatable output port for connection of peripherals such as printer, floppy disc, digital cassette, modem. RS-232 converter also available.
8. A Parallel User's Port for inputting or outputting digital signals under program control. May also be used to control external switches, etc.
9. An internal real-time crystal controlled clock accessible by both program and keyboard.

These features allow the PET to be used as a convenient, low cost, data collection device when equipped with an A-D converter and a multiplexer.

A significant advantage is that a "lab based" PET can be used to process the tapes from many field units. In transposing the data to a digital cassette or floppy disc, the data may be printed simultaneously for rapid visual examination. The digital cassette (or floppy disc) can then be used to input a large computer, eliminating the need to process data manually (with the attendant cost and error potential). The advantages in the field are:

1. Since the PET is a computer, all data can be reduced to physical units and rounded off to a reasonable number of places before recording.

2. This allows the use of low cost thermisters (almost half that of thermilinear networks), as the PET can easily compute their resistance-temperature curve.

3. The internal clock allows timing of the data taking as well as recording time and date.

4. The PET "Interrupt" Bus allows timing of external events.

5. The PET with external audio cassette costs less than a digital cassette recorder alone, but will provide about the same recording time, including the preprocessing.

SECTION XI

CONCLUSIONS

The first step in energy audit, from the standpoint of information gained versus cost, is determining the energy signature. Past utilities records and a knowledge of prevailing weather are necessary to establish this energy vs. temperature difference plot. Additional information gained through a carefully directed homeowner questionnaire adds to the usefulness and accuracy of the energy signature which can be applied before and after retrofit.

The house doctor kit described herein emphasizes fundamental measurements of the key loss factors in the home energy audit. Air infiltration reduction through retrofitting has been shown to be feasible while the audit is in progress, thus providing instant benefits that can recover audit expenses. The use of several approaches to infiltration measurement and location of leakage sites has been described. Development of the simplest approach for such measurements uses bottle samples from a tracer gas seeded house. This technique can be employed prior to an actual house visit saving time and money.

A key feature of the house doctor kit is the use of the blower door to detect leakage sites and to rate the leakiness. The blower door design has resulted in a portable, flexible field unit. The use of a hand-held infrared camera when the house is depressurized, speeds the process of leak site detection. At the same time the quality and uniformity of wall and ceiling insulation is surveyed. Important energy bypasses are uncovered in this IR scanning process. These structural flaws allow air movement to pass through the building envelope degrading the performance of the insulation and raising infiltration levels significantly. Interior walls can be involved with these losses as well.

Another cost effective energy audit item that should not be overlooked is furnace performance evaluation. Ten percent improvements are not uncommon and these can be achieved in less than one half hour and also provides instant audit benefits.

Appliance performance is checked with a recently developed watthour meter. The meter design provides for monthly estimates to be made and covers appliances as complex as the refrigerator.

All of the energy audit items cited require accurate temperature measurements. This includes house and thermostat surveys. To meet this need we have developed both AC and battery-powered temperature probes. Measurements to 0.1°C accuracy are achieved on surfaces and air temperature, allowing accurate assessment of energy consumption factors.

The items in the house doctor kit, for the most part, can be easily used by the homeowner. Training is minimal. The approach of adding specialized instruments and techniques and thus move beyond the walk through audit has been demonstrated to have considerable merit. This applies to homeowner and professional.

In the case of homes requiring detailed or long-term monitoring specialized uses of today's "home computers" will allow analysis to be made accurately and inexpensively as described in this report.

The techniques that have been outlined for the residential sector need not be limited to small buildings. Tracer gas monitoring in the ducts, by battery-powered SF_6 detector equipment, and in rooms throughout the building, using the bottle technique, was demonstrated in a high-rise building on the Princeton Campus. The methods are fast and economical. The results are most revealing in that there are large differences between design (or calculated) infiltration rates and the rates actually present. These differences are highly dependent on the ventilation system.

TABLE I

WEATHER AND CENTRAL DUCT SF_6 READINGS

Standing Current = 86.5   Seeding at 17:45

Time	Peak Reading SF_6 conc.	Wind Vel.* (mph)	Temperature °F** Outside	Inside
18:00	64	6.6	31.3	
18:10	66			
18:15	69			
18:20	70.5	7.0	31.1	
18:22	71			
18:25	72			
18:30	73.5			
18:35	74.5			
18:40	76	7.4	31.0	
18:45	77			
18:50	78			
18:55	78.6			
19:00	79.3	9.6	31.1	61.5
19:05	80			
19:10	80.3			
19:15	81			
19:20	81.5	9.1	30.6	62
19:25	82			
19:30	82.5			
19:35	83			
19:40	83.5	7.6	30.5	61.5
19:45	83.8			
19:50	84			
20:00		10.5	29.9	

* Averaged over 20 minute period

**As measured at 3rd floor

TABLE II

BOTTLE SAMPLES

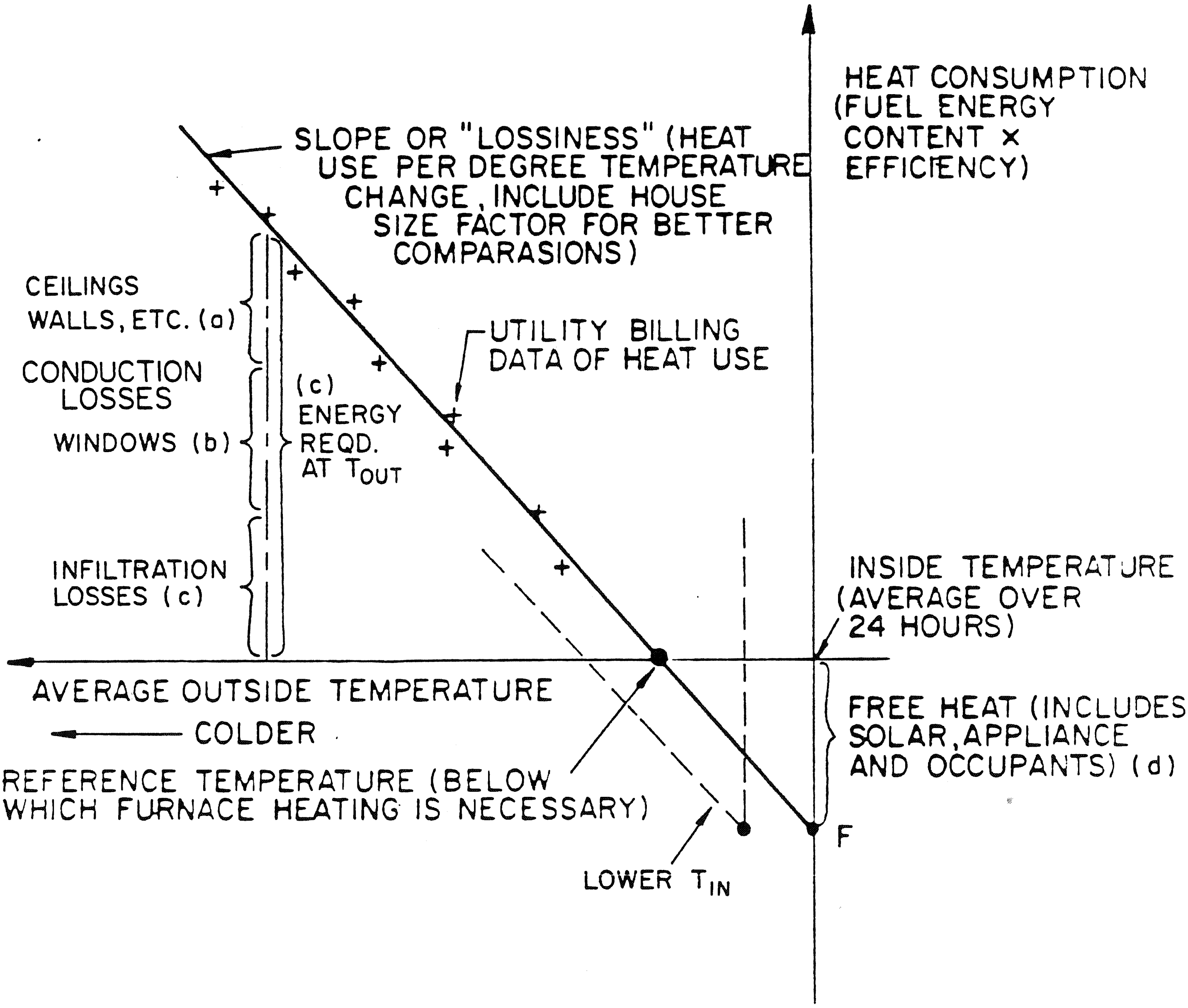
New South Building

Time	Floor	West			East
		Sampling Station (see Fig. 12)			
		D	C	B	A
	7	65.5*	67	65	71.5
18:20	3	68	70	70.5	69.5
	A	73.5	73.5	73.5	73.5
	7	74	73.5	72	74
18:40	3	74	75	75.5	77.5
	A	77	77	76.5	76.5
	7	77.5	76	77.5	78
19:00	3	78	78	78.5	79
	A	79	79	78.5	78.5
	7	79	79	80	80
19:20	3	82	81	80.5	80.5
	A	80.5	80.5	80	80.5
	7	81.5	81	81.5	81.5
19:40	3	82	81.5	81.5	82
	A	82	82	82	82

*These are typical SF_6 concentration readings. The scale number e.g. 65.5 is compared to 84, the case where no SF_6 is present. Thus the closer the reading is to 84 the lower the SF_6 concentration.

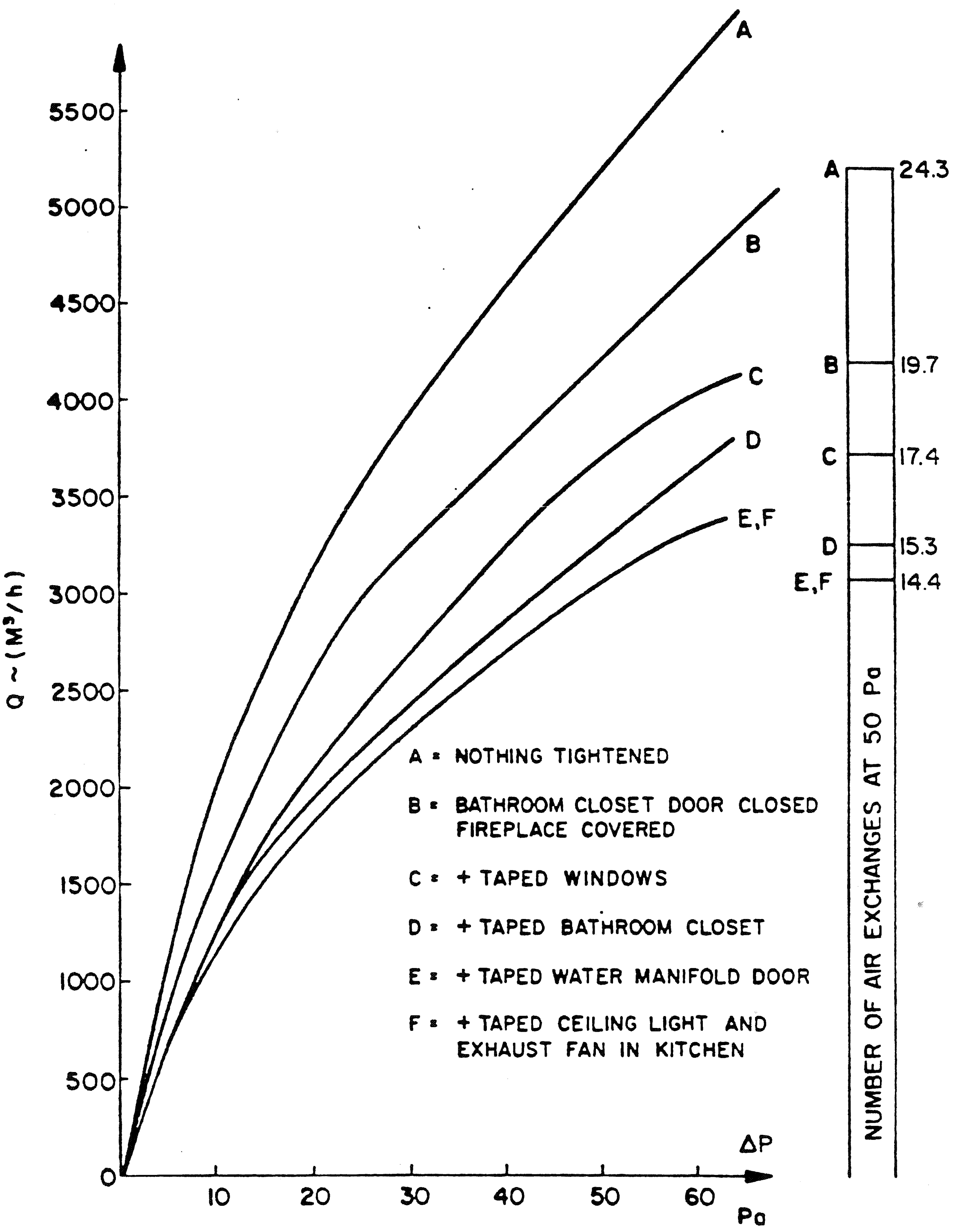
TIME INTERVAL	DUCT SAMPLES	BOTTLE SAMPLES FLOOR 7	BOTTLE SAMPLES FLOOR 3	BOTTLE SAMPLES FLOOR A		20 min. ave.
18:20 – 18:40	1.25	1.36	1.57	1.07	→	1.33
18:40 – 19:00	1.09	1.30	1.18	.91	→	1.13
19:00 – 19:20	1.03	1.14	1.75	1.04	→	1.31
19:20 – 19:40	1.43	1.51	.80	1.65	→	1.32
	1.20 AVE. A.I. DUCT	1.33	1.33	1.17		1.27 AVE. A.I. ALL FLOORS
		AVE. A.I. per FLOOR				

TABLE III. AIR INFILTRATION RATES FROM DUCT AND BOTTLE SAMPLING



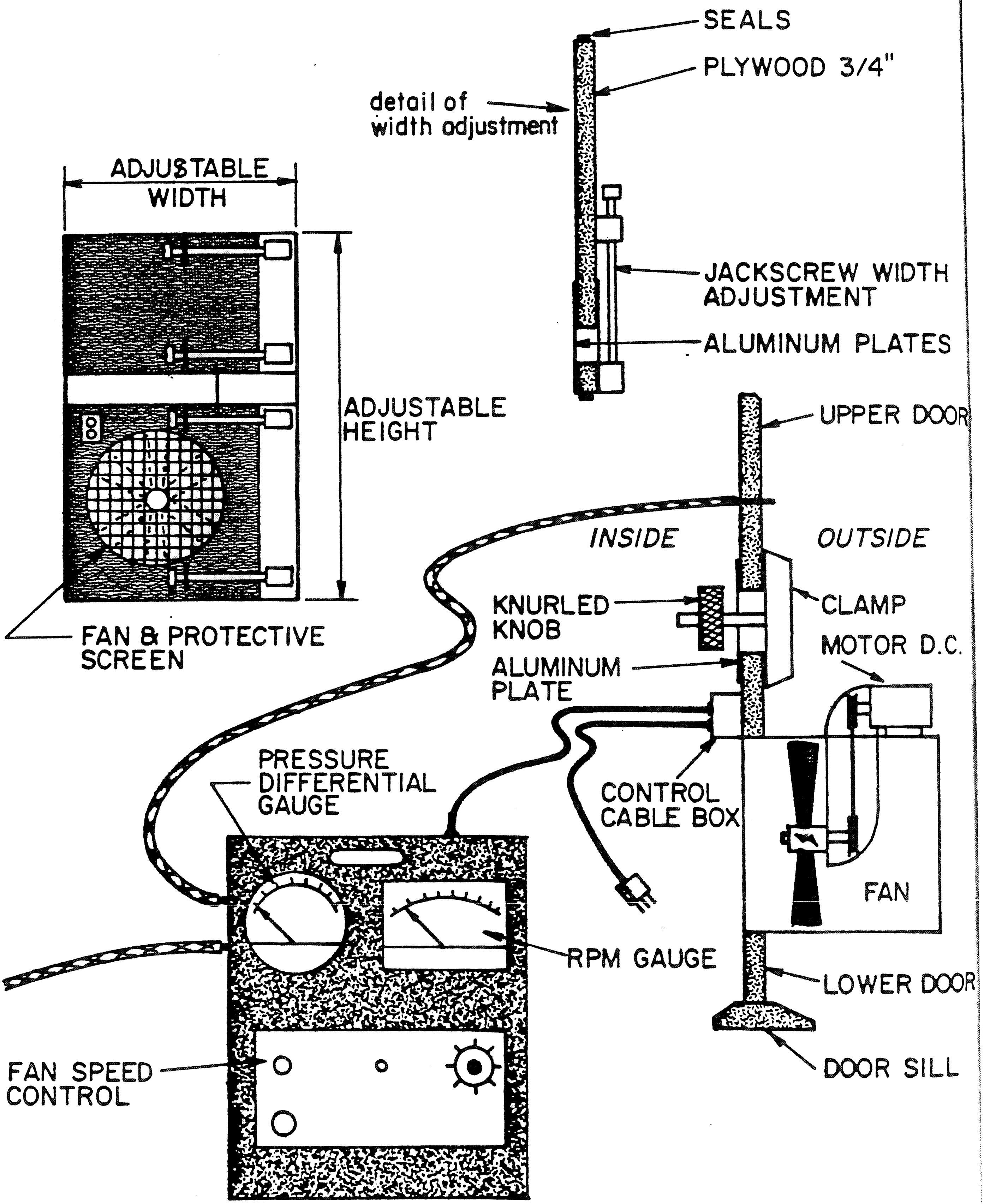
"ENERGY SIGNATURE" OF THE HOUSE, WHERE HEAT CONSUMPTION IS COMPARED TO PREVAILING OUTSIDE TEMPERATURE

