DEVELOPMENT AND IMPLEMENTATION OF SURVEY TECHNIQUES FOR ASSESSING IN-SITU APPLIANCE EFFICIENCIES

Sherman, M.H.

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**Lawrence Berkeley Laboratory**
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE
DIVISION

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M.H. Sherman, R.F. Szydlowski, P.G. Cleary,
M.P. Modera, and M.D. Levine

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M.H. Sherman, R.F. Szydlowski, P.G. Cleary, M. P. Modera, M.D. Levine

Energy Performance of Buildings Group
Lawrence Berkeley Laboratory
Berkeley, CA. 94720

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# ABSTRACT

A study was conducted to develop and field-test audit procedures that could be used in a large survey of in-situ appliance efficiency indicators. The appliances concerned were refrigerators, gas and electric water heaters, central air conditioners, and central gas furnaces. The efficiency indicators measured were compared to the manufacturer's rated values as determined by the California appliance standards procedures. The audit procedures field test involved 61 homes during summer 1986 and winter 1986-1987 and included actual in-situ appliance efficiency measurements using the same audit procedures that would have been used in a larger study. Appliances were submitted to one-day short-term efficiency tests and one-week long-term monitoring of energy use and operational characteristics. Some conclusions were drawn about the applicability of the audit procedures and comparisons were made between measured and rated appliance efficiencies. The accuracy objectives were met for refrigerators, for the recovery efficiency of water heaters, and for central gas furnaces. Based on the results of this study, the water heater standby loss and air conditioner efficiency audit procedures cannot be considered practical audit procedures to be included in a large survey of appliance efficiency. An examination of alternative air conditioner audit procedures is advisable, but development of a practical audit procedure for measuring water heater standby loss is very unlikely. Based upon the results of this study, the audit procedures for a large survey would consist of one-day testing of the water heater, air conditioner, and furnace, and one-week monitoring of the refrigerator. The costs for the audit procedures recommeded for the large survey are as follows. For a summer survey (refrigerator, water heater, and air conditioner), $1,000 per audit team and $950 per house in equipment, plus 6-8 man-hours per house, plus the equipment and labor costs for a to-be-developed air conditioner air flow procedure. For the winter survey (refrigerator, water heater, and furnace), $3,500 per audit team and $950 per house in equipment, plus 6-8 man-hours per house. The audit procedures field-test produced the following appliance efficiencies results. Water heater recovery efficiencies were 7% lower than their rated values on average, while air conditioner efficiencies were more than 20% lower than their rated values on average. Refrigerator consumption was 12% higher than rated on average, and furnace efficiencies were within 1% of the rated values.

## EXECUTIVE SUMMARY

The Pacific Gas and Electric Company (PG&E) and the California Energy Commission (CEC) are interested in collecting primary data on the efficiencies of equipment representing major single-family residential end uses: refrigerators, gas and electric domestic water heaters, central air conditioners, and central gas forced-air furnaces. The major objectives are: 1) to document the distribution of efficiencies of major household appliances, 2) to examine the degradation of appliance efficiency with age, and 3) to collect relevant on-site data on appliance characteristics. The results of the survey will be invaluable in: 1) improving understanding of energy use in residential building stock, 2) improving residential energy demand forecasting, and 3) establishing a sound basis for new residential energy conservation programs, such as appliance retrofits. As such, this work may have important consequences for future PG&E and CEC planning and programs.

In preparation for a large-scale appliance survey, Lawrence Berkeley Laboratory (LBL) has completed an audit methods study and a small-scale audit procedures field test. During the audit procedures field test, which involved 61 homes during summer 1986 and winter 1986-1987, actual in-situ appliance efficiencies were measured using the same audit procedures that would have been used in a larger study. Appliances were submitted to one-day short-term efficiency tests and one-week long-term monitoring of energy use and operational characteristics. Three appliances were audited at a time: the refrigerator and water heater in each house, and either the air-conditioner during the summer or the furnace during the winter. Installation of monitoring equipment and execution of short-term tests required approximately 12 man-hours per house, with equipment removal at the end of the long-term monitoring period requiring an additional man-hour.

Some conclusions about both the applicability of the audit procedures and comparison of measured and rated appliance efficiencies can be drawn. Relative to the measured and rated comparisons, it is important to note that the appliance test samples were based on availability, not on random selection criteria, so the distributions are not assumed to be representative of the PG&E service territory.

**Refrigerator:** Short-term operating consumption and temperature variations dictated that long-term monitoring be used to measure average energy consumption with acceptable accuracy. However, the long-term monitoring equipment required is fairly simple and inexpensive. A short-term monitoring period may be an alternative, but will result in a larger measurement uncertainty. Although the instrument measurement accuracy was acceptable, the data normalization algorithms induce a significant increase in the overall uncertainty. The average normalized measured refrigerator consumption was 12% higher than rated, with a large amount of scatter.

**Water Heater:** The gas water heater recovery efficiency audit procedure required short-term testing, used simple and inexpensive equipment, and produced results of acceptable accuracy. (Electric water heaters do not require this test.) An acceptable alternative procedure that required less time was not found. The measured values show a large scatter, partially due to thermosiphon loops that exist in the field, with an average recovery efficiency that was 7% less than rated.

The standby loss audit procedure for both gas and electric water heaters required a one-week long-term monitoring period using a complicated data acquisition system, and failed to produce the desired results. The audit procedure required long periods (more that 12 hours) without hot water use, which did not occur in most occupied residences. An acceptable alternative procedure was not found. We do not recommend that standby loss be measured in a large survey.

**Air Conditioner:** The audit procedure for measuring EER and SEER requires only short-term testing. However, the measurement accuracy was not acceptable due to problems with condenser coil air flow measurements. Alternative techniques are discussed, but require further evaluation. Long-term monitoring was conducted to gain further information about cyclic operation, but lack of air conditioner usage prevented sufficient data collection. The measured efficiencies were significantly below rated.

**Furnace:** The audit procedure for measuring steady-state and seasonal efficiencies requires only short-term testing using relatively simple (though expensive) equipment and produced results of acceptable accuracy. Long-term monitoring is not required. The average measured furnace seasonal efficiency was within 1% of the rated values, with little scatter.

This study has demonstrated practical in-situ appliance efficiency audit procedures for measuring refrigerator consumption (long-term), domestic water heater recovery efficiency (short-term), and furnace efficiency (short-term). Water heater standby loss and air conditioner efficiency audit procedures used in this study do not produce results acceptable for a larger study. A more detailed examination of alternative air conditioner audit procedures is advisable. A practical audit procedure for measuring water heater standby loss is very unlikely.

## INTRODUCTION

The Pacific Gas and Electric Company (PG&E) and the California Energy Commission (CEC) are interested in collecting primary data on the efficiencies of equipment representing major single-family residential end uses: refrigerators, gas and electric domestic water heaters, central air conditioners, and central gas forced-air furnaces. The full project has several major objectives: 1) to document the distribution of efficiencies of major household appliances, 2) to examine the degradation of appliance efficiency with age, and 3) to collect relevant on-site data on appliance characteristics. Completion of these objectives will provide input to forecasting activities and establish a sound basis for future appliance performance estimates.

The full project will give PG&E the opportunity to document, for the first time, the degree of performance deterioration of residential appliances. The results will be invaluable in: 1) improving understanding of energy use in residential building stock, 2) improving residential energy demand forecasting, and 3) establishing a sound basis for new residential energy conservation programs, such as appliance retrofits. As such, this project could have important consequences for future PG&E and CEC planning and programs.

The full project has four distinct activities which will be individually funded.

> *Phase I: Methods Study:* The objective of this phase is to develop and test audit procedures for use in a survey of in-situ appliance energy efficiencies. There are three tasks: 1) survey of existing methods and standards, 2) audit procedures development, and 3) audit procedures evaluation.
>
> *Phase II: Small-Scale Field Test:* The objective of this phase is to field test the audit procedures to identify and solve problems likely to occur in the full-scale survey. The data collected in this phase will also give preliminary estimates of in-situ appliance efficiencies. There are five tasks: 1) planning, preparation, and sample selection, 2) summer data acquisition, 3) summer data analysis and interim report, 4) winter data acquisition, and 5) winter data analysis and final report.
>
> *Phase III: Appliance Survey:* This is the main data collection phase which implements the full-scale survey of in-situ appliance efficiencies. The tasks for this phase have not been defined.
>
> *Phase IV: Analysis:* The objective of this phase is to analyze the data collected in the full-scale appliance efficiencies survey. The tasks for this phase have not been defined.

In preparation for the full-scale appliance survey, PG&E, with co-funding from CEC and DOE, funded Lawrence Berkeley Laboratory (LBL) to carry out an audit procedures development project, covering Phases I and II above. The remainder of the full-scale project, Phases III and IV, will be planned by PG&E and CEC based on the results of this audit procedures development project.

This report presents the in-situ appliance efficiencies audit procedures developed by LBL, and the in-situ appliance efficiencies measured during the audit procedures small-scale field test, which involved 61 houses during summer 1986 and winter 1986-1987. The discussion of audit procedures includes a summary of required equipment and associated costs, implementation time, field experience with the procedures, measurement uncertainties, and alternative measurement techniques. The appliance efficiency measurements collected during the audit procedures field test show the kind of results that can be expected from a full-scale survey.

## AUDIT PROCEDURES

The appliances in each house were submitted to one-day short-term efficiency tests and one-week long-term monitoring of energy use. Three appliances were audited at each site: refrigerator and water heater in each house, and either air-conditioner during the summer or furnace during the winter. Installation of monitoring equipment and execution of short-term tests, which took up to two hours per appliance, required approximately 12 man-hours per house. A computer-based data acquisition system, which was installed during the initial site visit, was used to collect data during both the short-term tests and, with some reprogramming, the one-week long-term test. Major components of the data acquisition system are shown in Figure 1. One man-hour was needed to remove this equipment at the end of the long-term monitoring period.

A summary of the efficiency indicators to be determined is shown in Table 1, with a breakdown of the summer audit test sequence shown in Table 2. A number of diagnostic tests were also carried out. These included checking the air conditioner refrigerant charge, measuring the water heater steady-state combustion efficiency, and observing the location of the refrigerator. A summary of the audit procedures for each appliance is presented in the following sections. Details of both short-term and long-term audit procedures are given in Appendix B.

TABLE 1
EFFICIENCY INDICATORS TO BE DETERMINED

| APPLIANCE | SHORT-TERM | LONG-TERM |
|---|---|---|
| Refrigerator | | Average energy use |
| Water Heater | Recovery Efficiency | Standby loss |
| Air Conditioner | Energy Efficiency Ratio (EER)<br>Seasonal Energy Efficiency Ratio (SEER) | EER v. temperature<br>Actual cyclic period |
| Furnace | Seasonal Efficiency | Actual cyclic period |

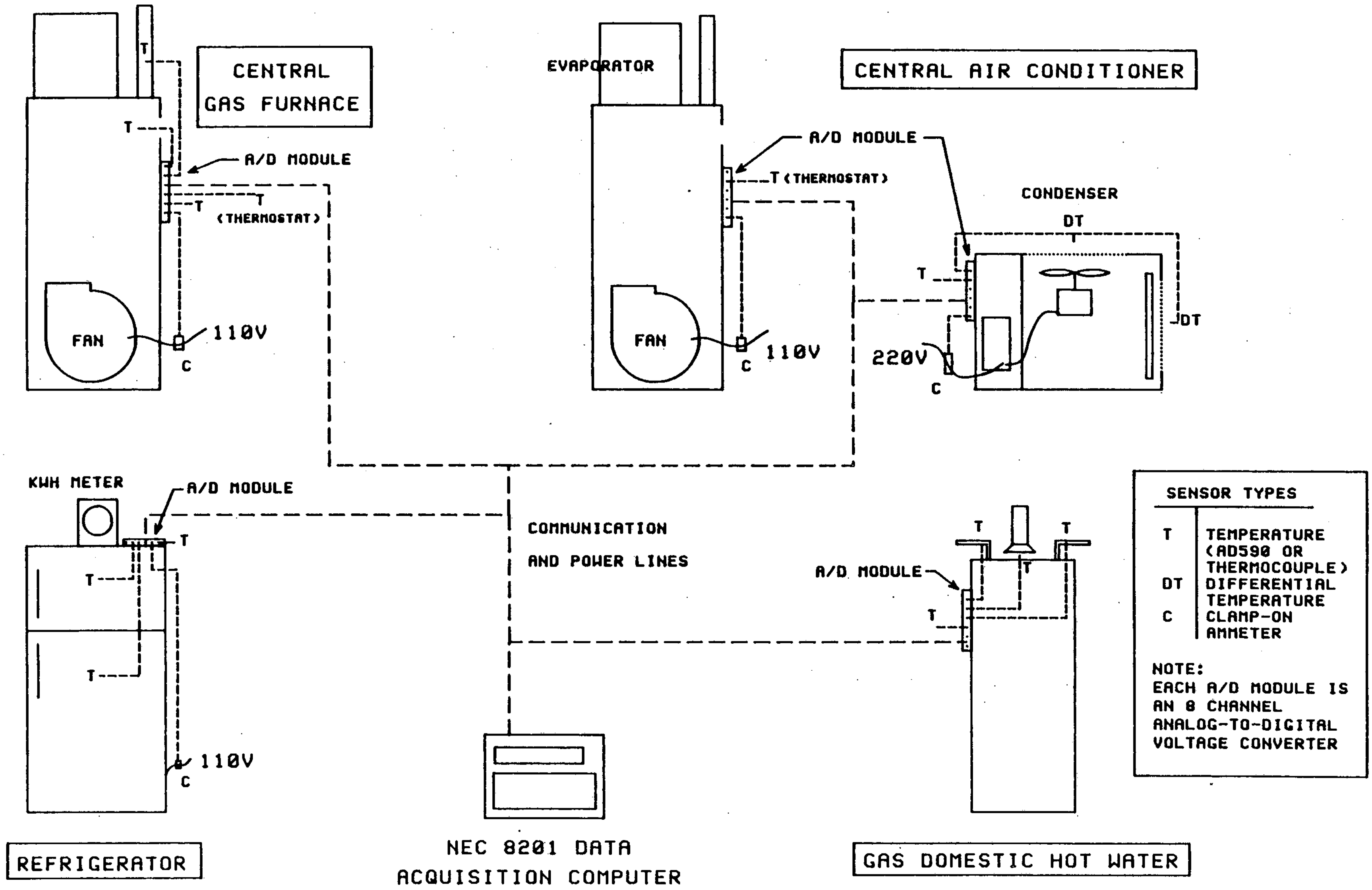

Figure 1. Schematic of the data acquisition system.

## TABLE 2
## TYPICAL TIME ON-SITE FOR SUMMER APPLIANCE MEASUREMENTS

| Time | Technician #1 | Technician #2 |
|---|---|---|
| 0800 | Talk to homeowner<br>Fill in questionnaire | Same as #1. |
| 0900 | Install sensors on air conditioner (A/C), both for tracer gas test and long-term tests. | Install sensors on refrigerator, water heater and inside fan.<br>Set up COMPAQ computer and run distribution boxes' wiring. |
| 1000 | Check out hardware and software | Same as #1. |
| 1030 | Perform anemometer traverse on A/C. | Same as #1. |
| 1100 | Perform tracer gas tests on inside and outside fans | Measure pilot lights usage<br>Tidy up wiring runs. |
| 1130 | Remove tracer gas piping.<br>Continue pilot measurement. | Begin water heater tests |
| 1200 | Start A/C cyclic test | Continue water heater test. |
| 1230 | Continue A/C test<br>Lunch | Continue water heater test.<br>Same as #1. |
| 1300 | Collect nameplate data<br>Draw floor plan. | Continue water heater test. |
| 1330 | Reconfigure software for long-term test.<br>Change to NEC computer. | Same as #1 |
| 1400 | Clean up site. | Same as #1 |

Note: These are typical times. Many of these procedures can take much longer or shorter than the allotted time period. The complete sequence of tests required as little as 4 hours to more than 8 hours.

### Refrigerators

For refrigerators the efficiency indicator is the monthly energy consumption. A detailed discussion of this indicator is presented in Appendix B. The audit procedure requires the monitoring of the refrigerator fresh food and freezer compartment temperatures, an ambient air temperature near the refrigerator, and the total electric energy consumption during a one-week long-term monitoring period. In addition, fresh-food and freezer compartment door openings were monitored in 13 units during the winter study. Due to the fluctuations in both compartment temperatures and electrical consumption over short time periods (e.g. less than 6 hours), a reliable short-term audit procedure was not developed for this study.

### Water Heaters

There are two efficiency indicators for gas domestic hot water (DHW) heaters: the recovery efficiency and the standby loss. The recovery efficiency is a measure of how much of the energy in the fuel goes into heating the water while the burner is operating. The standby loss is a measure of how much energy is consumed to maintain a constant water temperature with no hot water use. Electric DHW heaters, for which the recovery efficiency is essentially unity, use only the standby loss indicator. A detailed discussion of these indicators is presented in Appendix B.

The short-term audit procedure for determining recovery efficiency requires that a tank of cold water be heated to the water heater's maximum aquastat setting. The tank of cold water is created by turning off the burner (the pilot does not need to be turned off) and drawing hot water from a faucet until the hot water temperature is within 1 °C of the cold water supply temperature. The tank of cold water is then heated to the water heater's maximum aquastat temperature setting while measuring the gas consumption and recording flue gas analysis parameters. The hot water's final temperature is determined by measuring the hot water temperature at a faucet after the aquastat turns the burner off. At the conclusion of this short-term test the aquastat is returned to its original setting.

Diagnostics performed during the site visit included flue gas analysis, asking the homeowner about tank flushing, and a visual inspection of the installation. The visual inspection notes tank and pipe insulation, heat traps, and thermosiphon or pumped loop installations.

The long-term audit procedure for standby-loss determination involves monitoring the temperature of the flue for the gas units, or electric current to the heating elements of electric units, the hot and cold water pipe temperatures, and the ambient air temperature. This data is sufficient to identify time periods during which there were at least two main-burner (or electric element) operations without any intervening hot water use. The length of the burner operation and standby time, along with one-time measurements of pilot light and main burner gas consumption rates (or electric element power rating) that were measured during the short-term testing, are used to calculate a tank standby loss. The ambient air temperature is used to normalize the standby loss values to a common operating condition.

## Central Air Conditioners

Depending upon the year of construction, the efficiency indicator for air conditioners is either the Energy Efficiency Ratio (EER), or the Seasonal Energy Efficiency Ratio (SEER). Both indicators are ratios of heat removed to electric energy consumed. EER is a steady-state value, whereas SEER is a steady-state EER value that is adjusted for cycling of the air conditioner. A detailed discussion of these indicators is presented in Appendix B.

The short-term audit procedure involves measurement of both EER and SEER. The energy efficiency calculations are based on a one-time condenser coil air-flow measurement, condenser coil air temperature difference, and electrical consumption of both outside (compressor and fan) and inside (distribution fan) units of the air conditioner. EER is calculated based on sensor readings taken at the end of at least 30 minutes of continuous air conditioner operation. SEER is calculated based on the EER value and on readings taken during a forced air-conditioner cycling pattern of two successive 24-minutes-off and 6-minutes-on cycles.

The audit procedure determines both EER and SEER by measuring the heat rejection at the outside condenser coil instead of the heat removed from the house at the inside evaporator coil. This measurement technique was chosen due to the difficulties associated with field measurement of evaporator coil heat removal, which requires measurement of air flow rate, air temperature difference, and air moisture content. The outside coil is more accessible for sensor installation and air moisture content need not be measured.

A diagnostic to determine air conditioner freon charge by measuring the evaporator line temperature and pressure, along with ambient air temperature, was performed during the 30-minute steady-state air conditioner operation. Additional diagnostics were observation of the air conditioner outside unit location with regard to free air movement around the condenser and condenser coil clogging.

The long-term audit procedure was designed to determine the actual air conditioner cyclic characteristics and the correlation between instantaneous EER and outdoor air temperature. The actual air conditioner cyclic characteristics are important for calculating the actual SEER, as compared to the standard SEER, which is based on an assumed cyclic period of 24-minutes-off and 6-minutes-on.

## Gas Forced-Air Furnaces

Depending on the age of the unit, the efficiency indicator for a forced-air gas furnace is either the steady-state efficiency or the seasonal efficiency. Seasonal efficiency includes the effects of steady-state efficiency, electric energy use by fans, cycling losses, and flue losses. Flue and stack temperatures are measured 30 seconds and 2 minutes 30 seconds after burner start-up from a cold furnace, the furnace is operated continuously until it reaches steady-state, and flue and stack temperatures are measured 1 minute 30 seconds and 9 minutes after burner shut-down. The delays between burner-on and distribution-fan-on, and between burner-off and fan-off are also measured. Two complete furnace operation cycles, with an intervening 45 minute cooling period, were performed.

Long-term monitoring of the furnace provides additional information about actual operational characteristics of the furnace, such as a diagnostic for determining short cycling, but was not used to calculate the efficiency indicators.

## COSTS

Table 3 shows a cost breakdown for the equipment required for the individual appliance audit procedures. The equipment required for the short and long-term tests are listed separately to allow investigation of cost saving alternatives, such as conducting only short-term testing. Note that where the same equipment is used for both short and long-term tests, it is listed in each category. Although costs for three methods of measuring air conditioner condenser air flow are listed for comparison purposes, only one would actually be used in a large-scale survey. In addition to the individual equipment costs, a computer-based data acquisition system costing $2,300 per 3-appliance audit is required for the long-term tests.

The audit procedure for all four appliances as implemented in this study had equipment costs of approximately $10,700 per audit team (including $7,000 for tracer gas equipment used to measure air conditioner condenser air flow) and $2,500 per house for the long-term tests. Labor costs for the audit would be calculated based on two auditors spending approximately 6 hours per audit.

As an alternative, if the audit procedure was reduced to one-day testing of the water heater, air conditioner, and furnace, and an integrating thermometer was used to monitor long-term refrigerator temperatures (at a cost of approximately $400 each), the total audit test equipment cost would be approximately $3,500 per audit team (plus the cost of the equipment selected for measuring air conditioner condenser air flow) and $950 per house for the refrigerator long-term test. A single auditor should be able to conduct this shortened audit in 6-8 hours.

## PRACTICAL ISSUES

As with any field study, there were a number of practical problems associated with collecting the data. Each house presented a challenge to the auditor who had to install monitoring instruments and associated sensor wiring as unobtrusively as possible. As a matter of policy, no monitoring equipment installation was allowed to permanently alter the homeowner's property. The only exception was for conducting stack gas analysis and measuring the temperature difference across the furnace heat exchanger and inside air conditioner coil. Small holes were drilled in the stack and air ducts, which were easily repaired with aluminum duct tape when the sensors were removed. In general, some houses were more susceptible to damage than others, which meant that some sensors were omitted because of installation difficulties. In most cases, the sensor that was omitted was the furnace/air conditioner thermostat air temperature, which could be estimated from the refrigerator ambient air temperature. In other cases, extremely long outdoor cable runs around the outside of the house were installed to avoid possible damage to the interior house finish.