FIG. 1



AIR LEAKAGE vs. PRESSURE DIFFERENCE ILLUSTRATING STEPS TO REDUCE INFILTRATION

FIGURE 2



BLOWER DOOR AND CONTROL PANEL

FIGURE 3

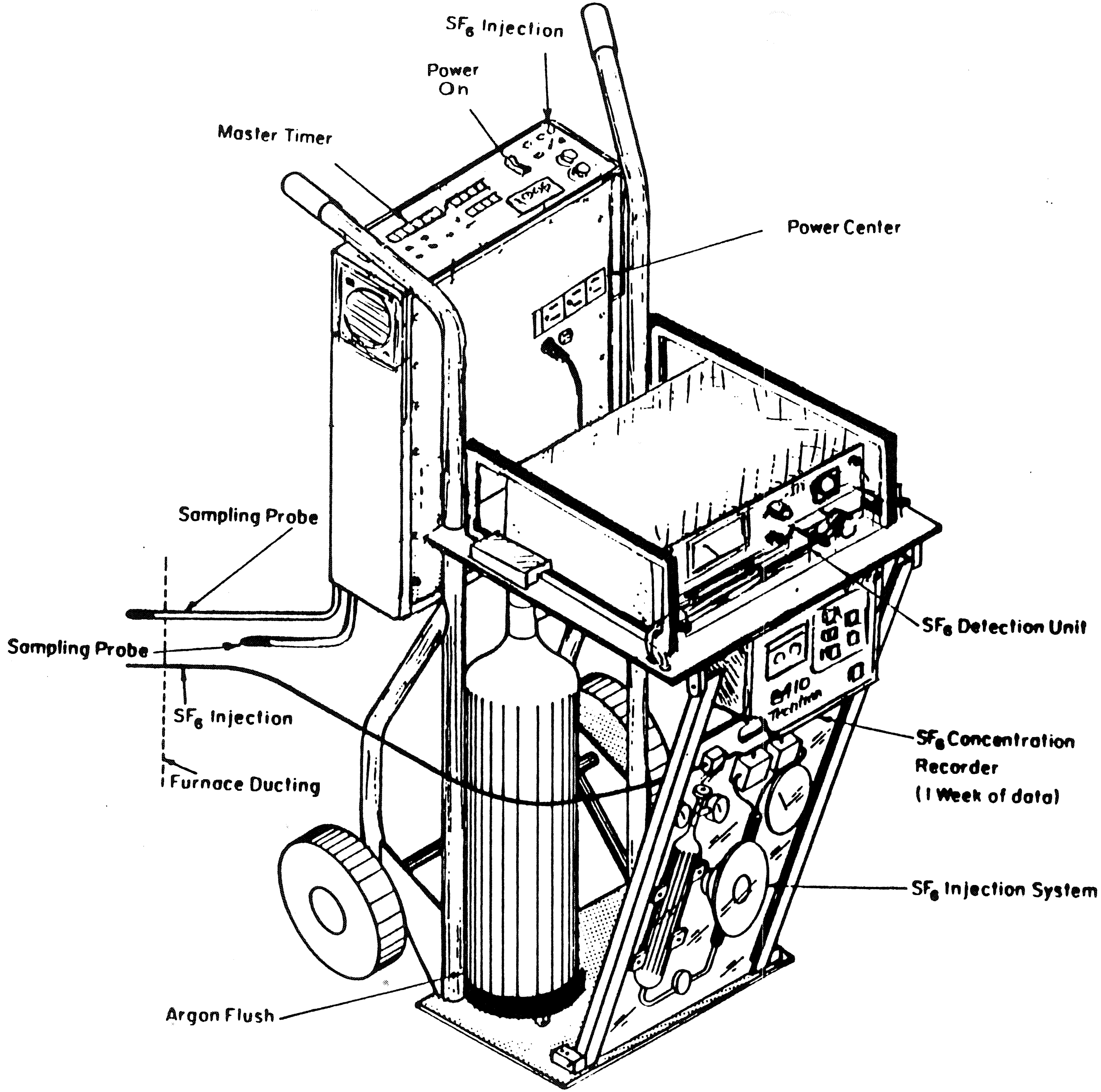
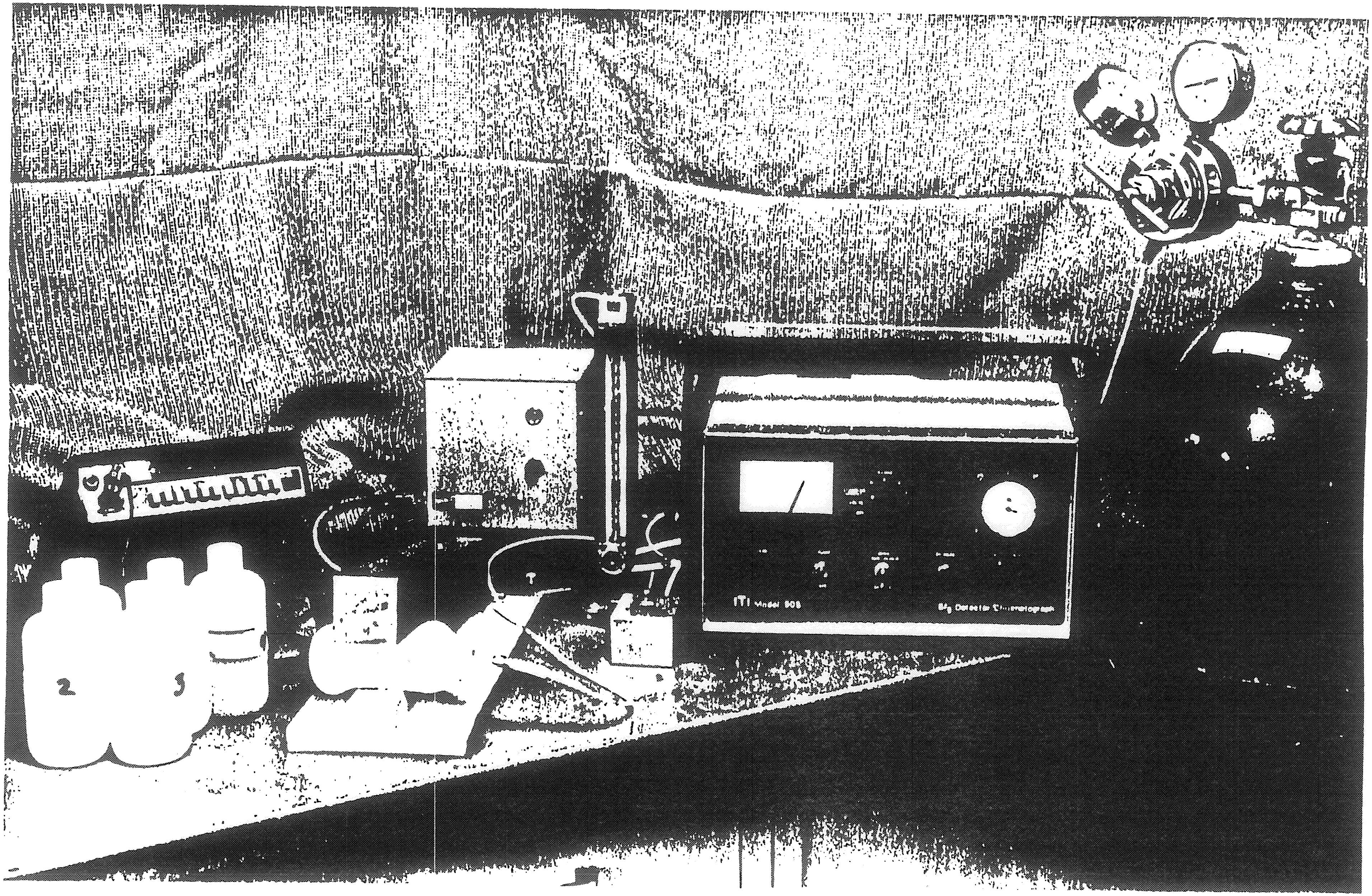
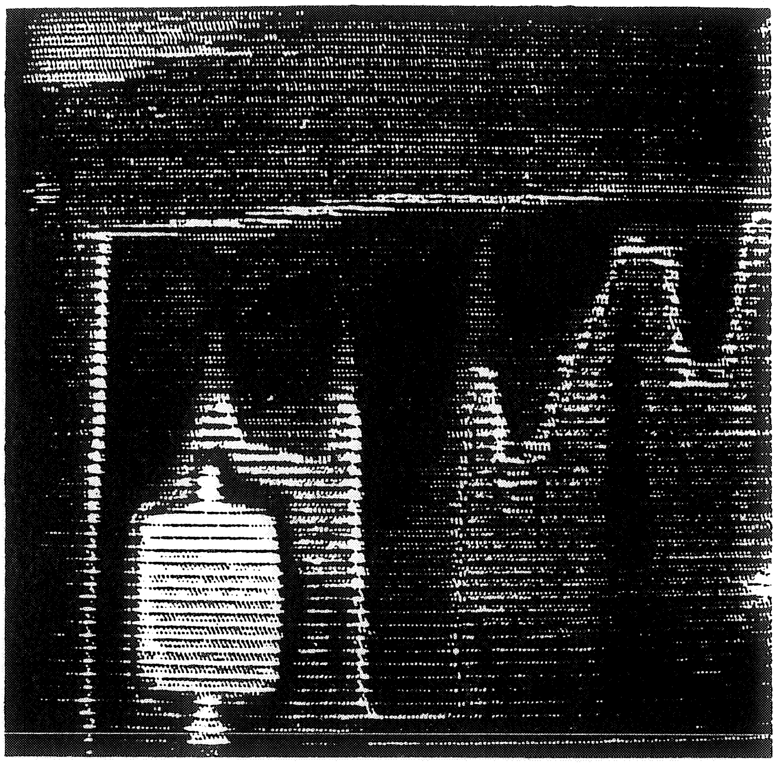


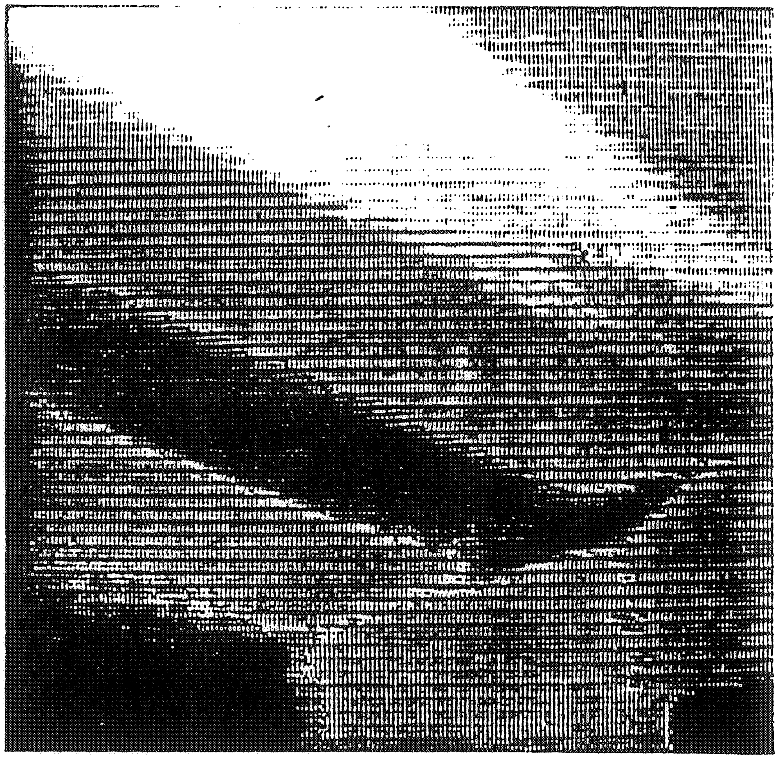
FIGURE 4 AUTOMATED AIR INFILTRATION



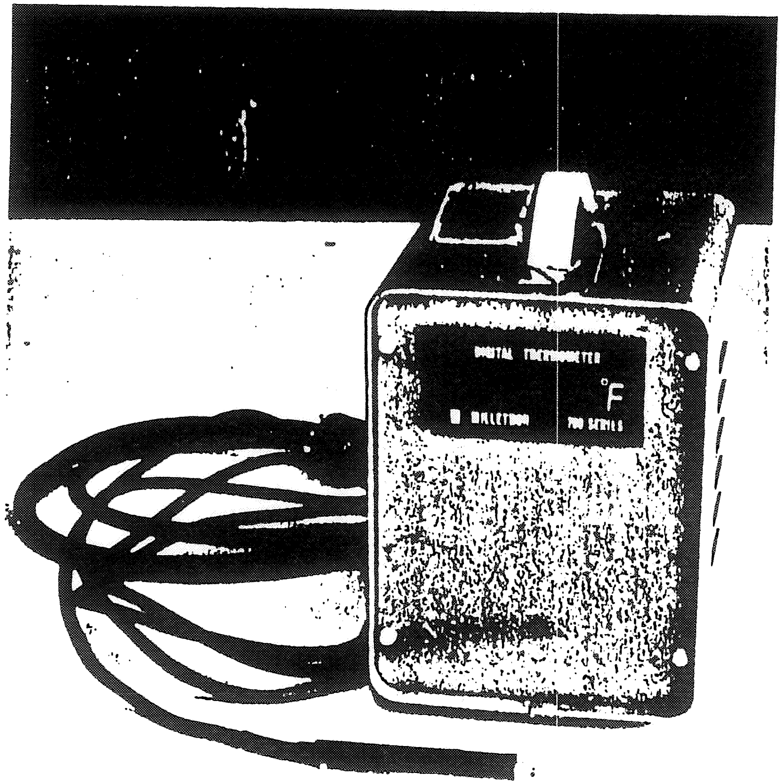
BOTTLE SAMPLE ANALYSIS FOR AIR INFILTRATION:
BOTTLE SQUEEZER, FLOW METER, SF_6 DETECTOR



6A. HEAT LEAKAGE PATH FROM ATTIC SHOWN BEHIND INTERIOR WALL.