## TABLE 3
## COSTS OF EQUIPMENT REQUIRED FOR APPLIANCE AUDIT PROCEDURES

| APPLIANCE | MEASUREMENT | EQUIPMENT | COST |
|---|---|---|---|
| a) Short term | | | |
| Refrigerator | Compartment temps | Temperature sensors | $30 |
| Water Heater | Recovery rate | Thermometer | $200 |
| | | Stop watch | $30 |
| | Flue gas efficiency | Stack gas analyzer | $2,650 |
| Air Conditioner | Energy Efficiency Ratio | Clamp-on KWH meter | $360 |
| | | Clamp-on watt meter | $400 |
| | | Temperature sensors | $50 |
| | Measure air flows<br>(Only one needed) | Flow hood | $600 |
| | | Hot-wire Anemometer | $1,000 |
| | | Tracer gas | $7,000 |
| Furnace | Seasonal Efficiency | Thermometer | $200 |
| | | Stop watch | $30 |
| | | Clamp-on watt meter | $400 |
| | | Stack gas analyzer | $2,650 |
| b) Long term | | | |
| Refrigerator | Cycle times | Clamp-on ammeter | $60 |
| | Energy use | KWH meter | $150 |
| | Compartment temps | Temperature sensors | $30 |
| | Door openings | Phototransistor | $5 |
| | | Counter | $50 |
| Water Heater | Standby Loss | Temperature sensors | $30 |
| | | Clamp-on ammeter | $60 |
| Air Conditioner | Energy Efficiency Ratio | Clamp-on ammeter | $60 |
| | | Temperature sensors | $50 |
| | Cycle times | Clamp-on ammeter | $60 |
| Furnace | Cycle times | Temperature sensors | $30 |

Note: For all of the long-term measurements except the refrigerator door openings and electric energy use, a data acquisition system consisting of a computer (cost $500) and an analogue-to-digital converter and associated wiring ($600 per appliance) are required. This is also required for the air conditioner short-term measurements.

Ensuring that children and pets stayed in designated areas sometimes caused problems, but no homeowner complaints were received. Difficulties commonly occurred in finding the nameplate on an appliance, and, once found, in reading that nameplate. Finding an electrical outlet to power the long-term monitoring equipment was sometimes difficult. In one case only one day of long-term data was recorded because the equipment was inadvertently plugged into a switched wall outlet that the homeowner turned off.

There were problems obtaining the rated performance indicators for many of the appliances. Rated values could not be determined either because nameplate information could not be found by the auditor, or because the appliance was not listed with the California Energy Commission. Since the major objective of the proposed large-scale appliance survey is the comparison of measured and rated efficiency, lack of rated values means that the measured efficiency values are of limited usefulness.

Finding homeowners that were both willing to allow LBL researchers to audit their appliances and that had the right combination of installed appliances was difficult. Because the audit procedures required that the auditor team have access to the whole house during approximately 6 hours one day and 1 hour approximately one week later, there was also a problem with scheduling a time that was mutually acceptable to both the homeowner and audit team. A few weekend and evening audits were conducted to accommodate homeowners schedules, which was inconvenient for the audit team.

House security and property damage during the 6 or more hours in which there are two unknown people (auditors) running free throughout their house was an area of concern for the homeowner. Although there were no problems with theft or damage with our auditor teams, this may be a problem in a large survey with a large number of temporary auditors. For this small-scale survey, homeowners handled auditor team access to the house in one of three ways.

(1) Someone from the household was present to unlock the house, showed the appliance locations, answered a brief questionnaire, and was present during the whole audit. This was a major commitment for someone from a single-person or working-couple household, requiring a day of vacation from work. This represented some inconvenience even to homeowners that are normally home during the day.

(2) Someone from the household was present to unlock the house, showed the appliance locations, answered a brief questionnaire, and left for the day. The auditors locked up the house when they finished. This represented some inconvenience for the homeowner, and a risk that the auditors would damage or remove some property without their knowledge.

(3) The homeowner arranged to leave the house key with a neighbor or in a preset location. The auditors were on their own to locate the appliances and lock up the house when they finished. There was no opportunity for the auditor to question the homeowner about the appliances, although most questions could be answered by telephone. The homeowner incurs a risk that the auditors would damage or remove some property without their knowledge.

After a significant effort finding and scheduling appropriate test houses, there is still a chance that the test will need to be rescheduled or canceled at the last minute. Most of the summer test houses were selected from friends and associates of the researchers, and there were only two last-minute scheduling problems out of 31 test houses. The winter test houses, which had more selections from housing developments that had no personal contact with the researchers, proved to be more of a problem. There were 7 last-minute scheduling problems out of 30 test houses. This included a test site in which the audit team awoke the homeowner on a Saturday morning, for which there had been special weekend scheduling, only to be told by the homeowner that it was too much of an inconvenience to go through with the audit.

It is important to maintain a good working relationship with the homeowner. In general, the homeowners did not mind our monitoring of the appliances if they found no changes when the testing was completed. To that end, each appliance's setup was noted during initial equipment installation (e.g. thermostat and aquastat settings, wall outlet used to power refrigerator, etc.) so that the initial setup could be duplicated when the monitoring equipment was removed.

A $20 incentive fee was paid to each survey participant to defray any minor inconvenience and damage. This is a minor cost to the survey, and shows that the audit team is concerned about the homeowner. For the participants in this small-scale survey, the $20 fee did not significantly affect decisions about whether or not to participate. Of greater concern to most of the homeowners was the fact that they would receive some feedback about their appliance efficiencies.

### Refrigerators

Access to the refrigerator wall outlet, which was necessary for installation of the KWH meter and clamp-on ammeter, required that the refrigerator be moved. Movement of refrigerators without causing permanent damage to floors or walls was particularly difficult for large refrigerators without built-in rollers, refrigerators located in carpeted kitchens, and refrigerators located in alcoves. Movement of the refrigerator during equipment removal by a single auditor posed an additional problem. Use of an appliance skid would alleviate this problem.

In one case the refrigerator lost power because of a bad electrical contact between the electrical consumption sensor and the wall outlet. Luckily the homeowner noticed and corrected the situation before any permanent defrost damage occurred.

Installation of refrigerator compartment and ambient air temperature sensors, and door opening sensors, was not a problem. The utility KWH meter that was used for monitoring electric energy consumption is relatively large, and was sometimes hard to locate unobtrusively. It was usually placed on top of the refrigerator, which blocked cabinets located above the refrigerator. A smaller KWH meter would alleviate this problem.

### Water Heaters

In most cases the water heater was easily accessible, and the temperature sensors could be installed in an unobtrusive manner. A problem occurred on units with insulating blankets that could not be removed without permanent damage, and therefore were not removed, making it impossible to gain access to the nameplate. This is a particular problem for electric water heaters, since installation of a clamp-on ammeter on the heating element wiring is hindered by the presence of an insulating blanket.

When measuring the stack-gas efficiency of gas DHW heaters, it was often difficult to locate the gas probe in the flue rather than in the stack. A flexible gas sampler would help in this regard. Plastic DHW heater flush valves, which are located near the bottom of the tank, would often begin to leak slowly when the tank was filled with cold water. Although the leak was disconcerting, it would stop as soon as the water warmed up again.

To measure the gas consumed by water heater pilot lights, pilots for other gas appliances (i.e. spa heaters, cooking ranges, furnaces, and clothes dryers) had to be turned off, some of which were difficult to relight. In addition, two of the utility gas meters would not reliably measure gas flow at the low pilot light consumption rate.

### Central Air Conditioners

For older air conditioners the freon pressure taps were often corroded, making it impossible to attach pressure gauges without breaking the taps. During one of the early tests, the auditor that installed the pressure gauges failed to tell the second auditor, who would later remove the gauges, that a freon valve had to be turned off before the gauge was removed. (Very few of the air conditioners had manually operated valves.) The second auditor removed the gauges without closing the valves, which resulted in a complete freon discharge and a call to a local cooling contractor to recharge the air conditioner.

Ground-mounted air conditioners were often placed in cramped, overgrown areas. To make air flow measurements was then both difficult and unpleasant. In some cases special care had to be taken with the long-term sensors left on the units. No dangerous voltages are present, but the sensors could have been easily disturbed or damaged by the inquisitive probings of children or pets. A more critical concern was the clamp-on ammeter that was attached to the 220 volt circuit breaker box located near the outside air conditioner unit. It was often impossible to fully secure the breaker box with the clamp-on ammeter installed, which presented a potential danger to inquisitive children. A modified technique is required to insure safety in a larger study.

A number of roof-mounted combination air conditioner and furnace units were encountered. Access to these units was often easier than for ground mounted types, but, along with the usual hazards associated with working on roofs, they presented some unique difficulties. Because drilling through the outside air duct casings could lead to future water leakage and the inside air ducts were inaccessible in small attics, the inside coil air temperature difference could not be monitored. Additionally, for these units it was usually impossible to install a four-foot-long mixing tube that was used with tracer gas air flow measurements.

Conducting the air conditioner audit requires the auditor to force the air conditioner on and off at prescribed time intervals. This presented a problem in houses with complicated programmable and multi-zone thermostats. In some cases the homeowners were not available to explain or did not understand how to set the thermostat to force a particular condition, such as fan only operation. Without a manual, the auditor was also occasionally unable to master the thermostat. Dual thermostats required resetting both thermostats to force an operation, and some had long delays before initiating an operation.

### Furnaces

In most cases the unit was easily accessible, and temperature sensors could generally be installed in an unobtrusive manner. No roof-mounted furnaces were audited. In one unit there was an unusual interlock switch which prevented furnace operation unless the doors to the supply air plenum were securely latched. The auditor who removed the sensors after the long-term test did not close the doors correctly, leaving the furnace inoperative. Within hours, the homeowner noticed that the furnace was not operating, and a short on-site visit was required to solve the problem. Other than the drilling of up to five holes in the air ducts and two holes in the stack, both of which were easily repaired with aluminum duct tape, there was only one instance of furnace related damage. In that house the door fell off the furnace closet, knocking a hole in a nearby hollow-core bedroom door as it fell.

In most furnaces there was poor mixing of the flue and stack gasses, and therefore significant temperature stratification. In addition, some furnaces used multi-port heat exchangers which had large differences in outlet temperature. In the field, a single thermocouple was placed at what appeared to be a representative point in the flue or stack. Measurement uncertainties could be reduced by implementing some temperature averaging sensors, such as the thermocouple grid used to measure the spatial average temperature during laboratory testing.

Conducting the furnace audit requires the auditor to force the furnace on and off at prescribed time intervals. As with the air conditioner audit, this presented a problem in houses with complicated programmable and multi-zone thermostats.

There is another difficulty with multi-zone control thermostats. During the furnace short-term test in one house, the temperature in one zone reached the maximum setpoint value 26.7 ° C (80 ° F), which shut off air flow to that zone without shutting down the furnace. Thus, the zone control can change the total air flow through the furnace, and the associated furnace efficiency, during a test without the auditor's knowledge or control. Larger houses had as many as eight zones under a single thermostat's control. It was impossible to monitor the position of all the zone dampers, which resulted in an uncertain furnace air flow rate during the audit.

## APPLIANCE SELECTION

Since the primary goal of this study was the development and implementation of audit procedures useful for a large-scale survey of in-situ appliance efficiencies, the appliances tested during the small-scale audit procedures field test were not expected to form a representative sample of the appliances in the PG&E service territory. The appliance selection was based on availability, usually from friends and associates of the researchers, not on random selection criteria. Some appliances are over-represented, e.g. high-efficiency furnaces, and some appliances are under-represented, e.g. electric water heaters.