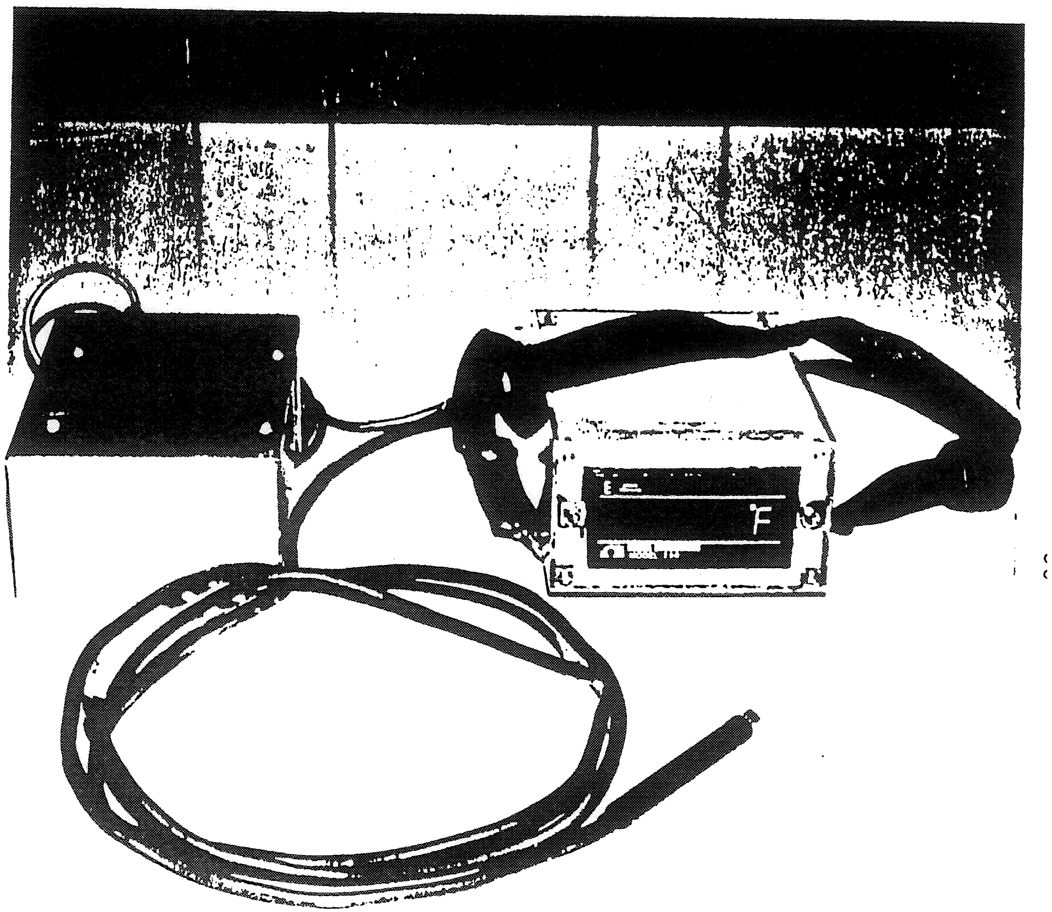


6B. HEAT LEAKAGE FROM ACROSS CEILING (BETWEEN 1st AND 2nd FLOOR) — ALSO SHOWN IS HEATER DUCT PATH.



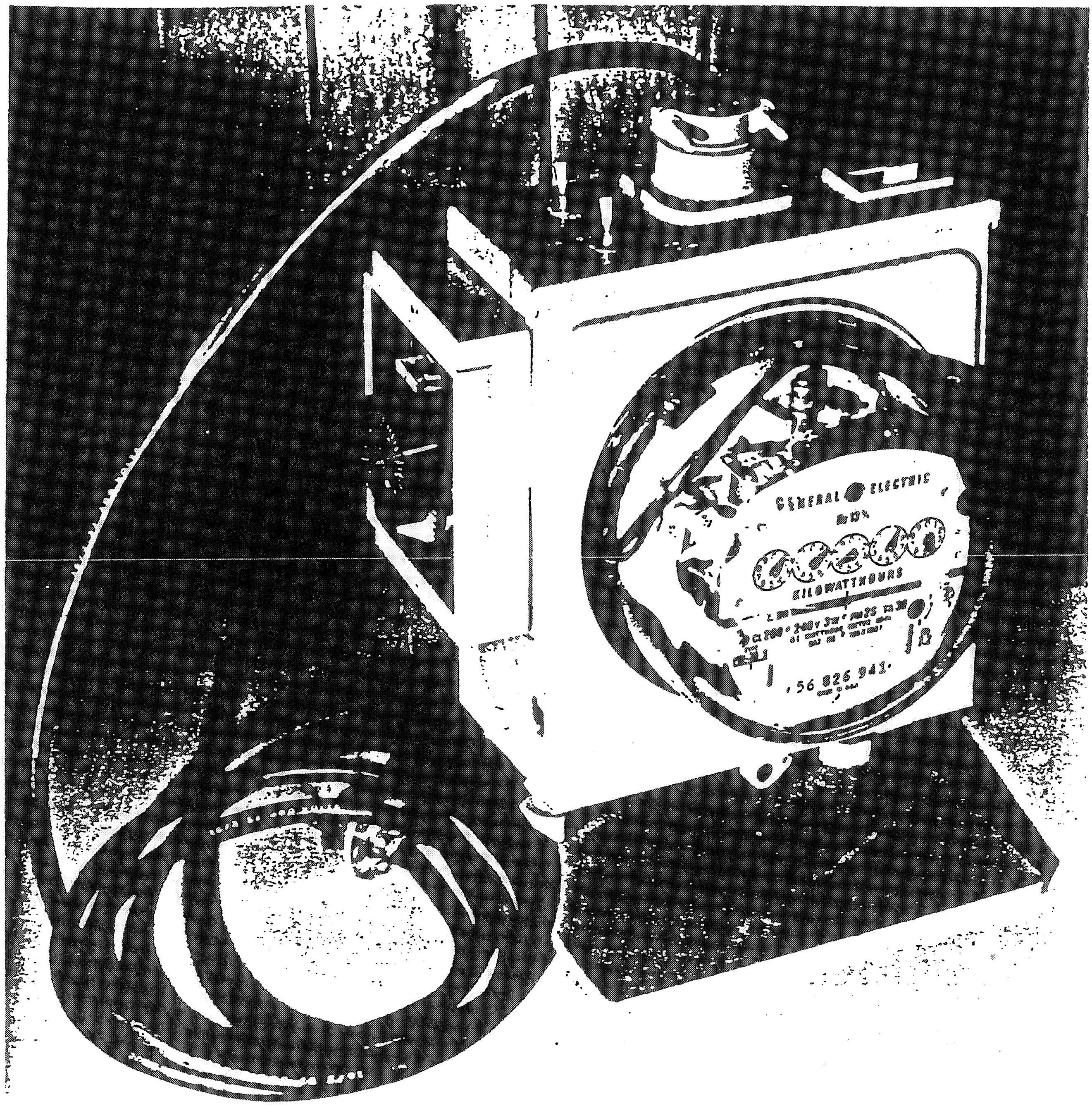
A.C. POWERED TEMPERATURE PROBE

FIGURE 7



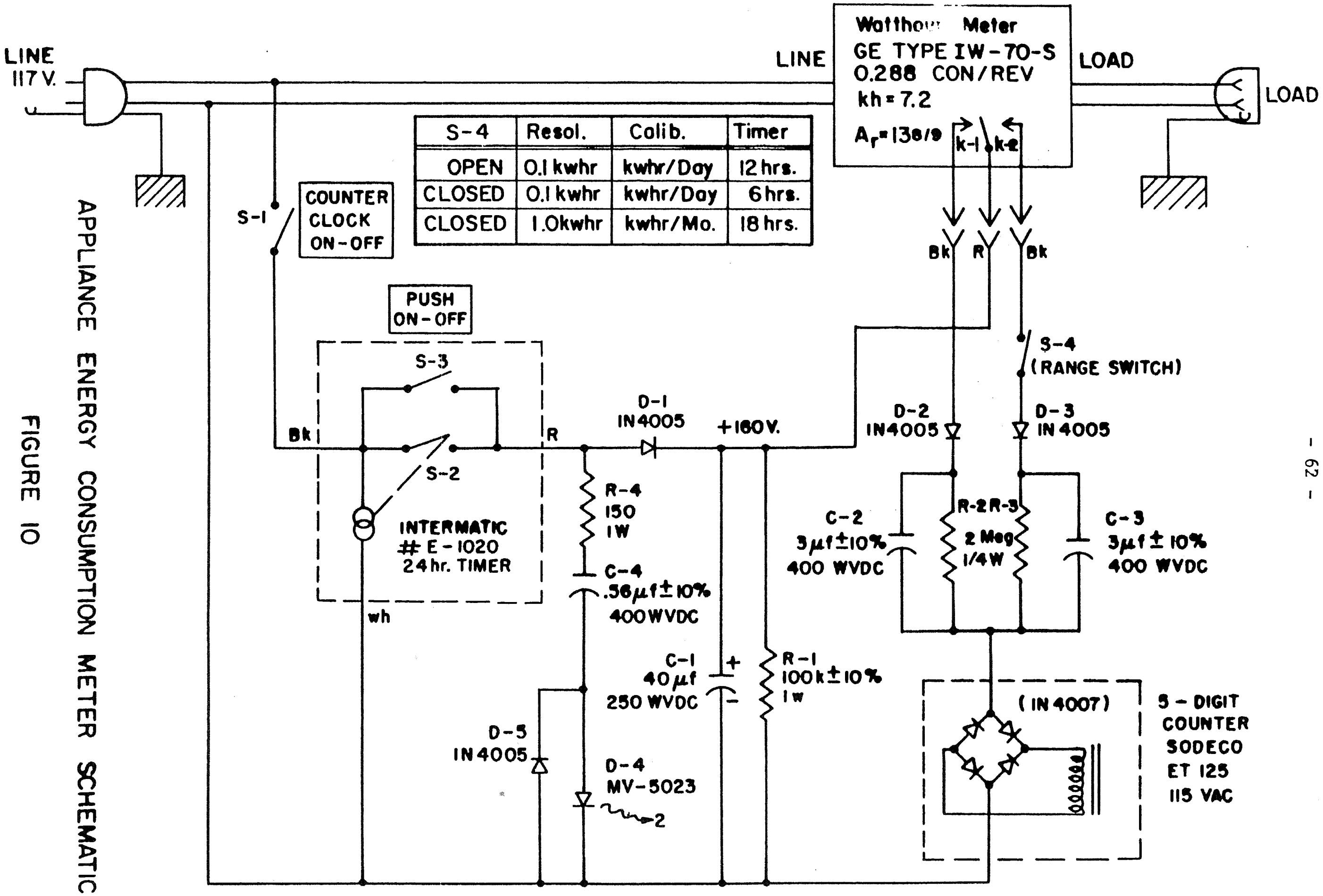
BATTERY POWERED TEMPERATURE PROBE

FIGURE 8



APPLIANCE ENERGY CONSUMPTION METER

FIGURE 9



S-4	Resol.	Calib.	Timer
OPEN	0.1 kwhr	kwhr/Day	12 hrs.
CLOSED	0.1 kwhr	kwhr/Day	6 hrs.
CLOSED	1.0kwhr	kwhr/Mo.	18 hrs.

APPLIANCE ENERGY CONSUMPTION METER SCHEMATIC

FIGURE 10

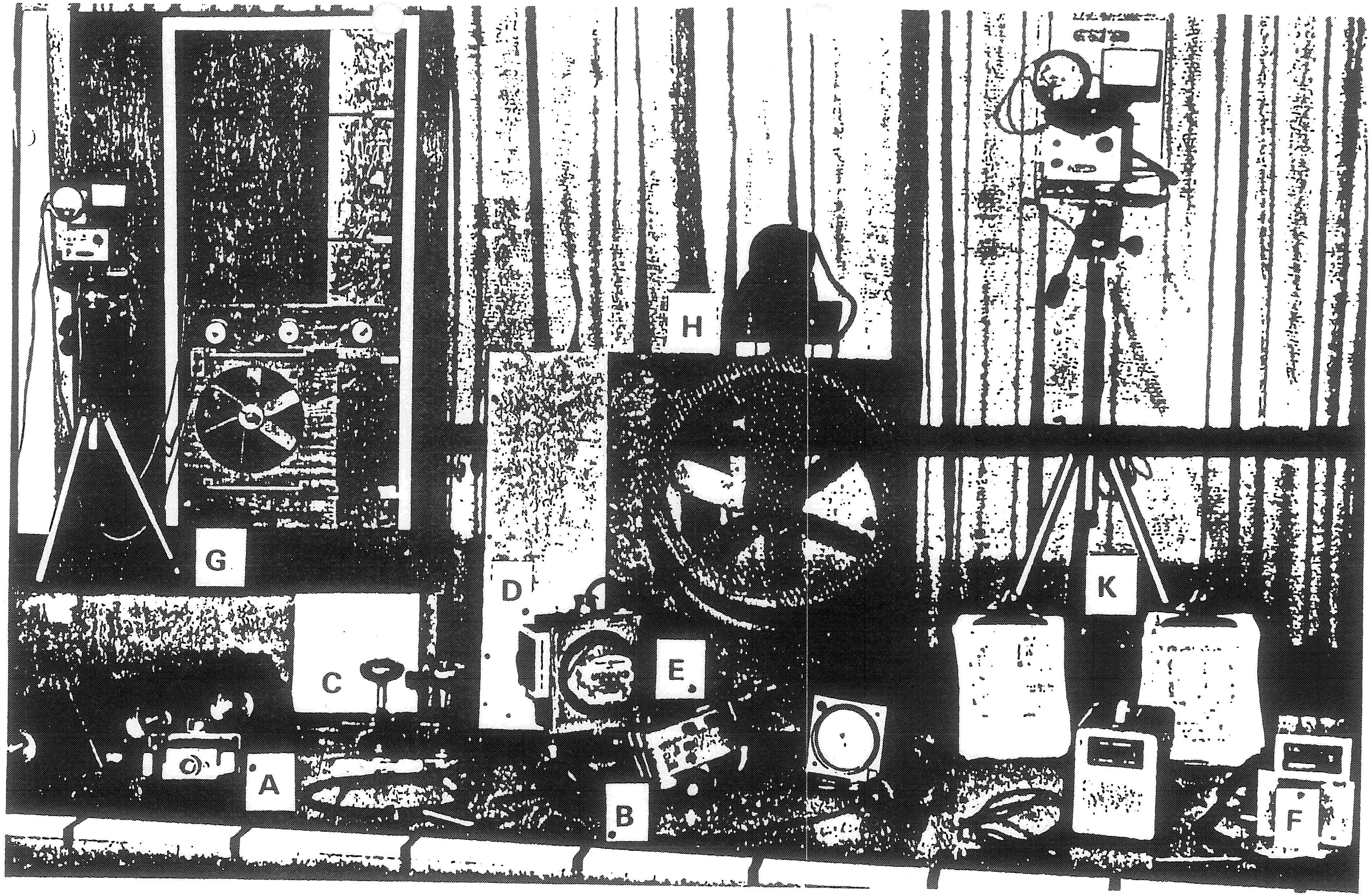
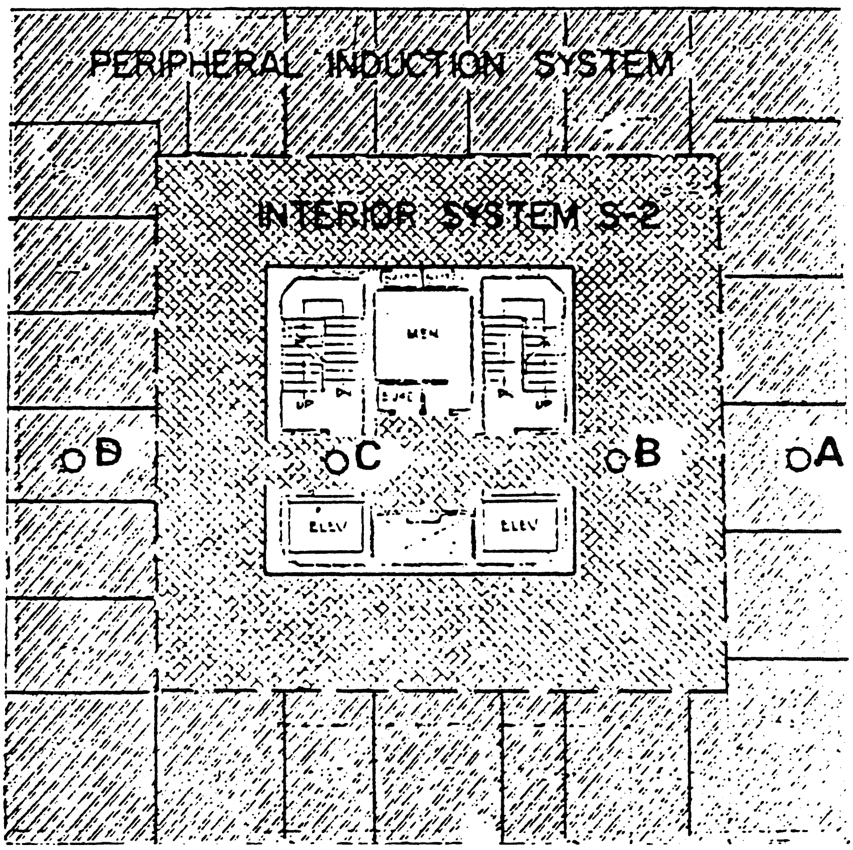
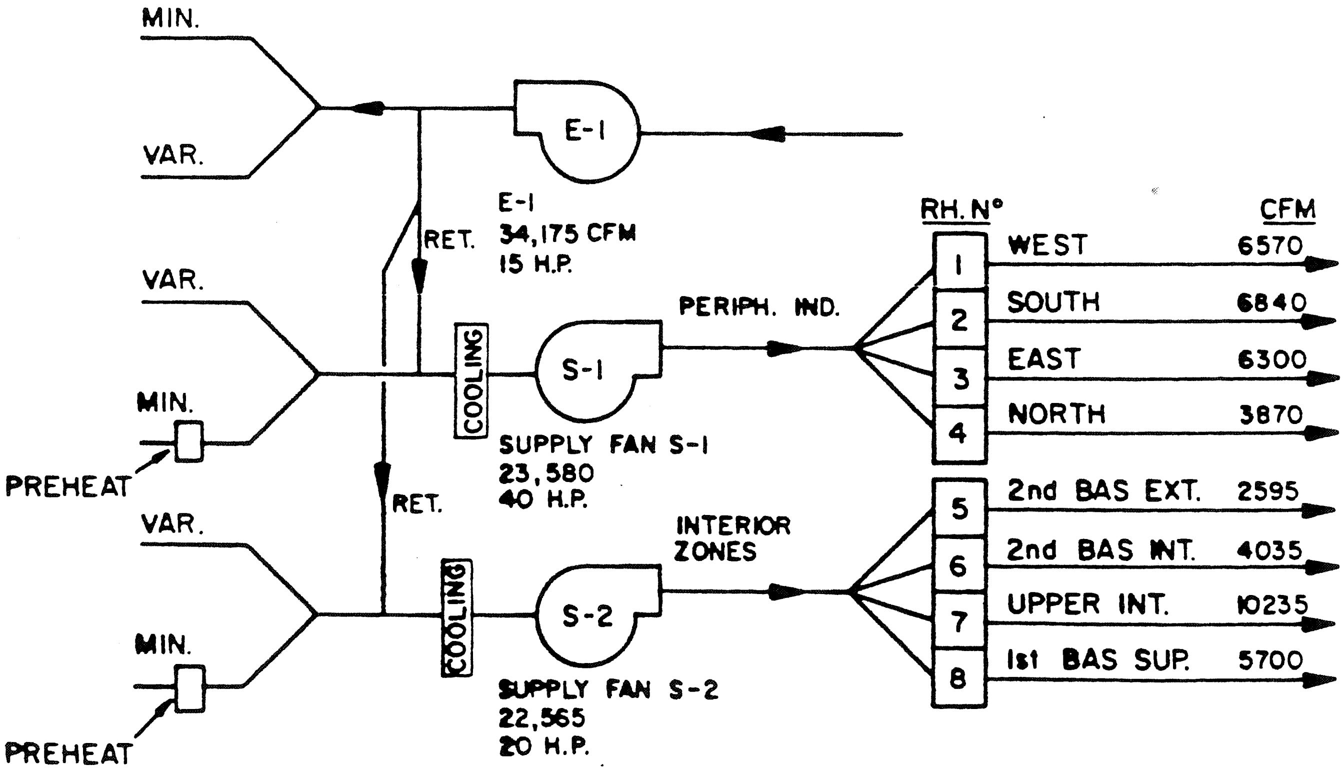


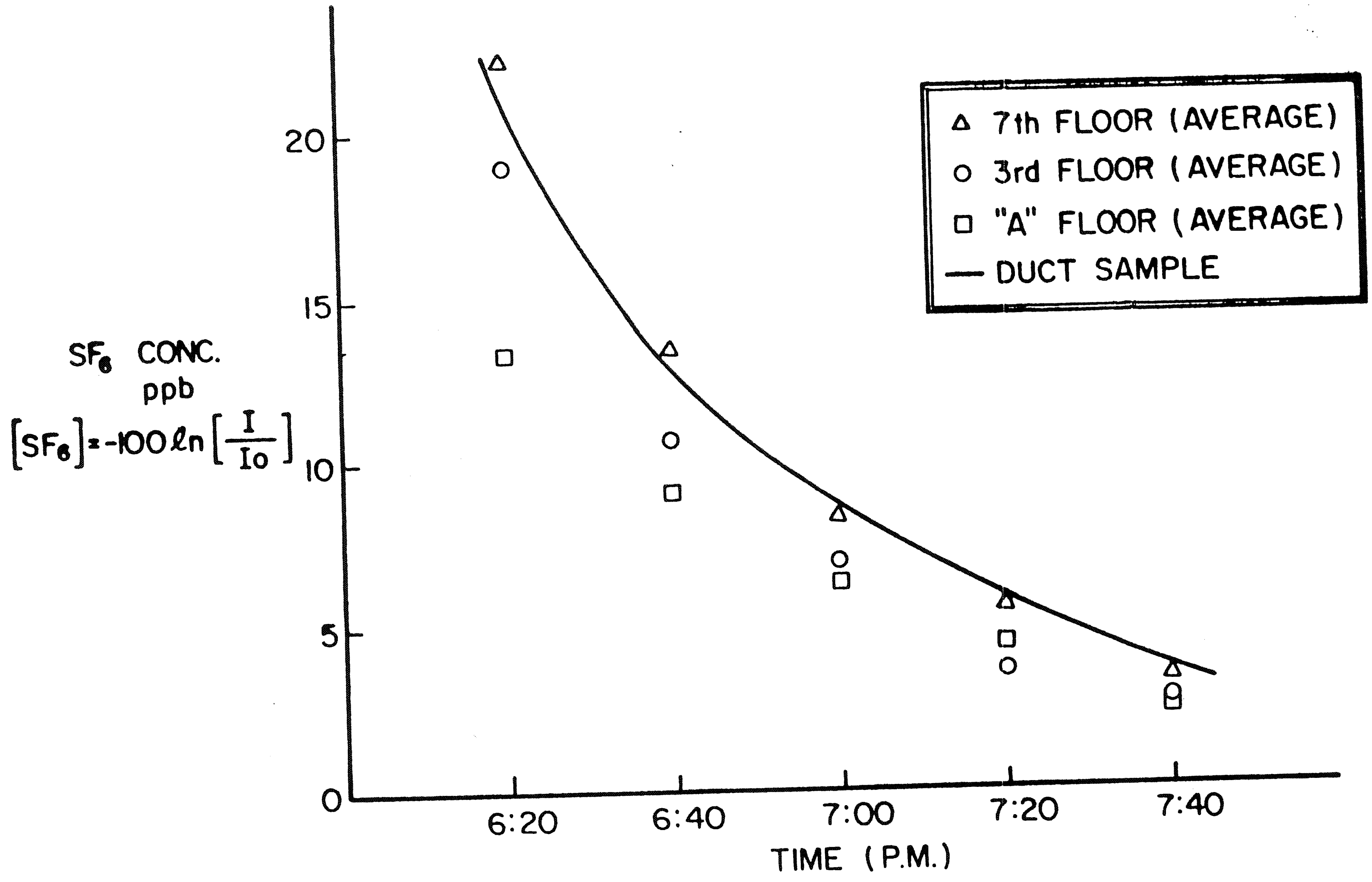
Fig. 11. The energy auditing equipment includes: camera A; measuring stick to appear in outer wall photographs B; furnace efficiency measuring devices C; appliance energy consumption meter D; portable infrared scanning equipment E; temperature measurement probes (AC and battery powered) F; (insert) the blower door assembled in a doorway where principle components include G; the lower door (18-in.) blower powered by a variable speed DC motor H; and blower door control panel with differential pressure and rpm readout J. Clipboards, K, are used to record on-site data.





NEW SOUTH BLDG., FLOOR AND VENTILATION DETAILS.

FIGURE 12



COMPARISON OF SF_6 CONCENTRATION READINGS

FIGURE 13

REFERENCES

1. Energy and Buildings - Special Princeton Issue, Vol. 1, No. 3, April 1978, Elsevier Sequoia S.A., Lausanne, Switzerland) and Saving Energy in the Home, Princeton's Experiments at Twin Rivers, ed. Socolow, R.H., Ballinger Publishing Co., Cambridge, Mass., 1978.

2. Sonderegger, Robert C., "Dynamic Models of House Heating Based on Equivalent Thermal Parameters," Princeton University Center for Environmental Studies, Report #57, September 1977.

3. Sinden, Frank W., "A Two-Thirds Reduction in the Space Heat Requirement of a Twin Rivers Townhouse," from Ref. 1.

4. Schrader, Thomas, "A Two-Parameter Model for Assessing the Determinants of Residential Space Heating," Princeton University Center for Environmental Studies, Report No. 69, June 1978.

5. Harrje, David T., Dutt, Gautam S., and Beyea, Jan, "Locating and Eliminating Obscure but Major Energy Losses in Residential Housing," ASHRAE TRANSACTIONS 1979, Vol. 85, Part 2.

6. Grot, Richard A., Private conversation concerning NBS current residential retrofit program.

7. Becker, Lawrence J., Seligman, Clive and Darley, John M., "Psychological Strategies to Reduce Energy Consumption: Project Summary Report." Princeton University Center for Energy and Environmental Studies 1979.

8. Becker, Lawrence J., and Dutt, Gautam S., "Will the Residential Energy Audit Program Save Energy," Testimony for the U.S. Dept. of Energy -- Proposed Rulemaking and Public Hearings on the Residential Conservation Service Program, April 24, 1979.

9. Taumura, George T., "Measurement of Air Leakage Characteristics of House Enclosures," ASHRAE TRANSACTIONS 1975, Vol. 81, Part 1, 1975, pp. 202-211

10. Caffey, Garry E., "Residential Air Infiltration," ASHRAE TRANSACTIONS 1979, Vol. 85, Part 1, pp. 41-57.

11. Harrje, David T., Blomsterberg, Ake K, Persily, Andrew K, "Reduction of Air Infiltration due to Window and Door Retrofits in an Older Home," Princeton University, Center for Environmental Studies Report No. 85, May 1979.

12. Hunt, Charles M. and Richtmyer, Thomas E., "Remeasurement of Air Exchange Rates in the Norris Cotton Federal Office Building After Retrofitting to Reduce Leakage," Letter Report to DOE, April 1979.

13. ASHRAE Handbook - 1977 Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., N.Y.

14. Blomsterberg, Ake K., and Harrje, David T., "Evaluating Air Infiltration Energy Losses," ASHRAE Journal, Vol. 21, No. 5, May 1979, pp. 25-32.

15. Grimsrud, David T., Sherman, M.H.,Diamond, R.C., Condon, Paul E., and Rosenfeld, Arthur H., "Infiltration -- Pressurization Correlations: Detailed Measurements on a California House," ASHRAE Transactions 1979, Vol. 85, Part 1, 1979.

16. Mattingly, George E., and Peters, Eugene F., "Wind and Trees: Air Infiltration Effects on Energy in Housing," Princeton University Center for Environmental Studies Report No. 20, May 1975. Also see Journal of Industrial Aerodynamics, Vol. 2, 1977, pp. 1-19.

17. Buckley, Charles E., Harrje, David T., Knowlton, Marcus P., Heisler, Gordon, "The Optimum Use of Coniferous Trees in Reducing Home Energy Consumption," Princeton University Center for Environmental Studies, Report No. 71, 1978.

18. Mattingly, George E., Harrje, David T., and Heisler, Gordon M., "The Effectiveness of an Evergreen Windbreak for Reducing Residential Energy Consumption," ASHRAE TRANSACTIONS 1979, Vol. 85, Part 2.

19. Kronvall, Johnny, "Testing of Houses for Air Leakage Using a Pressure Method," ASHRAE TRANSACTIONS 1978, Vol. 84, Part 1.

20. Blomsterberg, Ake K., "Air Leakage in Dwellings," Royal Institute of Technology Division of Building Construction, Stockholm, Sweden, Report No. 15, 1977.

21. Dutt, Gautam S. and Beyea, Jan, "Hidden Heat Losses in Attics -- Their Detection and Reduction," Princeton University Center for Environmental Studies Report No. 77, May 1979.

22. Grimsrud, David T., Discussions of tests in progress at Lawrence Berkeley Laboratories.

23. Harrje, David T. and Grot, Richard A., "Automated Air Infiltration Measurements and Implications for Energy Conservation," Proceedings of the International Symposium on <u>Energy Use Management</u>, ed. Fazzolare and Smith, Pergamon, New York, 1977, pp. 457-464.

24. Harrje, David T., Hunt, Charles M., Treado S. and Malik, Nickolaus, "Automated Instrumentation for Building Air Infiltration Measurements," Princeton University Center for Environmental Studies Report No. 13, 1975.

25. Grot, Richard A., "A Low Cost Method for Measuring Air Infiltration Rates in a Large Sample of Dwellings," Special ASTM Publication 1979 (Presented at ASTM-ASHRAE Symposium on Air Infiltration and Air Exchange Rate Measurement, Washington, D.C., 1978).

26. Crenshaw, Richard, Clark, Roy, Chapman, Robert, Grot, Richard and Godette, McClure, "Community Services Administration Weatherization Demonstration Project Plan," NBS IR 79-1706, March 1979.

27. Grimsrud, David T., Sherman, M.H., Janssen, John E., Pearman, A.N., and Harrje, David T., "An Intercomparison of Tracer Gases Used for Air Infiltration Measurements," LBL Report 8394, April 1979.

28. Drivas, P. J., Simonds, Peter G., and Shair, Frederick H., "Experimental Characterization of Ventilation Systems in Buildings," Environmental Science and Technology, Vol. 6, No. 7, 1972, pp. 609-614.

29. Grot, Richard A., Harrje, David T., and Johnson, L. C., "Application of Thermography for Evaluating Effectiveness of Retrofit Measures," Proceedings of the Third Biennial Infrared Information Exchange, AGA Corp., St. Louis, Missouri, 1976, pp. 103-118.

30. Pettersson, Bertyl, "Infrared Thermography and Thermal Insulation in Buildings," Statens Provningsantalt, Tech. Report 1978: 22 Boras, Sweden, 1978.

31. Sonderegger, Robert C. and Modera, M.P., Electric Co-Heating: A Method for Evaluating Seasonal Heating Efficiencies and Heat Loss Rates in Dwellings," Proceedings of the Second International CIB Symposium on Energy Conservation in the Built Environment, Copenhagen, 1979.

32. EPRI Load and Use Characteristics of Electrical Heat Pumps in Single Family Residential Housing, Westinghouse Electric Corp., Interim Report to Project RP-432-1, January 1977.

33. "Individual Oil-fired Heating Plant in Denmark (Annual Average Efficiency), Laboratory for Heating and Climatic Technique, Danish Tech. University and Heating and Installation Technique Report, Technological Institute, May 1976.

34. Bonne, Ulrich and Langmead, J. P., A Short Method to Determine Seasonal Efficiency of Fossil-Fired Heating Systems for Labeling Purposes," ASHRAE TRANSACTIONS, Vol. 84, No. 1, 1978.

35. Kelnofer, William J., Hunt, Charles M., and Didion, David A. Determination of Combined Air Exfiltration and Ventilation Rates in a Nine-Story Office Building," Proceedings of the Conference on Improving Efficiency and Performance of HVAC Equipment for Commercial and Industrial Bldgs., Vol. II pp. 322-328, Purdue University, April 1976.