The appliances from a total of 61 single-family houses were audited, 31 during summer, July-September, 1986, and 30 during winter, November 1986-January 1987. All of the houses had frost-free electric refrigerators. The breakdown for water heaters was 58 gas units and 3 electric units. All of the summer study houses had central air conditioners. All of the winter study houses had gas-fired central-forced-air furnaces. The age distribution of the appliances studied is shown in Figure 2. Most of the appliance audits were conducted in three geographic zones; north central valley, e.g. Sacramento, south

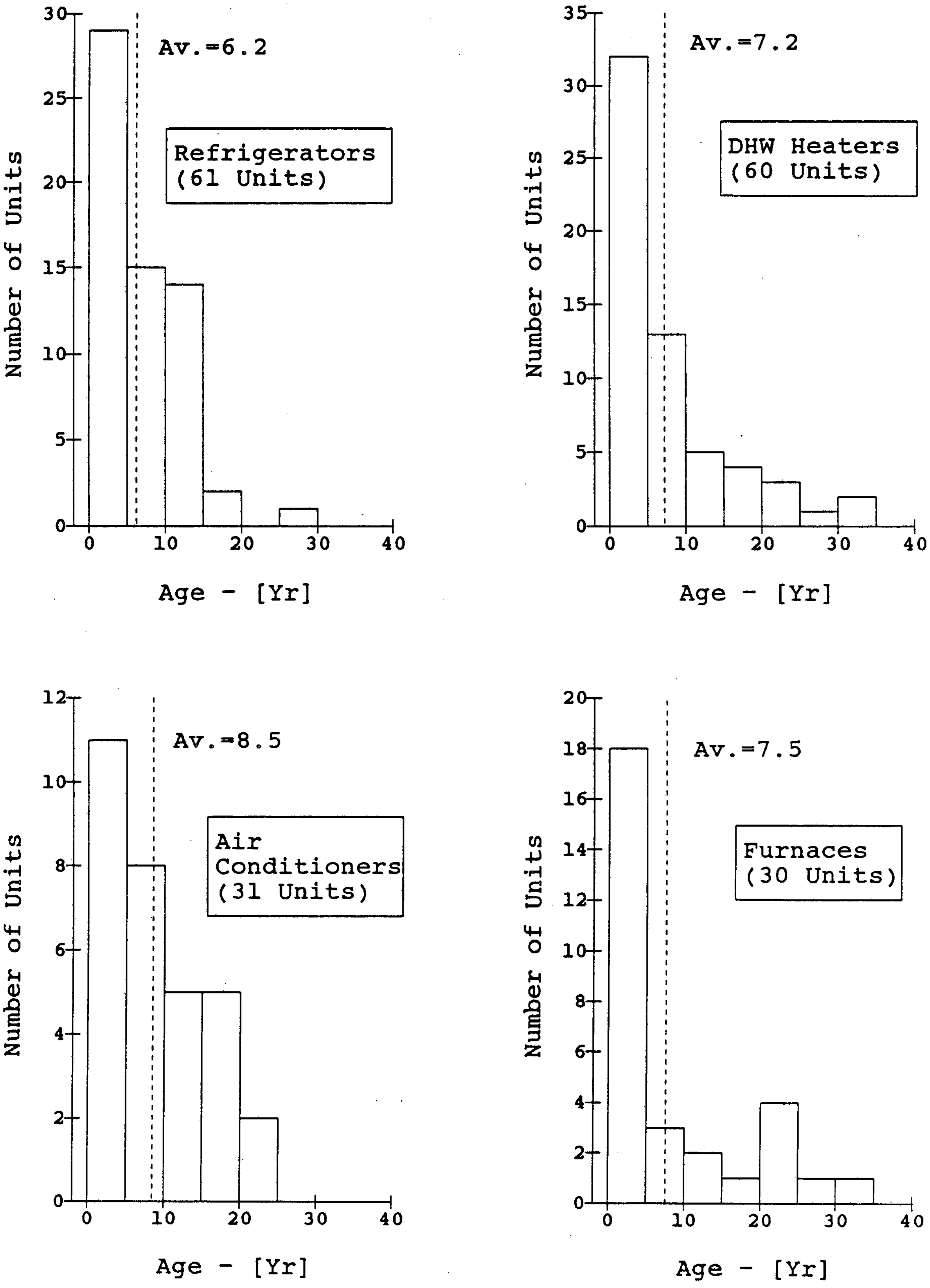

Figure 2. Age distribution of the appliances studied.

central valley, e.g. Fresno, and intercoastal valley, e.g. San Ramon/Livermore/Tracy. The house locations are shown in Table 4. The appliance age distributions are presented in Table 5, and the complete set of data is presented in tabular form in Appendix A. The number of appliances that have been replaced since the house was built (e.g. are newer than the house) is shown in Table 6.

TABLE 4
LOCATIONS OF HOUSES STUDIED

| Location | Number of Test Sites | Location | Number of Test Sites |
|---|---|---|---|
| Albany | 1 | Martinez[a] | 1 |
| Concord | 2 | Pacifica | 1 |
| Castro Valley | 7 | Pleasanton | 2 |
| Danville | 2 | Sacramento | 7 |
| Dublin | 1 | San Ramon | 9 |
| Fresno | 8 | Sunol | 1 |
| Livermore | 9 | Tracy | 9 |

Note:
a) This test site was tested during both summer and winter studies.

TABLE 5
AGES OF APPLIANCES STUDIED

|  | Refrigerator | Gas DHW | Electric DHW | Air Conditioner | Gas Furnace |
|---|---|---|---|---|---|
| Total Number of Units | 61 | 57 | 3 | 31 | 30 |
| Average Age in Years | 6.2 | 7.3 | 5.0 | 8.5 | 7.5 |
| Age Distribution in Years: |  |  |  |  |  |
| 0-2 | 31% | 47% | 0% | 23% | 57% |
| 3-5 | 25% | 9% | 67% | 19% | 3% |
| 6-10 | 28% | 21% | 33% | 26% | 13% |

TABLE 6
APPLIANCES REPLACED SINCE HOUSE WAS BUILT

|  |  | Hot water |  |  |  |
|---|---|---|---|---|---|
|  | Refrigerator | Gas | Electric | A/C | Furnace |
| Number/Total Units | 32/61 | 18/57 | 1/3 | 12/31 | 7/30 |
| Percent | 52 | 32 | 33 | 39 | 23 |

## RESULTS OF APPLIANCE EFFICIENCY MEASUREMENTS

As part of the audit-procedures field test, actual in-situ appliance efficiencies were measured as they would have been in a larger study using the same audit procedures. The results of these appliance efficiency measurements are presented in this section. The discussion section presents issues of concern about the audit procedures, some of which are based on the results of the appliance efficiency measurements presented in this section.

The in-situ appliance efficiency data presented in this report is similar to that expected from a full-scale survey, except that more inferences about the population can be made from a representative sample. The main goals of the full-scale appliance efficiency survey are to compare the field-measured (audit) and rated (laboratory) performance indicators (e.g. average energy use, recovery efficiency, standby loss, EER, SEER, and seasonal efficiency), and to determine the major factors affecting efficiency degradation. The results from this study are therefore presented in two formats:

(1) measured performance indicator versus rated indicator

(2) measured performance indicator versus appliance age

A description of the complete test sample for each of the appliances is presented in Appendix A. The raw data used to compute the measured appliance efficiency indicators presented in this section, as well as the indicators themselves, are also presented in tabulated form in Appendix A. Appendix C contains a discussion of the errors associated with these results. In addition, the measured-minus-rated indicator differences versus both rated indicator and appliance age are presented in Appendix D. This presentation format makes it easier to detect a performance degradation trend with appliance size or age. Appendix D also includes a short discussion of the interpretation of the 95% confidence intervals used in many of the following figures.

## Refrigerators

The refrigerator energy consumption test results are presented in Figures 3 and 4. The measured electric energy consumption, in kWh/Day, was normalized for door openings and freezer-to-ambient temperature differences, as explained in Appendix B. An energy consumption correction factor of 0.86 was used to normalize electrical consumption for compartment door openings and food load, which are not part of the laboratory test. In addition, the average field-measured ambient, fresh-food compartment, and freezer compartment temperatures were 22.8, 3.9, and -16.1 ° C, (73, 39, and 3 ° F), compared to laboratory test conditions of 32.2, 7.2, and -15.0 ° C, (90, 45, and 5 ° F), respectively. Normalization of electrical consumption for differences in operating temperature resulted in energy consumption correction factors of 1.05 to 2.13, with a mean of 1.42. The combined effect of these two normalizations was an average normalized consumption that is 20% greater than average measured consumption.

Figure 3 shows the normalized energy consumption compared to the rated value. Both measured and rated energy consumption data were available for only 46 of the 61 refrigerators tested. One refrigerator, which had a very high energy consumption (13.26 kWh/Day) and a very high freezer temperature even though the thermostat was at its coldest setting, was assumed to be malfunctioning and was not included in this data set. The diagnostic data provided no explanation for the high consumption of the other apparent outliers. An examination of consumption vs food load and door openings, which is believed to be responsible for much of the variation, is beyond the scope of this study.

There is a lot of scatter in the measured data in Figure 3, with some units consuming over twice as much as the rated value, and others consuming little more than half the rated value. The data are not consistent with the hypothesis that the normalized energy consumption is equal to the rated consumption (within a 95% confidence level) but indicate that on average the measured is higher than rated. For those units for which rated values are available, the average measured electrical consumption was 3.99 kWh/Day, the average normalized value was 4.65 kWh/Day, and the average rated value was 4.15 kWh/Day. The average normalized measured refrigerator consumption was 12% higher than rated.

The electrical consumption data group is broken into two sets, those for which the anti-sweat heater was turned on, and those for which the heater was turned off or there was no anti-sweat switch. Of the units with their anti-sweat heaters on, all except one consumed more than the rated value, with an average normalized value of 4.90 kWh/Day compared to an average rated value of 3.54 kWh/Day. The rating procedure requires these heaters to be on one-half of the time, whereas they were turned on during the whole in-situ test. For the off-or-none anti-sweat heater category, the average normalized value was 4.56 kWh/Day compared to an average rated value of 4.38 kWh/Day. Note that no anti-sweat or energy-saver switch does not mean that there is no anti-sweat heater, only that there is no option to turn it off.

Figure 4 compares normalized specific energy consumptions for 59 units with unit age and with the applicable California standards, where specific consumption is the normalized measured electricity consumption, adjusted for volume. Details of the computation of specific consumption are presented in Appendix B. This allows all volumes of refrigerators to be compared in the same figure. Data points above the standards line consume more than the standard, whereas data points below the line consume less than the standard. Newer units clearly consume less energy than the older units, and the effect of the introduction of the 1979 standard is quite apparent.

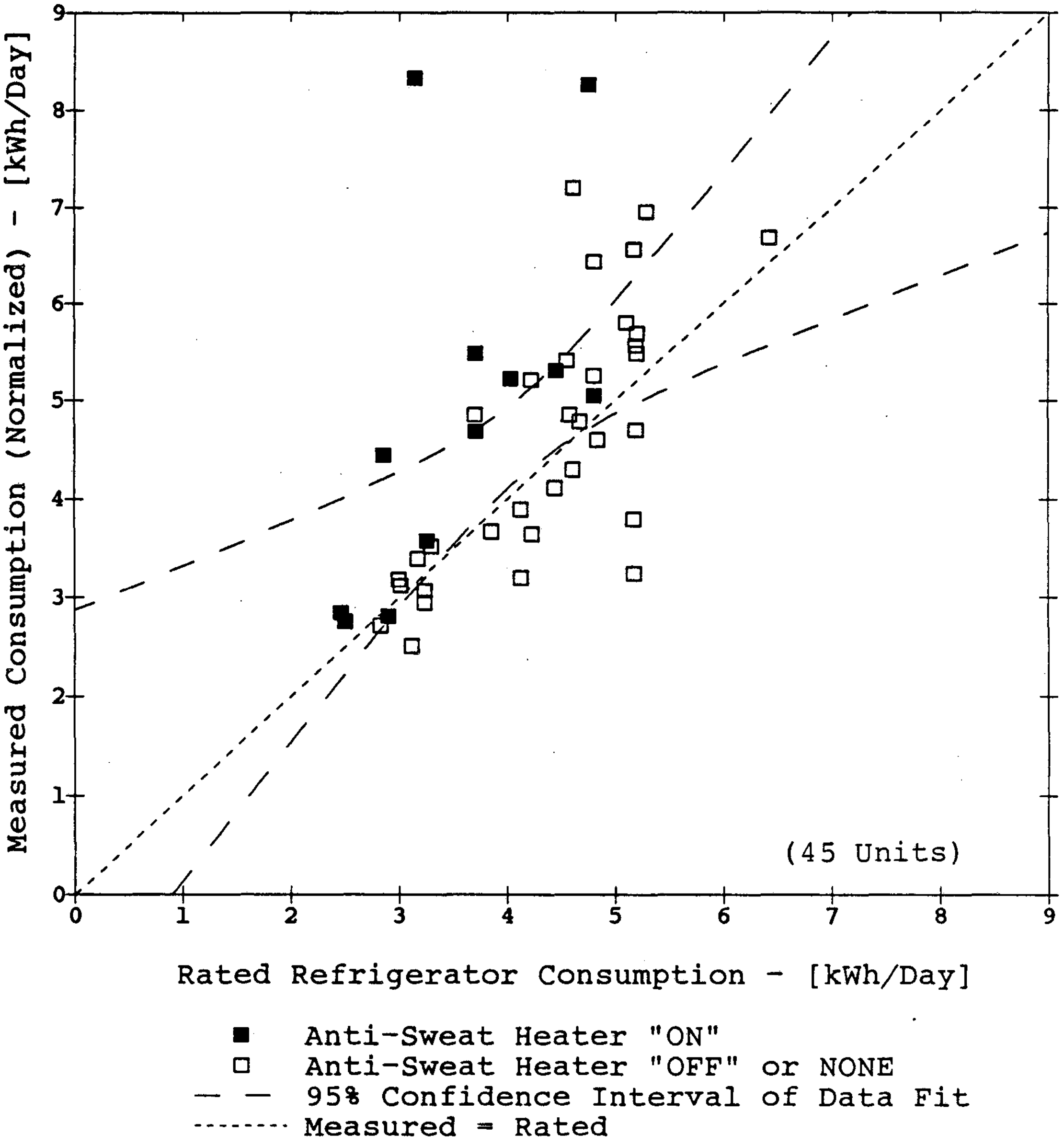

Figure 3. Normalized measured refrigerator consumption as a function of the rated value.