36. Honma, Hiroshi, "Ventilation of Dwellings and Its Disturbances," Tekniska Meddelander, Vol. 3, No. 2, 1975.

37. Grimsrud, David T., "Case Studies in Air Infiltration," LBL 1978.

38. Dick, J.B., "Measurement of Ventilation using Tracer Gas Technique," Heating, Piping, and Air Conditioning, Vol. 22, 1950, pp. 131-137.

39. Ross, Howard D. and Grimsrud, David T., "Air Infiltration in Buildings: Literature Survey and Proposed Research Agenda," Report prepared for the International Energy Agency by U. S. DOE under contract W-7405-ENG-48, May 1978.

40. Mills, Thomas, Jr. "Proposal for Tracer Gas Air Infiltration Measurement in a High Rise Structure - New South Building," Princeton University Center for Environmental Studies Project Note - September 1978.

41. Harrje, David T. and Grot, Richard A., "Instrumentation for Monitoring Energy Useage at Twin Rivers," From Ref. 1.

42. Grot, Richard A., "Field Performance of Gas and Electric Water Heaters," Proceedings of the Conference on Major Home Appliances for Energy Conservation, Purdue University, March 1978.

43. Hall, Shawn A. and Harrje, David T., "Instrumentation for Omnibus Experiment in Home Energy Conservation," Princeton University Center for Environmental Studies Report No. 21, May 1975.

44. Harrje, David T., "Heat Pump Performance Measured Using Ten Residential Units Operating in the Northeastern United States," Procedings of the International Conference on Energy Use Management, ed. Fazzolare and Smith, Pergamon Press, New York, 1977, Vol. I, pp. 447-456.

45. Harrje, David T., "Heat Pump Performance as Measured in Ten Residential Dwellings," Princeton University Center for Environmental Studies Report No. 82, July 1978.

46. Omega Engineering, Inc, "The Omega 1978 Temperature Measurement Handbook." Omega Engineering, Inc., Box 4047, Stamford, Connecticut 06907.

47. Yellow Springs Instrument Co., Inc., "YSI Precision Thermistors," (November, 1978). Industrial Division, Yellow Springs Instrument Co., Inc.; Yellow Springs, Ohio 45387.

APPENDIX A

Components of the House Doctor Kit

The following is a listing of components that make up the House Doctor Kit. Other key auxiliary instrumentation is also listed. Approximate cost is shown in the last column

Item	Source	Approximate Cost
"Probeye" Infrared Viewer	Hughes Aircraft Company Industrial Products Div. Image Device Marketing 1284 No. Broad Street Hillside, N.J. 07205 (201) 289-7770	$7000
Omega Model 250EF2-03 Temperature Sensor with Model 68007-E Surface Pyrometer and standard Thermocouple assemblies	Omega Engineering, Inc. One Omega Drive, Box 4047 Stamford, Conn. 06907 (203) 359-1660	$295
Blower-Door Components		
Cat. #2z846 Constant-Torque, Adjustable-Speed D.C. Motor	W. W. Grainger 819 East Gate Drive Mt. Laurel, N.J. 08504	$ 235
Cat. #4C249 Aluminum Duct Type Fan w/o Motor		$ 95
Simpson Wide-Vue Panel Meter Model 1329 0-1 Ma DC (4 1/2")	Any Major Electronic Supply House	$ 29
Dwyer Magnehelic Gauge 0-.5" Water	Dwyer Industries Hightstown, N.J. 08520 (609)448-9200	$ 30
Dwyer Air Meter No. 460		$ 18
Camera Tripod (for Blower-Door control panel and camera)	Any Camera Store	$ 100
Tachometer circuit designed and built in house		

Item	Source	Approximate Cost
• Bacharach Test Equipment		
Fyrite No. 10-5020 Combustion Kit	Tyrol Distributors, Inc.	$ 145
Truespot Smoke Test Set No. 21 7006	517 South East Blvd. Vineland, N.J. 08360	$ 37
Draftrite Pocket Draft Kit No. 13-3001	(609) 691-6740	$ 26
• Dial Thermometers, 150-750 F (18") and 200-1000 F(5")	Abbeon Cal., Inc. 123-50 Gray Ave. Santa Barbara, Calif. 93101	$ 30
• Appliance Time-Sequence Meter		
General Electric Type IW-70-S Watthour Meter 0.288 con/rev)		$ 35
General Electric Model 742X5G11 SI-70 Meter Box	Electrical Supply House	$ 15
Sodeco Model ET125-115 5 Digit Counter	Sodeco Div. Landis & Gyr 4 Westchester Plaza Elmsford, N.Y. 10523 (914) 592-4400	$ 18
Intermatic Model E-1020 24 hr. Timer	Electronic Supply House	$ 18
Electronic Circuit designed and built in house		$ 150
• Optical Tapemeasure (6-100 feet)	Ranging Inc. 90 Lincoln Rd., North East Rochester, N.Y. 14445	$ 25
• Spectran/Instruments Model 640-1 Heat Flux Meter	Spectran Instruments La Habra, Calif.	$ 400
• Polaroid "The Reporter SE" Camera	Any Camera Store	$ 50
• 100 Ft. Tapemeasure	Any Tool Supplier	$ 20
• 10 Foot Measuring Gauge (made from 1x3 clear pine wood)	Lumber Yard	$ 10

Item	Source	Approximate Cost
• Alnor Thermo-Anemometer with Model 1520 Probe	Alnor Inst. Co. 7301 N. Caldwell Ave. Niles, Ill. 60648 (312)647-7866	\$ 450
• Sling Psychrometer #210 Maximum-Minimum Thermometers #110-40/120 F	Science Associates, Inc. 230 Nassau St., Box 230 Princeton, N.J. 08540 (609) 924-4470	\$ 36 \$ 16
• Automated Air Infiltration Unit		
Techtran Datacassette Model 8410. Will be replaced with Model 817 @ \$1295	Techtran Industries, Inc. 200 Commerce Drive Rochester, N.Y. 14623 (716) 334-9640 attn: Judy Monje	\$2000
I.T.I. Model 505 SF_6 Detector Chromatograph	Ion Track Instruments 3 A Street Burlington, Mass. 01803 (617) 272-7233	\$4895
• Automatic SF_6 Injection Panel Components:		
Matheson Model 70 Low Pressure Regulator	Matheson 932 Paterson Plank Road	\$ 49
Matheson Model 8 Brass Two Stage Regulator, CGA No. 580; 4 to 40 psi delivery pressure	P. O. Box 85 East Rutherford, N.J. 07073	\$ 84
Catalog No. 63-3131 Chrome-plated Brass Gauge 2 1/2" Diameter		\$ 9
Catalog No. 4HD300 Sampling Cylinder 300 ml Stainless Steel		\$ 67
Catalog No. 3812 F4B Brass Hoke Valve 1/4" NPT (Fem)		\$ 12
• Mylar/Aluminum Sample Bags	Calibrated Instruments, Inc. 729 Saw Mill River Road Ardsley, N.Y. 10502	\$ 11
• Smoke Air Flow Indicators Model 410	National Mine Services POB A Green River, Wyoming 82935	\$ 20

Item	Source	Approximate Cost
Commodore PET 2001 (8K Bytes) Computer with No. 2 Cassette Recorder	Commodore Business Machines Inc. 901 California Ave. Palo Alto, Calif. 94034	\$ 795 \$ 90
Teletype Model 43 with TTL Interface (4320AAA)	Owens Associates 147 Norwood Ave. New York, N.Y. 10304	\$ 985
CMC ADA 1200C 300 Band RS232C Printer Adapter for PET	Connecticut Microcomputer 150 Pocono Road Brookfield, Conn. 06804 (203) 775-9659	\$ 169

APPENDIX B

Temperature Probe Design Considerations

The uses of the Temperature Probe are outlined in Section V. Field testing the first version of the probe (powered by AC) indicated the following characteristics:

1. AC line operation proved to be a definite drawback: it resulted in excessive lengths of either AC extension cords or thermocouple extension wires.
2. Very bad response to thermal shock was evidenced when going from attic to basement or indoor to outdoor environments. This was shown to result in a long recovery time -- up to 45 minutes.
3. Surface probe proved to be very fragile and subject to breakage when used by inexperienced personnel. (Replacement cost $95).
4. Surface probe took a measureable amount of heat away from the spot being measured. On bare metal surfaces, this was not a problem. However, on wood paneling, painted walls, glass, etc. the response time was about 10 seconds. This meant that to achieve a final reading the probe had to be moved to a second position where the proper temperature was present, and wait another 10 seconds to get a final reading.
5. Overall readout accuracy = $\pm$ 0.6 + 0.1°F (- 0.5 to 0.7°F) or (-0.3 to +0.4°C) at constant temperature. Reference junction drift (50 to 104°F, 10 to 40°C ambient) = 0.8°F (.4°C). Probe accuracy (ANSI limits of error) = $\pm$ 3°F ($\pm$ 1.7°C). Worst case overall accuracy (over temperature range) becomes essentially $\pm$ 4.4°F ($\pm$ 2.5°C).

6. An operating temperature range of 50 to 104°F (10 to 40°C) was achieved combined with a storage temperature range of - 40 to 167°F (- 40 to 75°C).

7. A readout range of 0 to 400°F (-18 to 204°C) with 0.2°F (0.1°C) resolution.

By Mid-1978, Digital Panel Thermometers were becoming quite competitive. Another survey was made and an Omega Engineering, Inc. Model 250B was purchased (complete specifications are given in Ref. 46). Improvements achieved included:

1. Readout range of - 110 to 400°F (- 79 to 204°C).
2. Resolution of 0.1°F (0.05°C).
3. Overall readout accuracy of ± .3°F (± 1.7°C).
4. 5 V DC operation.
5. Provision for holding reading.
6. Provision for display blanking.

Thermal shock testing was done on the unit. In response to a -35°F (- 19°C) change shock, a thermal transient peak of + .90F (+0.5°C) was noted after 1 minute and ending by 30 minutes, with final stability being achieved in 50 minutes with a -0.2°F (-0.1°C) change in reading. The sensor was held at room temperature and its temperature was monitored during the test.

There are apparently two contributing factors for this effect. They are:

1. Cold junction compensation. In this meter, cold junction compensation is accomplished by potting a transistor in a hole in the terminal block near the TC input terminals. Obviously, there is a considerable time and temperature lag between the cold junction and its temperature sensor.
2. Thermal storage capacity in sensor cable. The surface probe cable is quite bulky, and though flexible, has considerable thermal storage capacity. This will help to reduce the thermal shock slightly as the previous temperature is conducted to the reference junction, but delays stabilization until the cable stabilizes.

To overcome these difficulties, the meter was mounted in a plexiglass box lined with 3/8" thick styrofoam (See Fig. 8). The box was made long enough to provide 1.5" (3.8cm) of air space between the back of the meter and the rear insulation. This provided room for about 1 ft. (30 cm.) of TC extension wire to connect the cold junction to the rear panel TC connector. This provides some isolation of the thermal storage capacity of the sensor cable from the cold junction. The styrofoam thickness was chosen to limit the internal temperature rise to 18°F (10°C) above ambient (due to meter power dissipation). This effectively reduced the thermal shock transient to less than + .4°F (+ .2°C) peak with final stability being achieved in 100 minutes with no change in reading. The unit returned to within .1°F (.06°C) in 40 minutes. Warm-up time for room temperature start was 60 minutes.

This meter is powered by a 12V, 4.5 Amp. Hr. Gel Cell and a 12V to 5V DC-DC converter mounted in a separate minibox that can be belt mounted or worn with a shoulder strap.

The meter itself is provided with a neck strap, display blanking switch, and a switch to hold the reading.

Field tests were made in the Fall of 1978 and showed the following:

1. Battery operation and neck strap portability a definite plus. However, the battery pack was too heavy for belt use and was noticeable with a shoulder strap.
2. Response to thermal shock was acceptable, but recovery time increased to 100 minutes. However, recovery to within .1°F (.06°C) shortened to 40 minutes.
3. Warm-up time lengthened to 60 minutes. This was overcome by turning the unit on with display blanked when leaving for the field, as more than an hour would always elapse before use. This also meant that unit was never turned off in the field, but the display was blanked when not in use.
4. The need for continuous operation combined with a DC-DC converter efficiency of 55 to 65% required a heavy battery to achieve 7 to 8 hours of operation.

5. All the prior probe criticisms still apply. This time, one could note hand effects, i.e. heat conduction to junction through the probe handle.
6. Overall readout accuracy of ± .3°F (± .17°C), T constant. A reference junction drift ±0.4°F (± .22°F)*. Probe accuracy (ANSI ERROR LIMITS) ± 3°F.(1.7°C). Worst case overall accuracy (over temperature range) becomes essentially ± 3.7°F (± 2°C)
7. An operating temperature range of 50 - 104°F was achieved combined with a storage temperature range of -40 to 158°F (-40 to 75°C).
8. The provision for holding the reading, combined with 0.1°F (.06°C) resolution were definitely desirable.

In the overall view this unit would appear to be useable by trained personnel, but not suitable for use by the average homeowner. A rugged, more accurate surface probe is required along with a lighter battery pack and better performance under environmental temperature changes to achieve a practical unit. It is also noted that the Model 250B has been dropped from Omega Engineering's 1979 Catalog. Table B-1 contains a summary of a 1979 literature search of Digital Panel Thermocouple Meters. Table B-2 lists the ANSI limits of error of thermocouples (Standard C96.1). Reference to Tables B-1 and B-2 will indicate that the practical limit of thermocouples has been reached, except for type T with special calibration. Also, no commercially available surface probes appear suitable.

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*50° to 104°F, 10 to 40°C ambient.

The other available methods of measuring temperature are Semiconductor, Resistance Temperature Detector (RTD) and Thermistor.

All semiconductor methods (diode, transistor, diode-connected transistor, or I.C.) can be dismissed because each unit will require calibration. In addition, the packaging does not lend itself to surface probe construction.

RTD's are basically bulky, exhibit slow response (i.e. about 10 times TC's or thermistors), low output, and even in the best (platinum) case are still non-linear. The thin film types, are of course, faster, but still objectionably large and fragile.

Bead thermistors, however, exist as both individuals and composites. The individual thermistor, though highly non-linear, is of high output. The composite (two thermistors within the same bead), of similarly high output, can be highly accurate and linear over restricted ranges when used with the correct resistors and circuit (See Ref. 47). While four published ranges are "standard," (see Table B-3) dozens of special ranges exist (see Table B-4). The important thing is that all the ranges may be obtained by using different combinations of resistors with the same thermilinear composite.

In general, the worst case "accuracy and interchangeability" is ± 0.27°F (± .15°C) over the range of -22 to + 212°F, (-30 to 100°C) and generally ± .15°F (± .08°C) for less over any particular linear range. The non-linearity over the "standard" ranges varies from ± .06°F to ± .39°F (± .03 to ± .21°C) (see Table B-3) and may be corrected if desired. A typical data sheet and error curve is shown in Fig. B-1. The composites are useable over a temperature range of -40 to 302°F (-40 to 150°C), sufficient for all applications except stack temperatures. Also, double (± .13°F) accuracy and interchangeability (± .07°C) thermilinear composites are available on special order for approximately a 65% price increase.

The small physical size of the bead (see Fig. B-1 and low thermal inertia and time constant make a good candidate for use in a surface probe. Such a proposed design is shown in Fig. B-2.

The above characteristics combined with high level output (tenths of volts), excellent interchangeability and accuracy and moderate cost make the thermilinear network a logical choice for the temperature sensor. Table B-5 compares the characteristics of typical sensors of each type.

The recent introduction by Intersil of the ICL 7106, 7107 3½ Digit Single Chip A/D converter I.C. has made the 3 1/2 Digit DPM a highly competitive field. Units are now available at prices from $31 up (complete). The 7106 is designed to drive a LCD display while the 7107 is designed to drive a LED display.

The chips are CMOS with high input impedance (>1000 megohms), auto-zero, true differential input and reference, and uses the integrate up-integrate down conversion technique. It has a low supply current (1 ma + 8 ma/segment) and a very high stability and accuracy and can be set for a full scale of ± 2000 counts with any input voltage from 0.2V to 2V by selecting the reference voltage and a few external components. Thus, ratiometric operation is possible. A summary of the characteristics of the ICL 7106, 7107 is contained in Ref. 48.