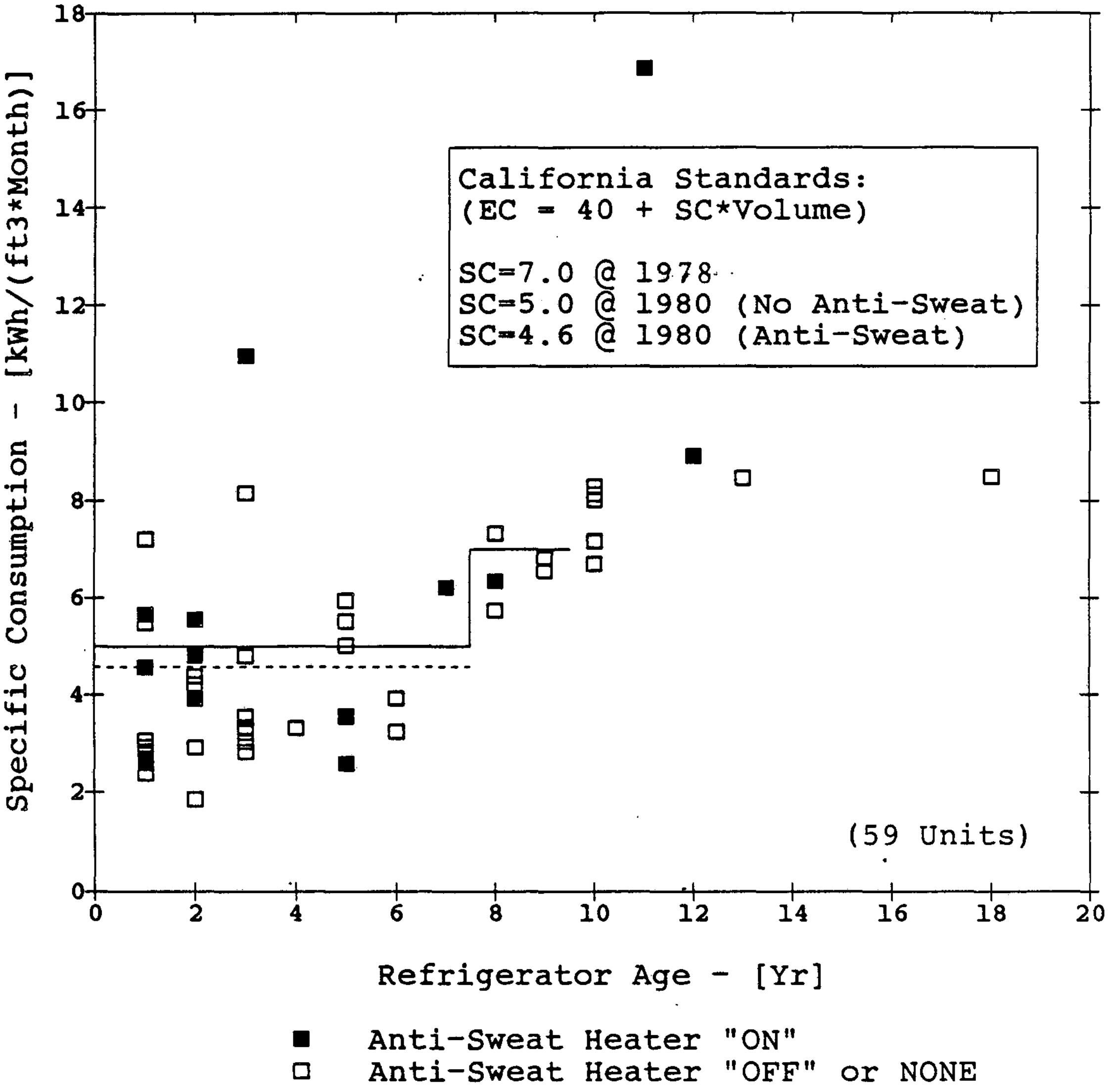

Figure 4. Measured refrigerator specific consumption as a function of the age of the unit. Horizontal lines indicate State of California standards.

### Water Heaters

The recovery efficiency results for gas water heaters are presented in Figures 5 and 6. Figure 5 shows the measured recovery efficiencies versus rated recovery efficiency. Data were available for 33 of the 57 gas DHW heaters tested. For all except two units, the rated value was 76%. The measured data exhibits a large scatter, with a maximum value of 82.4%, a minimum of 52.4%, and an average of 70.6%.

A large amount of scatter is also evident in Figure 6, which compares measured recovery efficiency with unit age and with the applicable California standards of 74% and 76%. Data were available for 57 units. There is no clear trend of efficiency with age. Some 30-year old units are as efficient as 1-year old units. Some of the low values are attributable to thermosiphon loops or other loss mechanisms which would not be found in a laboratory test setup, although they may be common in the field.

The standby loss could not be determined for most of the water heaters due to a lack of main burner operation (or electrical consumption) during time periods with no hot-water use. The reasons for this are presented in the discussion section. The results for the test sites in which the main burner (or electric element) did operate during a hot water no-use period are presented in Figure 7. Unfortunately, five of the eight gas DHW heaters for which there were data were also special cases. The homeowners were on vacation at two sites, the aquastat was set at maximum setpoint at one, and in two others the pilot light consumption was estimated because the utility gas meter did not operate correctly at the very low gas flow rate of a pilot light.

For gas units the standby losses vary between 5.7 and 8.9%/h with a mean of 5.73%/h. For comparison, the rated values vary between 3.3 and 4.95%/h, with a mean of 3.71%/h. In all cases the measured standby losses are significantly higher than the rated values; an average of 54% higher. It should be noted that due to the nature of the audit procedure, houses with high standby losses are much more likely to have measurable standby losses, which results in a biased sample.

Only three electric water heaters were tested, and standby loss results were obtained for only one of the three. The measured electric water heater standby loss was measured as 97 W, but, unfortunately, no rated value was available for this unit.

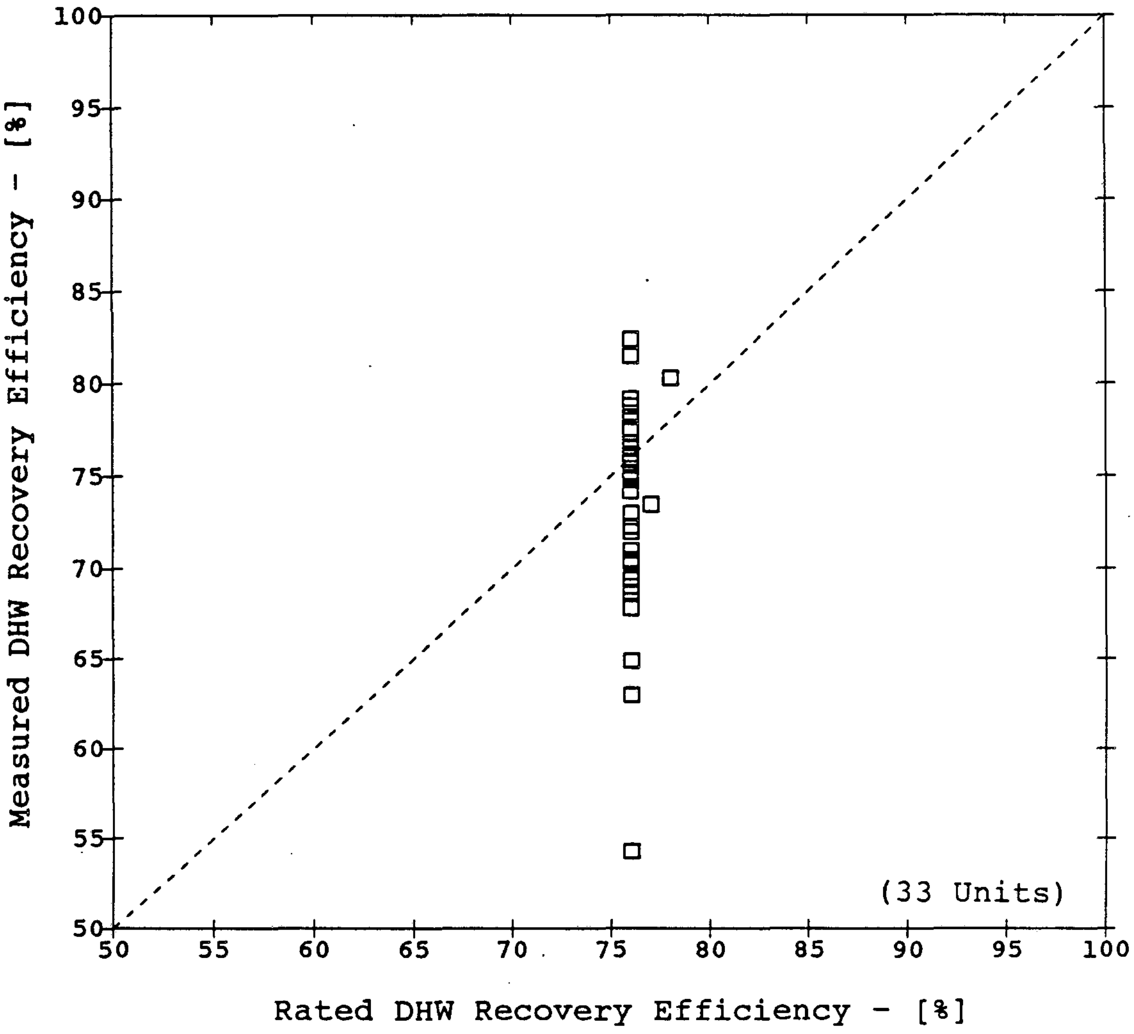

Figure 5. Measured DHW recovery efficiency as a function of the rated value.

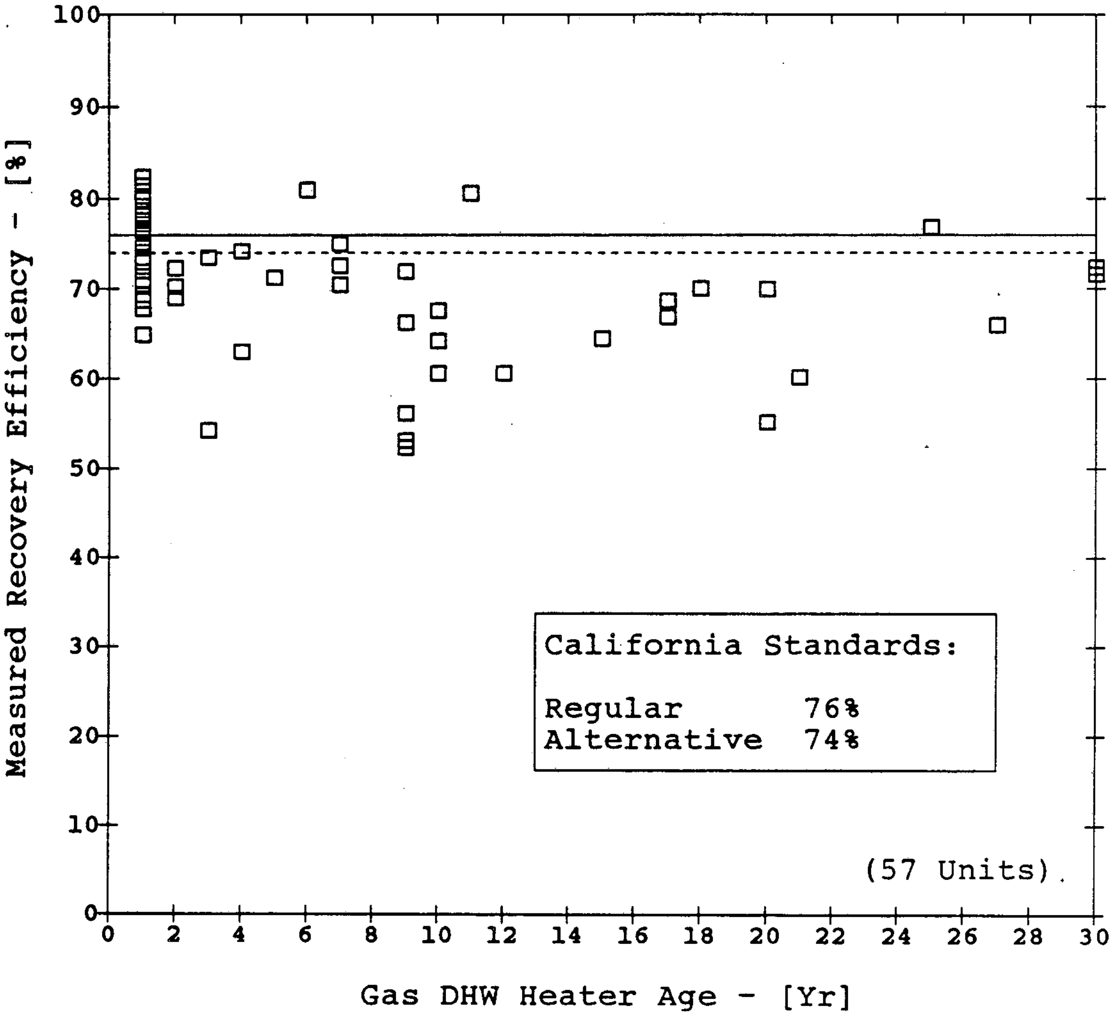

Figure 6. Measured DHW recovery efficiency as a function of age of the unit. Horizontal lines indicate State of California standards.

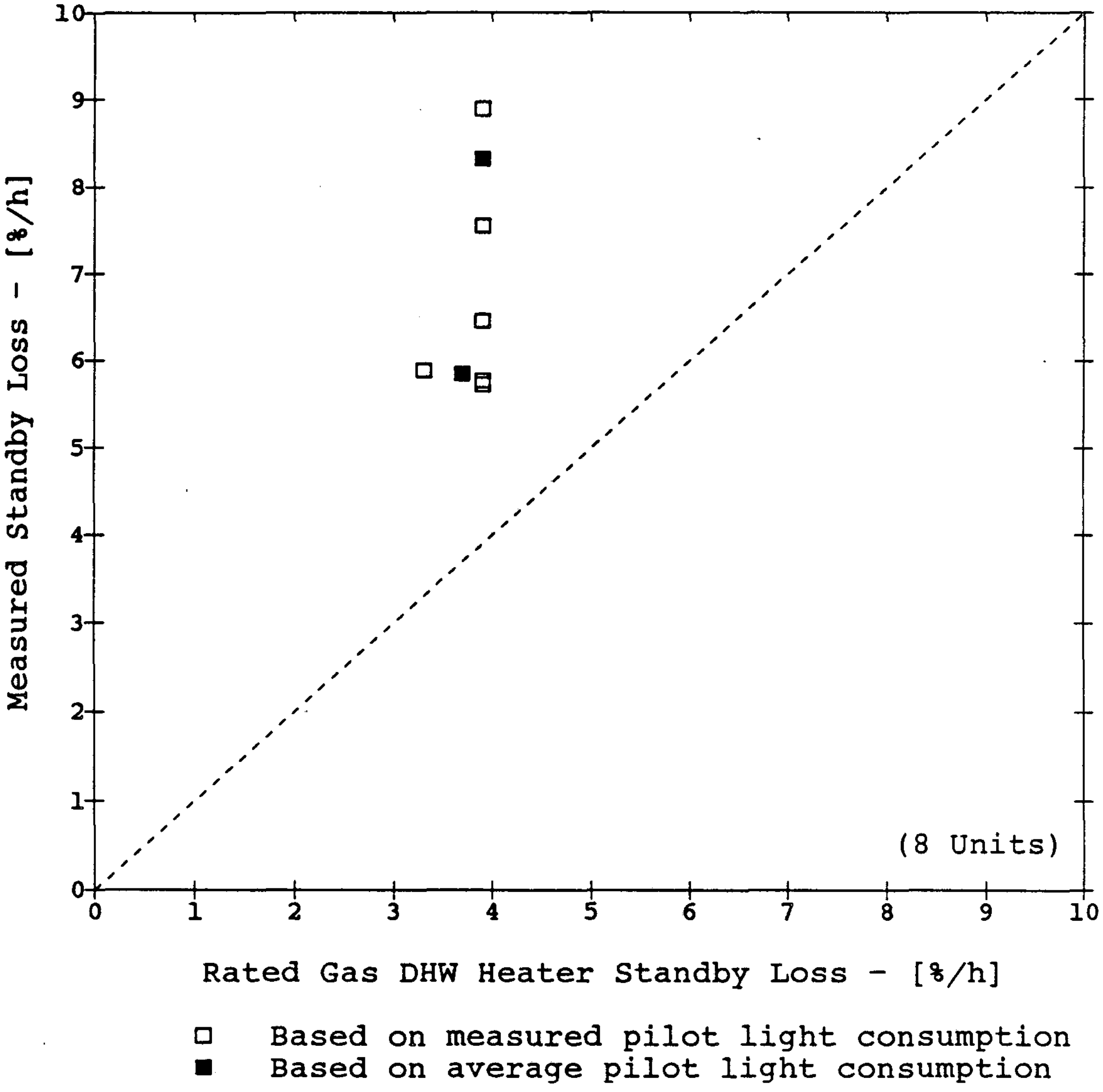

Figure 7. Measured DHW standby loss as a function of the rated value.

## Central Air Conditioners

The air conditioner efficiency results are presented in Figures 8 and 9. Figures 8 shows measured ERR versus rated EER (Fig. 8a) and measured SEER versus rated SEER (Fig. 8b). Data for EER and SEER were available for only 10 and 17 of the 31 air conditioners that were tested, respectively. It is evident that there is a large amount of scatter to the data. Even given this scatter, it is clear that the measured EER is consistently lower than the rated EER, with average values of 5.81 and 7.40 Btu/Wh, respectively. The same is true of the SEER data, with a measured average of 6.07 Btu/Wh compared to a rated average of 7.90 Btu/Wh. There are also a large number of outliers, such as the point with a measured SEER of almost 15, which, given the state of current air conditioning equipment, is very unlikely. Given this level of uncertainty in the data, it is clear that the experimental methods require considerable improvement, and interpretation of the data must be done carefully. This point is discussed in detail in Appendix E.

Figure 9 shows the variation of measured EER or SEER, as appropriate, with the unit age. Data were available for 10 EER and 17 SEER units. It appears that the measured value is almost always below the standard, but that there is no clear trend with unit age.

It had been hoped to document the variation of air conditioner EER with outdoor temperature. However, there was so little air conditioner usage in the sample houses that no such data analysis was possible. Usage was an average of only 8 hours per week and in 12 houses there was no usage at all.

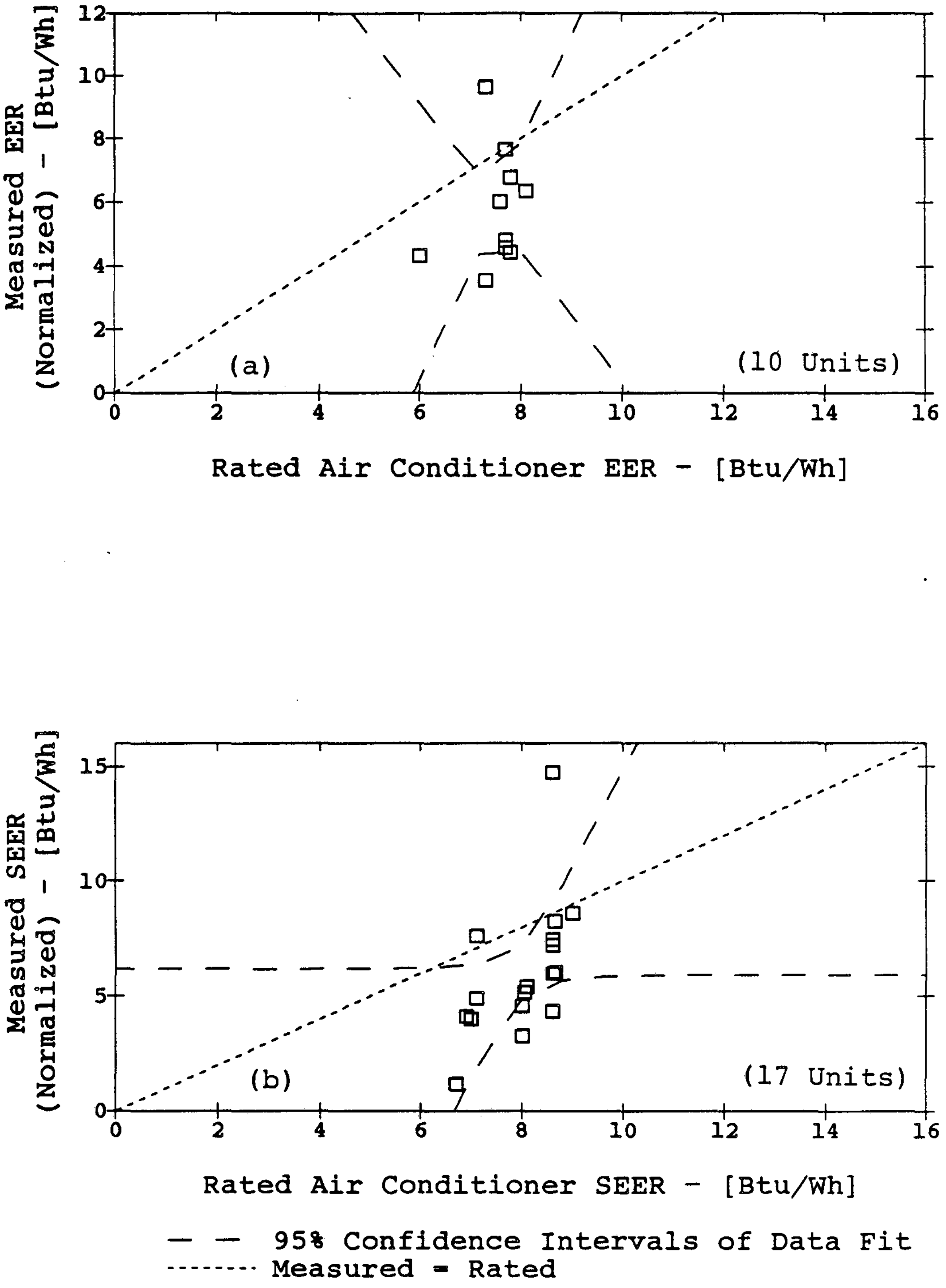

Figure 8. Measured air conditioner EER (above) and SEER (below) as a function of the rated value.