An International Microtronics Corp. Model 1100 DPM (Intersil ICL 7107 CPL based) was bought (see Fig. B-3) for $31 and tested for warm-up drift, response to thermal shock, thermal drift, and supply current drain.

Warm-up drift was found to be less than 23 counts (out of 2000) lasting 10 minutes, with the reading coming within 6 counts of final value within 3 minutes. The response to a -35°F thermal shock was a smooth drift of -7 counts (out of 2000), beginning after 10 minutes and ending by 25 minutes There was no zero drift during either warm-up or thermal shock. Thus, the warm-up transient may be expressed as + 1.15% of reading lasting 10 minutes and thermal drift as + .01% of reading per degree F. change in ambient.

The supply current at 5 V was measured as 200 ma. maximum (display reading "- 188.8") and 27.5 ma with the display blanked.

If commercially available DC-DC converters (typical efficiency 55 to 65%) are abandoned in favor of a custom designed high-efficiency switching regulator (> 80%), then a light battery pack can be used (i.e. 12 V .9 AH). Such a design is in process, based on the 723 I.C. precision voltage regulator.

Such a DPM -- Thermilinear Network -- Hi Efficiency Power Supply combination would make a temperature measuring device suitable for use by the average homeowner, and have an overall accuracy and interchangeability of better than 0.5°F. A Simplified diagram of the meter is shown in Fig. B-4.

The recent introduction by International Microtronics of their Series L500 DPM opens an attractive alternative for the "professional"

House Doctor. It is based on the Intersil ICL7106 3 1/2 digit single chip A/D converter and uses a Liquid Crystal Display (LCD), a complete set of specifications for the meter is included as (Fig. B-5. The L500 DPM offers the following significant advantages:

1. The LCD is easily readable in both very high light levels and direct sunlight.
2. Because of the LCD, the total power drain of the meter is very low (about 10 milliwatts). This will greatly reduce battery requirements and therefore weight.
3. Essentially no warm up time!
4. Accuracy and linearity is improved by a factor of 2.
5. Thermal drift is improved by an order of magnitude.

To take advantage of the improved performance of this meter an additional feature may be added for the professional. This would allow him to change thermilinear networks with a selector switch. Since the same thermolinear composite (YSI#44018) is used with all four thermolinear components, the same probe can be used for all. This then requires only switching R1, R2, R3 and R4 (See Fig. B-4) with a multipole switch. This then permits the professional to choose the most favorable range for accuracy and precision, specifically:

1. YSI#44201 +32 to +212 °F +/-0.388 °F Linearity Deviation (LD)
2. YSI#44202 +23 to +113 °F +/-0.120 °F LD
3. YSI#44203 -22 to #122 °F +/-0.290 °F LD
4. YSI#44014 +30 50 +100 °F +/-0.055 °F LD

However, the LCD meter does have three drawbacks:

1. In very dim light the display will require supplementary lighting.
2. The cost of the L500 is almost twice that of the 1100 ($59 vs. $31).
3. The LCD display is only .35" high compared to .50" for the LED.

TABLE B-1

DIGITAL PANEL T. C. METER SURVEY

YEAR	PRICE	T.C. TYPE	RANGE	RESOLUTION	OVERALL ACCURACY
1977	$275	E	0°F to 400°F	.2°F	+ .7° - 6°F
1978	$335	E	-110°F to 400°F	.1°F	± .3°F
1979	$199	T	-200°F to 700°F	1°F	± 1.1°F
1979	$375	T	-99.8°F to 752°F	.2°F	± 1.2°F
1979	$329	T	-328°F to 752°F	1°F	± 1.55°F
	$199	J	-170°F to 1400°F	1°F	± 1.5°F
[illegible]979	$249	K	-50°C to 999°C	1°C	± 1/2% of Reading
1979	$199	T	-245°F to 750°F	1°F	± 2.5°F

TABLE B-2. ANSI LIMITS OF ERROR OF THERMOCOUPLES
(ANSI STD. C 96.1)

ANSI TYPE	MATERIAL	TEMPERATURE RANGE IN °F	LIMITS OF ERROR	
			STANDARD	SPECIAL
J	Iron vs. Constantin	Below 32	**	**
		32 to 530	± 4°F	± 2°F
		530 to 1400	± 3/4%	± 3/8%
K	Chromel vs. Alumel	Below 32	**	**
		32 to 530	± 4°F	± 2°F
		530 to 2300	± 3/4%	± 3/8%
E	Chromel vs. Constantin	Below 32	**	**
		32 to 600	± 3°F	± 2 1/4°F
		600 to 1600	± 1/2%	± 3/8%
S,R	Platinum vs. Platinum-Rhodium	Below 32	**	**
		32 to 1000	± 2 1/2°F	± 2.5°F
T	Copper vs. Constantin	-150 to -75	± 2%	± 1%
		-75 to 200	± 1 1/2°F	± 3/4°F
		200 to 700	± 3/4%	± 3/8%

** No limit specified

TABLE B-3. "STANDARD" RANGE VALUES FO.. THE YSI-4401B THERMOLINEAR COMPOSITE

THERMO-LINEAR COMPONENT NO.	TEMP. RANGE (°F)	LINEARITY DEV. (°F)	$E_o = (\ ) E_{in} T + (\ ) E_{in}$	R_T = (Ohms)/o_t + (Ohms)	R_1 (Ohms)	R_2 (Ohms)	*E_{IN} MAX (Volts)	**SHE_M Temp (o_F)
44201	32 to 212	± .388	.00297127 + .0398500	-9.508 + 3072.48	3,200	6,250	.3187	200°F
44202	23 to 113	± .120	.00315810 + .0930830	-18.001 + 5.69.42	5,700	12,000	.4582	113°F
44203	-22 to 122	± .290	.00377588 + .228102	-70.608 + 14,435	18,700	32,500	.7780	108°F
44204	30 to 100	± .055	.00312890 + .0923200	-17,834 + 5173.8	5,700	12,400	.4716	100°F

* The maximum network input voltage that will keep the self-heating error below .01°F (in still air) throughout the range

** The temperature at which the maximum self-heating error occurs.

TABLE B-4. SPECIAL RANGE VALUES FOR THE YSI-44018 THERMOLINEAR COMPOSITE

The following are 44018 ranges which have been calculated, for which YSI does not stock fixed resistors.

The resistor's required tolerances are ±0.1% to achieve the linearity specified. As with all thermolinear networks, the load resistance should be 10 megohms or more. In many cases the linearization has not been optimized, but carried only far enough to meet a specific requirement.

44018 Temp Range °C	Linearity Dev. °C	E_o = () $E_{in}T$ + () E_{in}	R_T = Ohms/°T + Ohms	R_1	R_2
35 to 135°C	.2	.0046257 + .96434	-5.43526 + 1133.1	1175	2375
28 to 64°C	.04	.0047970 + .921358	-9.11442 + 1750.58	1900	4300
0 to 40°C	.27	.0048347 + .753067	-28.5226 + 4442.72	5900	12400
45 to 75°C	.04	.0049335 + .908	-9.867 + 1816	2000	3900
15 to 35°C	.01	.0053547 + .83813	-25.5611 + 3687.77	4400	10100
15 to 45°C	.03	.0054422 + .835753	-23.837 + 3660.6	4380	9450
20 to 120°C	.23	.0048887 + .930159	-8.29134 + 1577.55	1695	3385
20 to 65°C	.06	.0050589 + .893676	-12.6473 + 2234.19	2500	5360
0 to 10°C	.00	.0073988 + .520226	-310.753 + 21849.5	42000	67900
-5 to 125°C	1.11	.0051169 + .882889	-13.3552 + 2304.34	2610	5230
0 to 120°C	.81				
45 to 125°C	.22	.0045261 + .973301	-4.6619 + 1002.5	1030	2050
5 to 130°C	.88	.0049874 + .909235	-10.6233 + 1936.67	2130	4635
0 to 30°C	.06	.0063226 + .715584	-73.8485 + 8358.02	11680	22960
-30 to 50°C	.16	.0067965 + .65107	-127.096 + 12175	18700	35250
20 to 32°C	.00	.00534502 + .837875	-23.5181 + 3686.65	4400	10100
15 to 65°C	.07	.00590796 - .775471	-39.8117 - 5225.63	6740	12250
-5 to 45°C	.06	.00568456 + .805853	-32.402 + 4593.39	5700	12000
22 to 42°C	.02	.0056694 + .806006	-30.8702 + 4388.7	5445	10800
0 to 100°C	.22	.0053483 + .86507	-17.115 + 2768.23	3200	6250
0 to 60°C	.14	.0060508 + .76377	-47.045 + 5938.37	7775	14800
-30 to 55°C	.31	.00679018 + .65219	-128.334 + 12326.5	18900	37000
-30 to 70°C	.96	.00651575 + .69061	-94.4784 + 10013.9	14500	30000
50 to 100°C	.05	.00512938 + .88112	-12.8234 + 2202.82	2500	4530
-25 to 55°C	.2	.00666519 + .67413	-106.643 + 10786.1	16000	31000
-30 to 60°C	.37	.00651957 + .68761	-91.274 + 9626.57	14000	25500

TABLE B-4 (cont.d.)

44018 Temp Range °F	Linearity Dev. °F	E_o = () $E_{in}T$ + () E_{in}			R_T = Ohms/°T + Ohms			R_1	R_2
40 to 140°F	.21	.00302422	+	.9445	-11.6765	+	3646.52	3861	7900
95 to 275°F	.49	.00256986	+	1.04657	-3.01959	+	1229.72	1175	2375
0 to 150°F	.40	.00347982	+	.845015	-34.7982	+	8450.15	10000	19000
32 to 104°F	.48	.00268597	+	.839017	-15.8459	+	4949.78	5899.5	12400
88 to 108°F	.01	.00319286	+	.8935	-18.8379	+	5271.65	5900	11000
20 to 120°F	.19	.00325846	+	.892615	-21.18	+	5802	6500	13000
113 to 167°F	.08	.00274693	+	.99658	-5.49387	+	1993.16	2000	3900
59 to 95°F	.02	.00297434	+	.933282	-13.0871	+	4106.44	4400	10100
59 to 113°F	.07	.00302733	+	.932831	-13.2597	+	4085.8	4380	9450
68 to 248°F	.42	.00271598	+	1.01708	-4.60631	+	1724.96	1695	3385
68 to 148°F	.12	.0028104	+	.9836	-7.0262	+	2459	2500	5360
60 to 160°F	.22	.0029369	+	.963694	-9.1044	+	2987.45	3100	6250
79 to 103°F	.01	.00319536	+	.892892	-19.1722	+	5357.35	6000	11350
-35 to 135°F	1.29	.003775	+	.76125	-75.5	+	15225	20000	37000
-25 to 125°F	.39	.003775	+	.76125	-75.5	+	15225	20000	37000
0 to 100°F	.26	.00378237	+	.772305	-70.7303	+	14442.1	18700	35250
80 to 120°F	.03	.00293369	+	.951491	-10.2679	+	3330.22	3500	7400
45 to 85°F	.01	.00306173	+	.912216	-16.8395	+	5017.19	5500	12650
-22 to 78°F	.20	.00422799	+	.658794	-191.105	+	29777.5	45200	85200
80 to 260°F	.49	.00264627	+	1.03168	-3.77157	+	1470.15	1425	2875
60 to 110°F	.05	.00301416	+	.932425	-13.202	+	4084.02	4380	9525
20 to 200°F	.48	.00311397	+	.927836	-14.0129	+	4175.26	4500	8800
32 to 50°F	.00	.00411031	+	.651755	-172.633	+	27373.7	42000	679000
-10 to 40°F	.14	.00436352	+	.606864	-272.72	+	37929	62500	110000
100 to 200°F	.19	.00282122	+	.983242	-6.4888	+	2261.46	2300	4300
200 to 300°F	.13	.0021696	+	1.10217	-.92208	+	468.422	425	800
110 to 160°F	.04	.0027292	+	.998024	-5.4584	+	1996.05	2000	4060
35 to 110°F	.14	.00315393	+	.906675	-17.9774	+	5168.05	5700	12000
0 to 200°F 5 to 190°F	1.72 .88	.00321539	+	.899113	-18.8904	+	5282.29	5875	11300
23 to 257°F 28 to 248°F	1.7 1.47	.00284272	+	.973856	-7.4195	+	2541.76	2610	5230
113 to 257°F	.40	.00251447	+	1.05376	-2.5899	+	1085.37	1030	2050
41 to 266°F	1.58	.0027708	+	.997897	-5.9018	+	2125.52	2130	4635
32 to 86°F	.10	.00351258	+	.827986	-41.0269	+	9670.88	11680	22960
-22 to 122°F	.29	.00377587	+	.771897	-70.6088	+	14434.5	18700	35250
32 to 212°F	.39	.00297125	+	.96015	-9.508	+	3072.48	3200	6250
0 to 160°F	.64	.0038516	+	.863563	-28.0207	+	7148.16	8280	15470
30 to 100°F	.05	.0031287	+	.907684	-17.834	+	5173.8	12400	5700
100 to 140°F	.03	.0028672	+	.969191	-7.9933	+	2701.95	5575	2790
20 to 60°F	.03	.0037129	+	.775441	-69.0605	+	14423.2	37200	18600
0 to 50°F	.07	.0039879	+	.711396	-122.83	+	21911	59710	30800
-20 to 150°F	1.04	.003593	+	.814014	-46.7096	+	10582.2	13000	24500
-15 to 145°F	.55	.003593	+	.814014	-46.7096	+	10582.2	13000	24500
80 to 180°F	.17	.0030218	+	.940248	-11.1928	+	3482.68	3704	6843
32 to 140°F	.29	.00335849	+	.871115	-26.1123	+	6772.92	7775	14800

TABLE B-5. CHARACTERISTICS OI , RIOUS TEMPERATURE SENSORS

ID	TYPE	ABSOLUTE ERROR[1] STANDARD	ABSOLUTE ERROR[1] SPECIAL	LINEARITY ERROR	TIME CONSTANT	TEMPERATURE RANGE	UNIT COST[2] STANDARD	UNIT COST[2] SPECIAL
1	ANSI TYPE T THERMOCOUPLE	±1.5°F	±.75°F	-50°F	20 Sec	-75°F to 200°F	$32.00	$ 38.40
		±.75%	±.375%	-73°F		200°F to 700°F		
2	ANSI TYPE E SURFACE PROBE	±3°F	±2.25°F	-55°F	<10 Sec	32°F to 480°F	$95.00	$115.00
3	PLATINUM RTD	±.6°F	---	+18°F	<20 Sec	-220°F to 850°F	$14.00	---
4	SILICON I.C.	± °F	°F	±54°F	60 Sec	- °F to 300°F	$ 2.50	$ .00
5	THERMILINEAR NETWORK	±.27°F	±.13°F	±.055°F	<10 Sec	30°F to 100°F	$15.25	$25.25
6		±.27°F	±.13°F	±.29°C	<10 Sec	-22°F to 122°F	$15.25	$25.25

1 OMEGA ENGINEERING, INC. #CPSS-18U-12
2 " " " #68007
3 " " " #1PT100K4528
4 ANALOG DEVICES, INC. #AD590
5 YELLOW SPRINGS INSTRUMENT CO., INC. #44204
6 " " " " " #44203

NOTES:

1. Absolute error includes interchangeability.
2. Costs of April 1979.

YSI THERMILINEAR® COMPONENT

YSI 44204

RANGE 30° to 100°F

This Thermilinear Thermistor Network is a composite device consisting of resistors and precise thermistors which produce an output voltage linear with temperature, see Fig. 1, or a linear resistance with temperature, see Fig. 2. The precise thermistors can either be the YSI #44018 (as included in the #44204) or they can be a YSI 700 Series Probe since they are electrically identical.