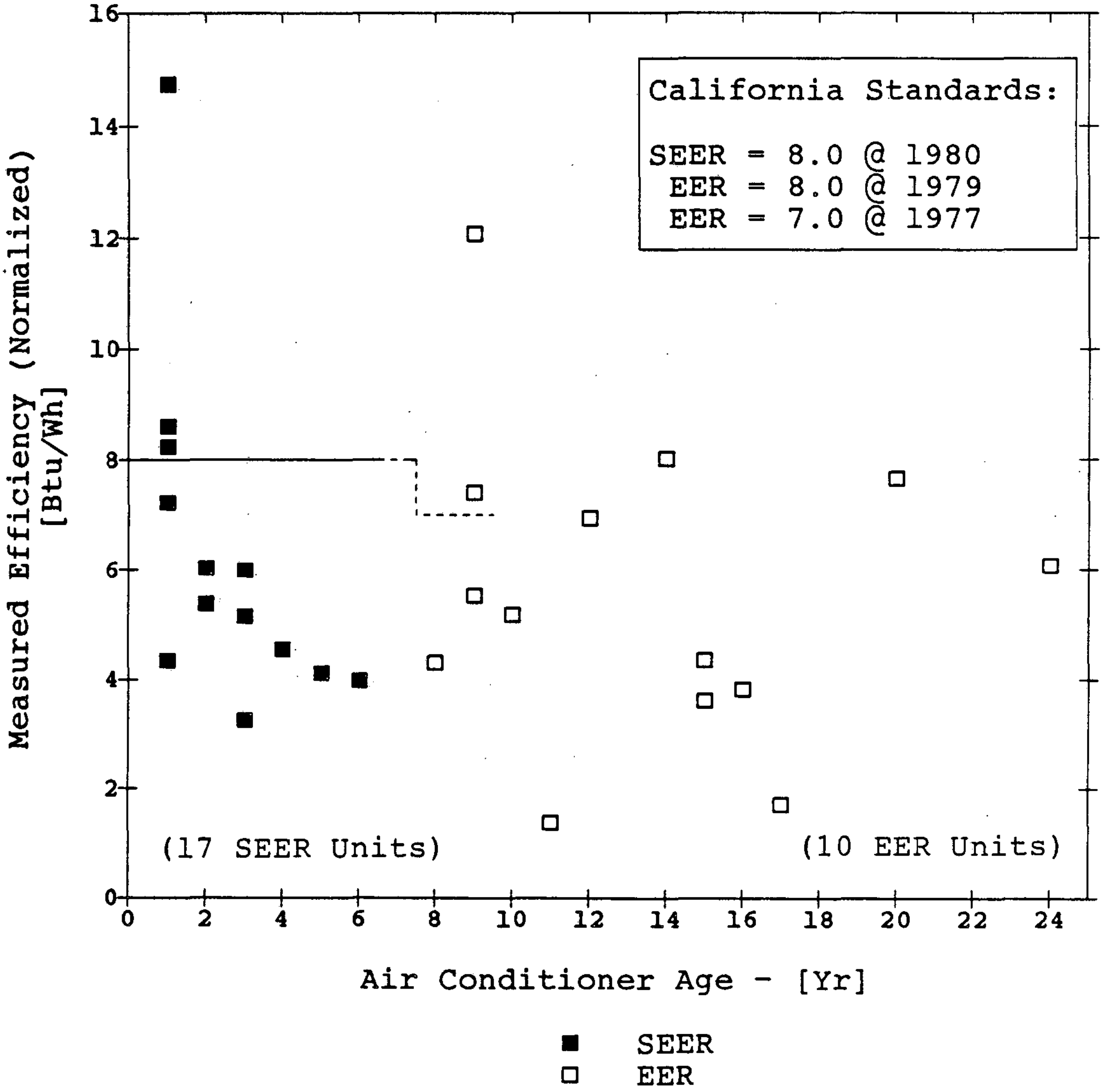

Figure 9. Measured air conditioner EER (or SEER as appropriate to the age of the unit) as a function of age of the unit. Horizontal lines indicate State of California standards.

## Furnaces

The gas furnace seasonal efficiency results are presented in Figures 10 and 11. Figure 10 shows the measured seasonal efficiencies versus the rated values. Rated data were available for 16 of the 30 furnaces tested. There is little scatter in the measured seasonal efficiences, perhaps because these units are all very new; all except one were less than 1 year old. The maximum measured value was 79.0%, the minimum 64.8%, with an average of 74.7%. The 64.8% seasonal efficiency furnace had a unusually high stack temperature, and thus lower steady state efficiency and much higher off-cycle losses than the other units.

The measured seasonal efficiency data is consistent with the hypothesis that measured equals rated values, within a 95% confidence level. The average measured seasonal efficiency was 74.7%, compared to an average rated value of 74.5%. Note that this conclusion applies only to the relatively new (i.e. less than one year old) furnaces in this sample. Older furnaces were required only to meet a steady state efficiency of 75%, so seasonal efficiency values were not available.

Figure 11 shows the variation of measured furnace efficiency with unit age, and its relationship with the applicable California standards. Data were available for 29 furnaces, 16 units with seasonal efficiency and 13 units with steady-state efficiency. The measured efficiency values should be compared with the California standards, which are: 1) 71% seasonal efficiency effective December 1982, 2) either 71% seasonal efficiency or 75% steady-state efficiency effective December 22, 1980, or 3) 75% steady-state efficiency prior to 1980 (ANSI standard Z21.47-1973, Gas-Fired Gravity and Forced Air Central Furnaces). There is no trend of efficiency with unit age. The older unit steady-state efficiencies cluster around the 75%, while the newer units seasonal efficiency is general better than the requirement.

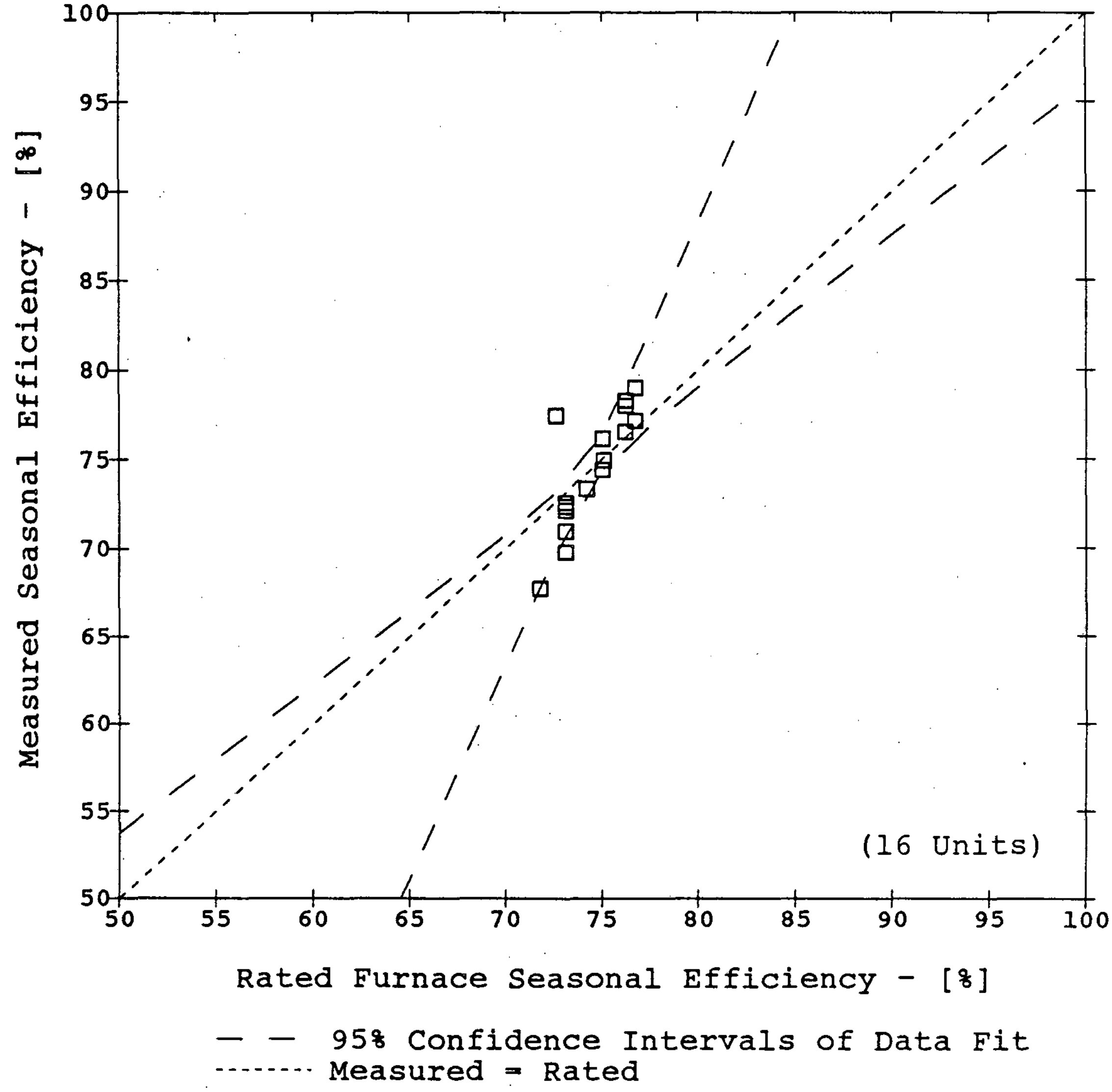

Figure 10. Measured furnace seasonal efficiency as a function of the rated value.

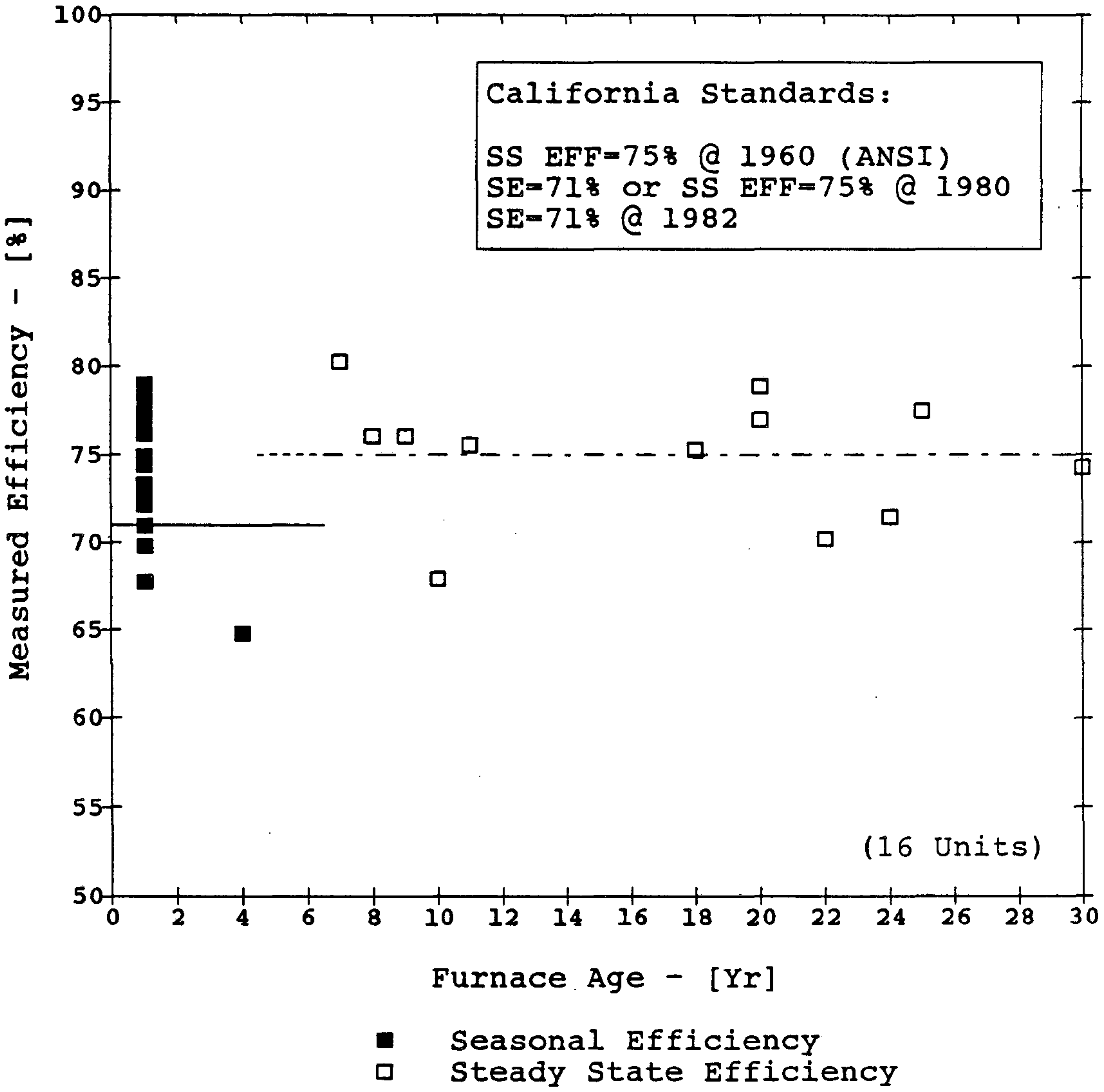

Figure 11. Measured furnace efficiency (seasonal or steady state, as appropriate to the age of the unit) as a function of age of the unit. Horizontal lines indicate State of California standards.