Equations which describe the behavior of the device are: (Refer to Fig. 1)

$Eout_1 = (-0.0031289\ Ein)T + 0.90768\ Ein$

$Eout_2 = (+0.0031289\ Ein)T + 0.09232\ Ein$

(Refer to Fig. 2)

$R_T = (-17.834)\ T + 5173.7$

$T = °F$

	Voltage Mode	Resistance Mode
Thermistor Absolute Accuracy and Interchangeability:	±0.27°F	±0.27°F
Linearity Deviation:	±0.055°F	±0.98 ohms
***Ein Max**	4 Volts	
***I_T Max**		685 ua
Sensitivity:	0.0031289 Ein/°F	17.834 ohms/°F
Load Resistance:	10 Megohm min.	
Time Constant:	The time required for the thermistor to indicate 63% of a new impressed temperature. In 'well stirred' oil, 1 sec.; in free still air, 10 sec.	
Storage Temperature:	-112° to +250°F (-80 to +120°C)	

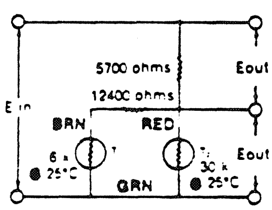


Fig. 1

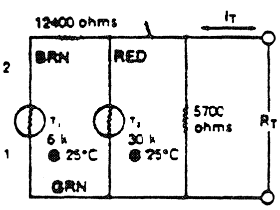


Fig. 2

***Ein Max. I_T Definition:**

Ein Max. I_T Max values have been assigned to control the thermistor self-heating errors so that they do not enlarge the component error band, i.e., the sum of the linearity deviation plus the probe tolerances.

Ein Max. I_T Max values are assigned using a thermistor dissipation constant of 8MW/°C in stirred oil. If better heat-sink methods are used or if an enlargement of the error band is acceptable, Ein Max. I_T Max values may be exceeded without damage to the thermistor probe.

WARNING

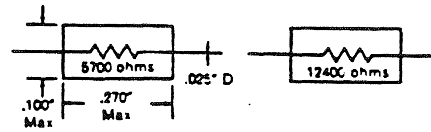
Use heat sinks when soldering or welding to thermistor leads.

U. S. Patent #3316765, Canadian Patent #782790

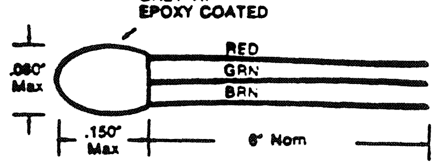
Industrial Division
Yellow Springs Instrument Co.
Yellow Springs, Ohio 45387, U.S.A.
Phone 513-767-7241

ITEM 003490 P/N 044524-C Printed in U.S.A. AB

YSI RESISTOR COMPOSITE 44304



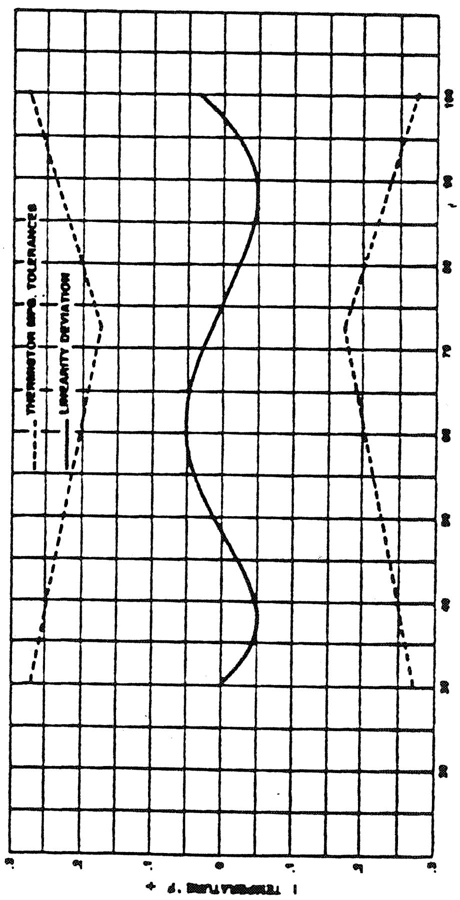
YSI THERMISTOR COMPOSITE 44018



#44204
30° to 100°F
$R_T = (-17.834)\ T + 5173.7$

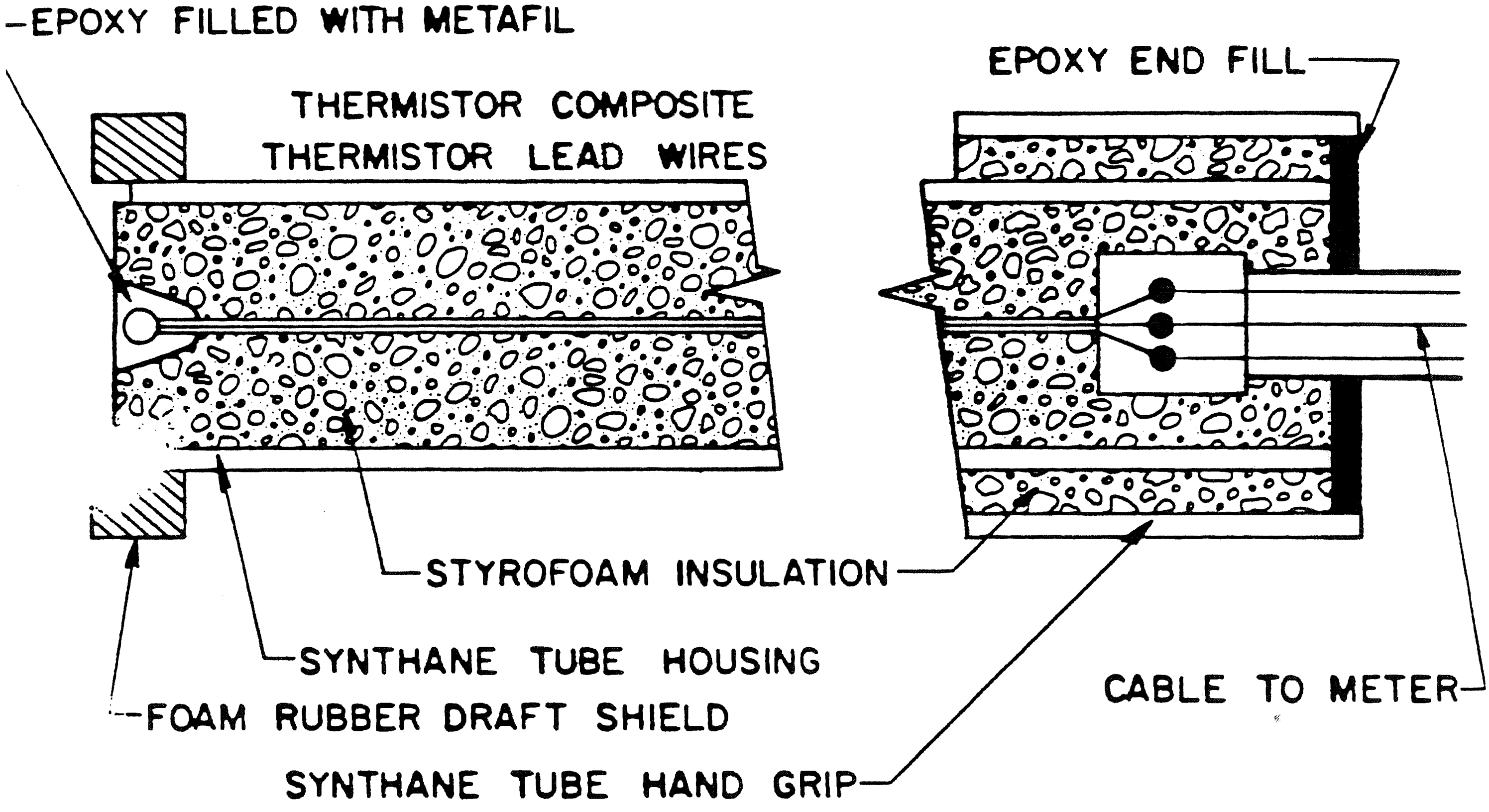
T (°F)	Ohms
30	4638.71
35	4550.41
40	4461.73
45	4371.60
50	4281.83
55	4192.17
60	4102.74
65	4013.6
70	3924.72
75	3836.02
80	3747.35
85	3658.55
90	3569.46
95	3479.89
100	3389.70

The values tabulated above are compiled using nominal thermistor values and may differ from values calculated by the stated equation. The differences constitute the Linearity Deviation Curve.



The maximum error at any point is the algebraic sum of the thermistor manufacturing tolerances plus the linearity deviation, a fixed network behavior. Since the linearity deviation is a known quantity, it may be eliminated from the error statement by consulting the linearity deviation curve at the temperature in question, and making the appropriate adjustment.

FIGURE B-1

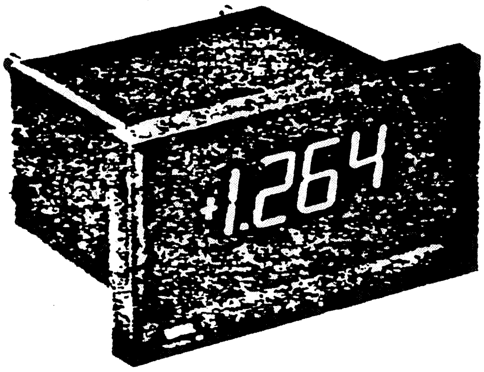


PROPOSED THERMISTOR WALL PROBE

FIGURE B-2

INTERNATIONAL
MICROTRONICS
CORPORATION
4016 E. Tennessee Street
Tucson, Arizona 85714
(602) 748-7900 TWX 910-952-1170

INSTRUCTION MANUAL
MODEL 1100 DPM



SPECIFICATIONS:

- 3 1/2 DIGIT .5" LED DISPLAY
- FULLY BIPOLAR
- AUTO ZERO
- ±2VFS DIFFERENTIAL/S.E.
- 0.1% ACCY & LINEARITY
- 1000MEGOHMS INPUT IMPEDANCE
- 200 pA BIAS CURRENT
- 200V OVERVOLTAGE
- RANGE PROGRAMMABLE
- DEC. POINT PROGRAMMABLE
- 0.01% /°C TEMP. STABILITY
- 750 mW @ 5Vdc
- 100% TESTED
- 100% BURNED-IN
- 100% GUARANTEED
- SAME PANEL CUT-OUT AS DATEL'S
- MADE IN AMERICA, BY AMERICANS WITH AMERICAN COMPONENTS

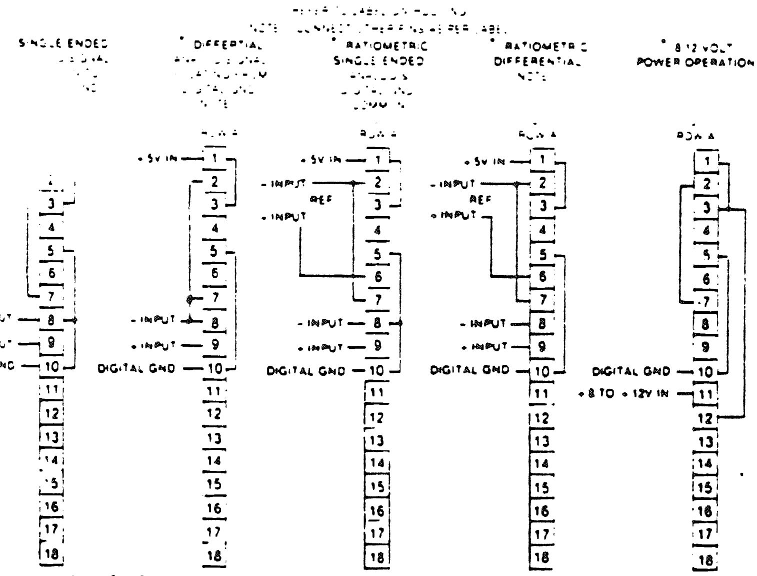
OPERATION

1. MAKE CONNECTIONS TO METER AS PER LABEL ON THE BACK OF THE HOUSING.
2. DO NOT APPLY POWER YET. CHECK OVER ALL YOUR CONNECTIONS AGAIN. VOLTAGES AND MISCONNECTIONS MAY DAMAGE IC BEYOND REPAIR AND VOID GUARANTEE.
3. APPLY POWER TO METER AND SHORT TOGETHER INPUT HI AND INPUT LO (PINS 8 & 9) METER SHALL DISPLAY 000 WITH THE MINUS (−) SIGN FLICKERING. IF IT DOES NOT, SLIGHTLY TURN P_1 UNTIL THIS CONDITION IS ACHIEVED. APPLY THE FULL SCALE SIGNAL AS PER RANGE OF METER, AND ADJUST P_1 FOR THAT READING.

TROUBLE SHOOTING TIPS

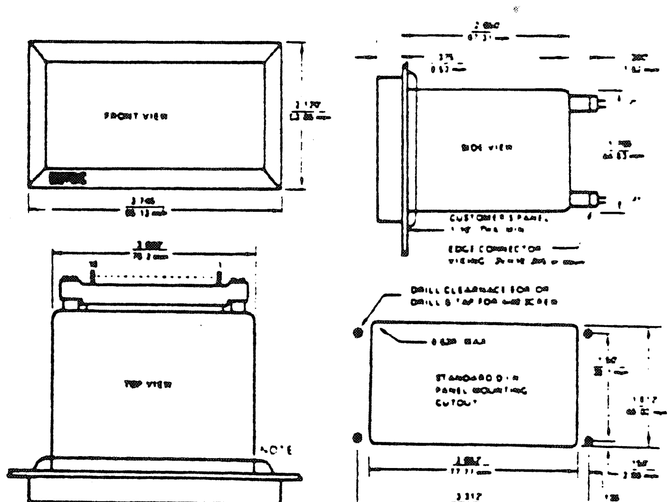
	SYMPTOM	POSSIBLE CAUSE
1	NO DISPLAY	DISPLAY BLANKED, OVERRANGE, NO POWER
2	DISPLAY ERRATIC	NO −5V POWER
3	NON-LINEARITY	NO −5V POWER
4	NON SYMETRY	GROUND LOOP

APPLICATIONS



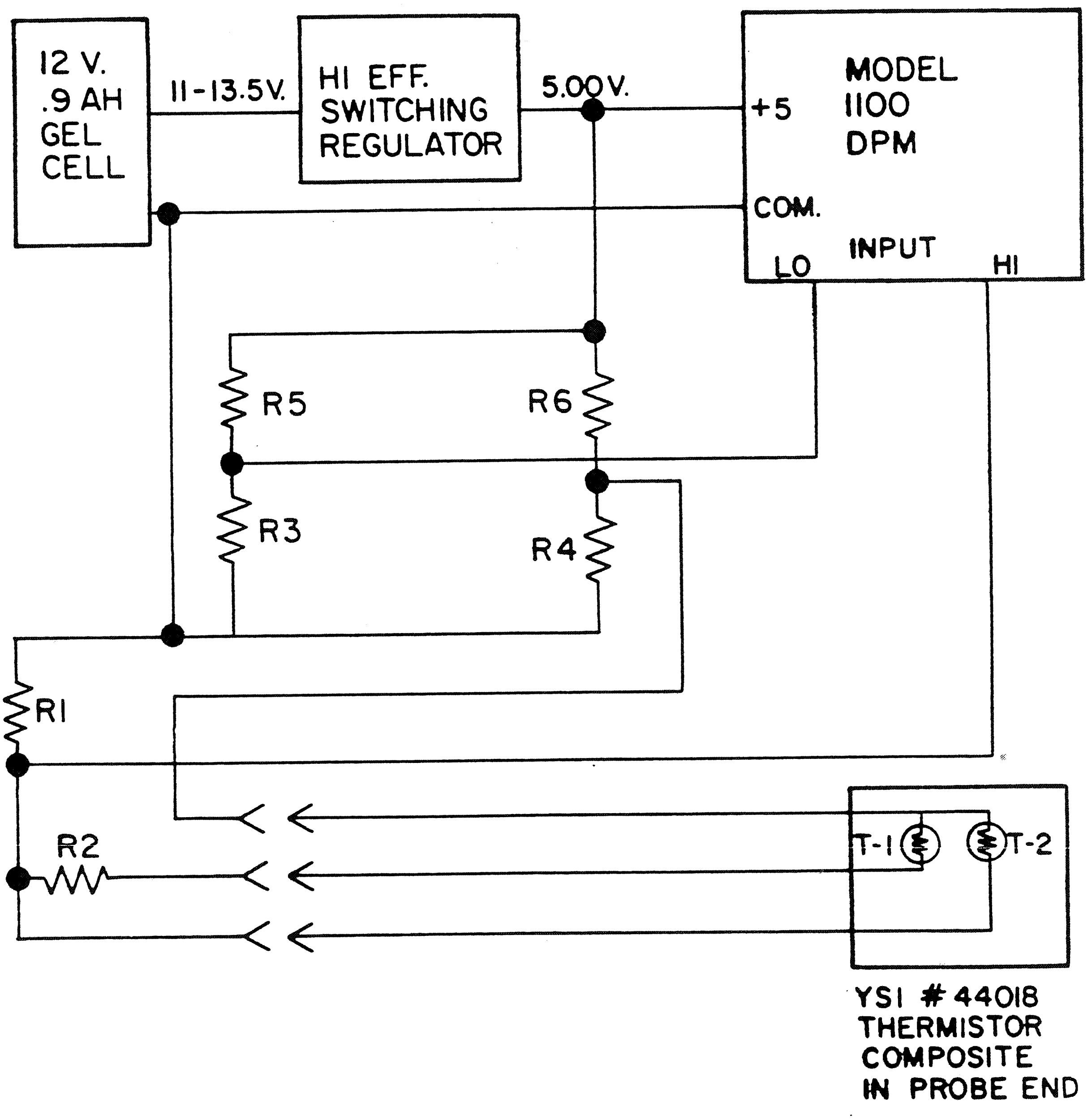
1. MAXIMUM COMMON MODE VOLTAGE ANALOG GROUND TO DIGITAL GROUND 1VDC
2. SIGNAL COMMON ... SHOULD NOT BE CONNECTED ... SIGNAL COMMON
3. ... GUARANTEE

MECHANICAL SPECIFICATIONS



MATERIAL: High impact black Cycolac, front matte finish
WEIGHT: 3 ozs. to 10 ozs.
CONNECTOR TERMINATIONS ARE INDICATED ON REAR PANEL.
Note: No Screws, Snap on Retainer Available on Request.

FIGURE B-3

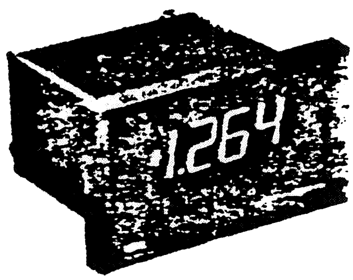


PORTABLE DIGITAL THERMOMETER BASED ON THERMILINEAR NETWORK

FIGURE B-4

SINGLE I.C.
LOW COST INDUSTRIAL GRADE DIGITAL PANEL METERS

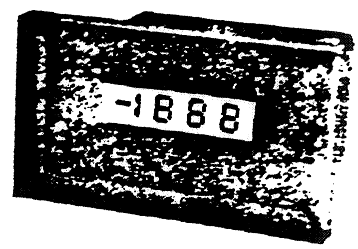
Series B500 L.E.D. Display



FEATURES

- 150 Hours Burn-in
- 100% Tested (3 Times)
- Automatic Zero
- Low Power Consumption
- Internal Attenuators
- Lamp Test
- Auto Polarity
- 50mV Input = 1000 Counts For Current Shunts

Series L500 L.C.D. Display



DESCRIPTION

Rugged reliability and dependable performance are offered in these low cost industrial grade DPM's. The single IC design gives you all these plus low power and clear viewable display. The 50mV version (Option S) is ideal for industry's standard 50mV shunts; at 50mV input the output is 1000 counts with 100% overrange to 2000 counts for 100mV input.

SPECIFICATIONS @ 25°C

L.E.D. Type		L.C.D. Type
Bipolar, Single Ended, Differential	Input Signal Type	Bipolar, Single Ended Differential
5 Pico Amps	Input Bias Current	5 Pico Amps
1000 Megohms	Input Impedance	1000 Megohms
Dual Ramp	Conversion Type	Dual Ramp
2 Volts	Common Mode Voltage (CMV)	2 Volts
.5" Red L.E.D.	Display Type	.35" Black Segments L.C.D.
4 Samples/Second	Conversion Speed	6 Samples/Second
±.005%/°C	Drift versus Temperature	±.0005%/°C
60 Seconds	Warm-up Time	Essentially None
±0.05% of F.S. ±1 digit	Accuracy and Linearity	±0.05% of F.S. ±1 digit
5, 12Vdc, 120/240Vac ±10%	Operating Voltage	5, 9, 12Vdc, 115/230Vac ±10%
800mW	Power Consumption	10mW @ 9Vdc
-5Vdc ±10% @ 3mA	Output Voltage Available @ 5V Input	-5Vdc ±10% @ 5mA
-10 to +60°C/-25 to +85°C	Operating/Storage Temperature	0 to 50°C/-25 to +80°C
Externally Selectable	Decimal Points	Externally Selectable

ORDERING INFORMATION

☐☐☐☐☐

Model No.
B5 — L.E.D.
L5 — L.C.D.
(Uses ISC-18 or TB-18 Conn.)

Input Range		Z in
0	200mV	1000M
1	2V	1000M
2	20V	10M
3	200V	10M
4	500V	10M
5	2V Ratiometric	1000M
6	200uA	1K
7	2mA	100 ohms
8	20mA	10 ohms
9	200mA	1 ohm
S	50 mV	1000M

Connector
0 — No Connector(s)
1 — ISC-18
2 — ISC-18 & ISC-6
5 — TB-18
6 — TB-18 & TB-6

Option
0 — No Option
1 — Blank Board

Power
0 — 5Vdc
1 — 120/240Vac (uses ISC-6 or TB-6 Conn.)
3 — 12Vdc
4 — 9Vdc (L.C.D. only)

Note. CONNECTORS:
ISC-18 & ISC-6 Solder Tabs Type
TB-18 & TB-6 Screw-on Type

TYPICAL CONNECTIONS (For Both Series)

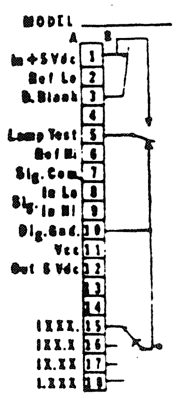


FIGURE B-5

APPENDIX C

Meter Design Considerations for Measuring Appliance Consumption

The basic functions of the Appliance Energy Consumption Meter are outlined in Section 6. The details are covered in this appendix.

Three design approaches may be used. They are All-Electronic, Hybrid, and All-Electromechanical.

The all electronic method would consist of a transformer coupled analog wattmeter, A-D converter, gated storage counters, and LED readouts. In addition, an electronic timer and elapsed time timer would be needed to gate the storage counters. Also, a regulated power supply with back-up battery would be required to avoid errors due to power line surges or total loss of stored data due to momentary power line failures. The all-electronic approach is precluded by cost considerations compared to the other methods. It is conceivable, however, that in high volume production where custom LSI chips are justified, that the cost could be competitive.

The "Hybrid" and all electromechanical approach both use commercial watthour meters now in mass production, such as G. E. type IW-70 -S, and both electro-mechanical timers and counters.

The "Hybrid" approach employs a slotted optical coupler to sense holes drilled in the eddy-current drag disc as described in Ref. 41. However, to have a direct-reading output in all kWh units, nine holes would be required in the drag disc followed by an electronic divide by 125 (for $K_h = 7.2$). This requires a programmable divide-by "N" counter such as a CD4059A or 3 divide by 5 stages using 3-CD4018A and 2-CD4011A total. The method requires a low voltage regulated power supply and is also subject to error from line conducted electromagnetic interference.

The all-electromechanical approach uses the contacts on the G.E. type IW-70-S watthour meter to operate an electromechanical counter directly. This method is free from line conducted EMI and does not require an involved, regulated, electronic power supply. In addition, the components can be contained in a standard meter box provided with a stand. See Fig.9 However, care must be taken in the design to minimize contact wear and errors due to contact bounce and/or dirty contacts.

The type IW-70-S watthour meter is available with several calibrations for the contacts. Chosen was 0.288 contacts per revolution with a K_h of 7.2 watthours per revolution of the drag disc. This provides a direct calibration of 25 watthours per count. Operation of the counter for 1/4 day (6 hrs.) would provide a scale factor of 0.1 kWh/day per count. Since there are two contacts closing alternately, use of only one contact yields the same scale factor when the counter is operated for 12 hrs. Fortuitously, operation of the counter for 18 hours makes the counter direct reading in units of 1.0 kWh per 30 day month (using both contacts). Thus, 3 scales may be selected by appropriate timer settings combined with one switch setting. When monitoring a refrigerator, for example, the 18 hr. period from 6 AM to 12 Midnight could be selected. This should correspond to a maximum demand period because of numerous door openings and the loss of cold food and introduction of warm. Conversely, the use factor can be eliminated by selecting the 6 hour period from 12 Midnight to 6 AM when the demand is primarily a function of the heat leakage and refrigerator efficiency.

Circuit Analysis:

The schematic diagram of the Time Sequence Meter wired for 110V service is shown in Fig. 10. The watthour meter and box can be connected for either 115V single phase 2 wire or 230V single phase 3 wire service; but different plugs and outlets are required. The associated circuitry was therefore designed to operate on 115 volts, as this would also be internally available in the 230 volt connection.

To eliminate the effects of contact dirt and bounce and prolong contact life, the counter is operated in high voltage, low current, impulse mode. This also prolongs counter life by minimizing heat dissipation in its coil.

The watthour meter contacts (K-1 & K-2) are cam driven as a snap action single pole double throw switch. When in good mechanical alignment, the contacts are closed for approximately equal times when metering a constant load. Each contact closure causes the counter to advance on count by charging a capacitor from a DC voltage source through the counter coil. Isolation between the contacts is provided by semiconductor diodes in series with each. Thus, contact K-1 actuates the counter through D-2 and C-2 while K-2 operates through D-3 and C-3. The diodes also permit the contacts to become so badly misaligned that a make-before-break situation can occur without causing lost counts. Resistors R-2 and R-3 are placed in parallel with C-2 & C-3 respectively to discharge each capacitor while the appropriate contact is open. The DC voltage source is provided by a simple half-wave rectifier (D-1) capacitor filter (C-1, R-1) operating through the timer contacts (S-2 or S-3) and on-off switch (S-1) from the 117V line. This provides an operating voltage of about 160V DC to actuate the counter through any dirt or oxide film buildup on the contacts.

A LED (D-4) is provided to visually indicate when power is applied to counter power supply. Current limiting for the diode is provided without power dissipation by the series reactance of capacitor C-4. Rectifier D-5 shunted across the LED, provides the required bilateral current path through C-4. Turn-on transient current is limited to a safe value (for the diodes) by resistance R-4.

In selecting the value of C-2 and C-3 consideration must be given to the electrical parameters of the counter. The counter, a Sodeco ET125 (115 VAC) with 5 digits and a mechanical reset is typical of its class. In addition, its internal full wave bridge rectifier (for AC operation) acts as a damping diode for its inductance during turnoff. This also eliminates the EMI normally associated with the turn-off of AC operated solenoids. Typically, such a counter will appear electrically as a 6 Henry inductance in series with a 3.3k resistor (before being energized). To prevent an oscillatory charging transient on contact closure, C should be chosen $> \frac{4L}{R^2}$ as well as providing sufficient current to operate the counter. The classic circuit equations predict a peak current of 38 ma being achieved in 4 milleseconds for the particular components used, along with termination of the transient after 35 ms. Fig.C-1 shows an oscillogram of the current through the counter with bounce-free contact closure to be close to prediction.

Of particular interest is the oscillgram shown in Fig. C-2. This is typical of the current through the counter when actuated by moderately dirty, bouncing contacts. The counter, however, responds with one count (and only one) as with clean contacts.

Conclusions:

The field trails of the time sequence meter have shown it to be easy and convenient to use while yielding the accuracies previously attainable only by lengthy, involved procedures.

The electronics has been designed from the aspects of simplicity, reliability, and low cost, as well as compactness.

Operating Instructions for Appliance Energy Consumption Meter

A. Plug kWh meter into 110V AC wall outlet.

B. Plug appliance into the meter box outlet.

C. Select proper range with "range" switch.

D. Insert trippers as per timer instruction sheet (on the back of the meter box) for the desired timing (6, 12 or 18 hrs.).

E. Set timer to one hour before silver tripper.

F. Reset counter to zero.

G. Put on-off switch to the "on" position.

H. The LED will come on when the timer switches "on" and turns off when the cycle is completed.

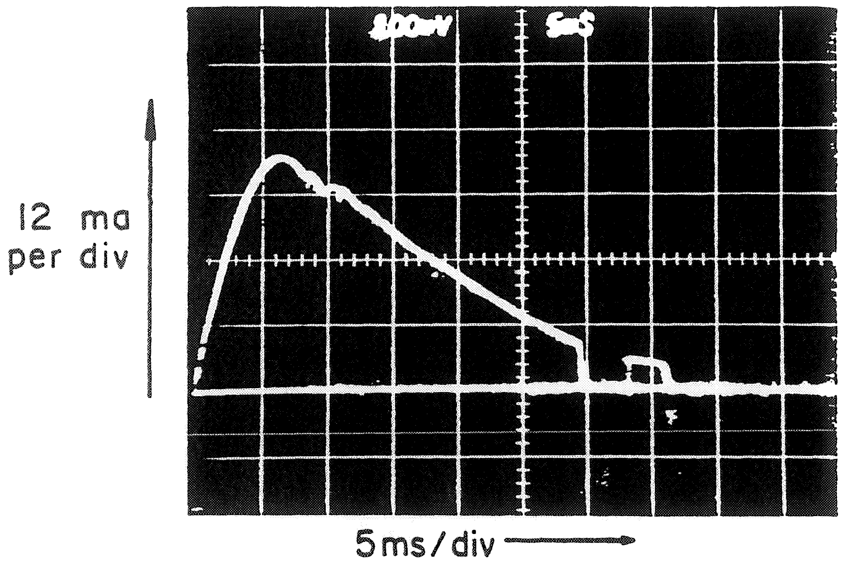
1. To check the operation of the system, depress the manual override switch which should start the circuit operating (counter operating

on meter switch closures and the LED on). After checking the operation, depress the manual override switch to turn off the system and reset the counter to zero.

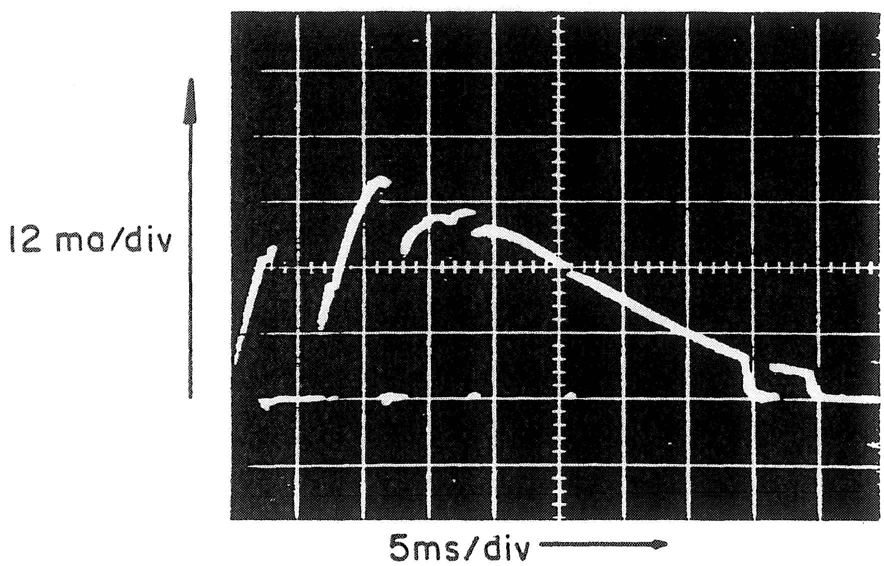
I. Take the counter reading after the timer switches "off".

  1. On the 6 hr. position, you have 18 hrs. to retrieve the reading.
  2. On the 12 hr. position, you have 12 hrs. to retrieve the reading.
  3. On the 18 hr. position you have 6 hrs. to retrieve the reading.

J. If the reading is not taken before the timer reaches the next "on" position, the counter will start again. If this happens, allow the cycle to repeat and divide the counts by 2 to get an average.



CLEAN, NON-BOUNCING CONTACTS
FIGURE C-1



MODERATELY DIRTY, BOUNCING CONTACTS
FIGURE C-2

OSCILLOGRAMS OF THE CURRENT THROUGH THE COUNTER
AT CONTACT CLOSURE