## DISCUSSION OF AUDIT PROCEDURES

Over the course of this study, audit procedures for measuring the in-situ efficiency of residential appliances have been field tested. The efficiencies of refrigerators, gas and electric water heaters, central air conditioners and central gas forced-air furnaces in 61 houses in three areas of the PG&E service territory were measured. The analyses performed to date have provided a number of refinements to the initial audit procedures. In addition to the general field experience gained in performing a four-appliance audit survey, a number of issues concerning each of the individual appliance audits merit further discussion.

### Refrigerators

The long-term refrigerator audit procedure is relatively simple except for installation of the the computer-based data acquisition system used to monitor temperatures and refrigerator cycling. Although the installation and operation of the data acquisition system used in this project is beyond the capabilities of the average auditor, use of simpler time-integrating thermometers could simplify future testing. (Refrigerator cycling is not required for determining the efficiency indicator.) Also, additional investigation of the relationship between 2-hour average temperature data (collected during the short-term test) and the long-term (one-week average) temperature data may reveal a potential for shortening the temperature measurement period. The average fresh food and freezer compartment temperatures gathered during the two hours of short-term testing were found to be comparable to the values gathered during the one-week long-term test. However, because of the unknown history and variability of food addition, door openings and defrost cycles, a short-term measurement of energy consumption has a high uncertainty. See Appendix E for a more detailed discussion.

A potential problem with the field-monitored energy use of refrigerators is occupant effects. Although the laboratory procedure is conducted under controlled refrigerator conditions (e.g. fixed compartment and ambient temperatures, an empty refrigerator, and no door openings) a field study has no such controlled operating conditions. Field variations must therefore be accounted for by normalizing the field measurements, as was done in this study. The compartment temperatures and ambient temperatures were monitored, and a door-openings sensor was developed for use during the winter study. Although normalizations were made with regard to temperatures and door openings, the flow of warm food into the refrigerator under normal use was not accounted for explicitly. A detailed discussion of these issues is presented in Appendix B.

### Water Heaters

Of the two efficiency indicator audit procedures developed for water heaters, the recovery efficiency procedure seems reliable and straightforward, whereas the standby loss procedure has proved to be more difficult and unreliable.

The recovery efficiency procedure, although somewhat time-consuming, does not require any long-term monitoring. The equipment required for this short-term test, a thermometer, the utility gas meter, and a stop watch, are rugged and easy to use. Any trained auditor should be capable of conducting the test. The recovery efficiency results appear to be reasonable in all cases except for systems with thermosiphon or pumped loops, which cause excessive tank heat losses that can not be accounted for by this measurement technique. A less time-consuming alternative procedure, stack-gas analysis, was also examined. Our results to date show that the steady-state stack-gas efficiency appears to follow the recovery efficiency, but that stack-gas measurements do not reflect much of the variability in recovery efficiency. This results from the fact that stack-gas measurements are insensitive to a number of heat loss mechanisms. If a higher level of uncertainty is acceptable, it may be possible to use stack-gas analysis, which uses a $2,650 instrument but takes only a half-hour, instead of measuring recovery efficiency, which uses $230 in instruments but takes over two hours (see Appendix E).

The standby loss audit procedure requires long-term monitoring, the objective being to measure the total energy consumption between two main-burner (or electric-element) operations during a period with no hot water use. The long-term test requires the installation and operation of a computer-based data acquisition system, and is presently beyond the capabilities of the average auditor. The major problem with the procedure was that the required consecutive burner operations with no hot water use were observed in only 8 of the 61 houses tested. One reason for the lack of main-burner operation during hot water non-use periods was the short length of these periods; less than 8 hours, except in houses where the owners were away. At 10.0 °C (50 °F) ambient air temperature, a typical water heater performing as rated (without an insulation jacket) would go 12 hours between burns. Also, many of the water heaters were in garages, which are very warm during the summer, or interior closets, which are relatively warm year around. Under these conditions, standby loss is quite low and could only be estimated based upon the pilot light consumption and the maximum time elapsed between a main-burner operation and a water use (see Appendix E).

Our experience with standby loss measurement to date, including examination of a number of measurement alternatives (Appendix E), suggests that it is impractical (or excessively expensive) to measure this indicator reliably in the field.

## Central Air Conditioners

The air conditioner audit procedure does not presently produce efficiency calculations within the uncertainty prescribed by the California Energy Commission. The major source of error comes from the difficulty associated with field measurements of condenser-coil air flow. Air conditioner operation is such that an error in the air flow is magnified when calculating the operating efficiency. Although three alternative techniques for measuring air flow were utilized during the study, none were deemed suitable. Several additional options are described in Appendix E, all of which require some additional development work.

The existing method for measuring SEER requires a method to measure air flow, a computer based-data acquisition system to measure temperatures, and a KWH meter. Depending on the set of instruments chosen, the cost ranges from about $2,000 to about $10,000. The present air-flow measurement procedures require between five minutes and one hour. The remainder of the SEER test takes about 90 minutes to complete. Operation of the tracer gas measurement equipment and data acquisition system is beyond the capabilities of average auditor. The simplest part of the test procedure is the diagnostic for determining if the air conditioner is properly charged, a technique commonly used by commercial air conditioning contractors.

The long-term air-conditioner tests did not provide the expected quantity of data. During this study the homeowners did not use their air conditioners as much as expected due to a combination of mild outside air temperatures and the large number of working couples in the study. Although a field study is always at the mercy of the weather and the habits of homeowners, the latter effect could be reduced in the future by convincing (or paying) the homeowners to use their air conditioners for one week. However, forced air conditioner operation under cool weather conditions would not give accurate data on actual cycling rate, the desired parameter. The long-term test is not required to measure SEER, but rather to obtain information about the actual cycling of air conditioners in the field, as previous studies have shown that actual performance is often different from that measured using cyclic conditions assumed by the laboratory test. The present long-term procedure does not require any equipment in addition to that used for the short-term test.

In general, the SEERs and EERs measured in the field were significantly lower than those measured in the laboratory, indicating that field SEER and EER are efficiency indicators that merit further study. Unlike DHW standby, there is no known bias that may have caused the poor measured performance in the field. The effort required to improve the present field procedure appears to be justified, since air conditioners contribute significantly to peak power loads. Some alternative techniques are examined in Appendix E.

### Furnaces

The furnace audit procedure was quite straightforward and, except for difficulties in obtaining an accurate average temperature in the flue and stack, presented few problems. For units rated by seasonal efficiency, the measured value was very close to the rated value. For older units, for which the only requirement was a 75% steady-state efficiency, there was no trend toward reduced efficiency with age.

The calculation method for seasonal efficiency is complex. However, the ASHRAE standard on which it is based is being revised, and there is some expectation that the new standard will be simpler. The furnace test procedure does not require long-term monitoring. The entire test takes two hours and can be performed by a trained auditor using approximately $3,300 in equipment.

## CONCLUSIONS

The main objective of this study was to develop and field-test appliance audit procedures that could be used in a large survey of in-situ appliance efficiencies in the PG&E service territory. It was further required that the appliance efficiency indicators measured in the field be comparable to the laboratory-measured efficiency indicators for refrigerators, gas and electric water heaters, central air conditioners, and central gas forced-air furnaces. This objective was met for refrigerators, for the recovery efficiency of water heaters, and for central gas furnaces. Based on the results of this study, the water heater standby loss and air conditioner efficiency audit procedures cannot be considered practical audit procedures to be included in a large survey of appliance efficiency. Furthermore, the experience gained in this study indicated that a more detailed examination of alternative air conditioner audit procedures is advisable, but that development of a practical audit procedure for measuring water heater standby loss is very unlikely. On an indicator-by-indicator basis, the pilot study demonstrated that:

(1) The refrigerator audit procedure required *long-term* monitoring with relatively simple and inexpensive equipment. Although the instrument measurement accuracy is acceptable, the data normalization algorithms induce a significant increase in the overall uncertainty and require some refinement. This audit procedure is recommended for a large survey.

(2) The gas water heater recovery efficiency audit procedure required *short-term* testing, used simple and inexpensive equipment, and produced results of acceptable accuracy. (Electric water heaters do not require this test.) This audit procedure is recommended for a large survey.

(3) The standby loss audit procedure for both gas and electric water heaters required *long-term* monitoring using complicated and expensive equipment. Although the measurement accuracy was acceptable, the test produced results in less than 15% of the houses, due to insufficient time periods without hot water use in occupied houses. An acceptable alternative procedure was not found, and no audit procedure is recommended for a large study.

(4) The air conditioner audit procedure for measuring EER and SEER required only *short-term* testing. However, the measurement accuracy was not acceptable due to problems with condenser coil air flow measurements. The present audit procedure is therefore not recommended for a large survey. It is recommended that an alternative procedure be developed for a large survey, although further study will be required.

(5) The furnace audit procedure for measuring steady-state and seasonal efficiency required only *short-term* testing using relatively simple (though expensive) equipment and produced results of acceptable accuracy. This audit procedure is recommended for a large survey.

Based upon the above recommendations, the audit procedures for a large survey would consist of one-day testing of the water heater, air conditioner, and furnace, and long-term monitoring of the refrigerator. The long-term refrigerator monitoring would consist of a KWH meter and two integrating thermometers instead of the data acquisition system used in the pilot study. Thus, the large survey audit procedure would be considerably less expensive than the pilot study audit. In the pilot study, the appliance audit procedures cost $8,000 per audit team and $2,500 per house in equipment, plus 12 man-hours labor for the air conditioner, water heater, and refrigerator (summer) survey. For the furnace, water heater, and refrigerator (winter) survey, the costs were $3,500 per audit team and $2,500 per house in equipment, plus 12 man-hours labor.

The costs for the audit procedures recommeded for the large survey are as follows. For the summer survey, $1,000 per audit team and $950 per house in equipment, plus 6-8 man-hours per house. In addition, there will be equipment and labor costs for the to-be-developed air conditioner air flow procedure. For the winter survey, $3,500 per audit team and $950 per house in equipment, plus 6-8 man-hours per house.

The audit procedures field-test, which included audits of 61 houses, produced the following appliance efficiencies results. Water heater recovery efficiencies were 7% lower than their rated values on average, while air conditioner efficiencies were more than 20% lower than their rated values on average. Refrigerator consumption was 12% higher than rated on average, and furnace efficiencies were within 1% of the rated values. No conclusions about field efficiencies in the PG&E service territory as a whole could be drawn due to the small size and potential bias of the appliance samples.

# ACKNOWLEDGEMENTS

The authors gratefully acknowledge the efforts of Carol Stoker, who was instrumental in locating test house volunteers, scheduling the audits, and assembling and polishing the final report. The field audit team, including Darryl Dickerhoff, Les Lewicki, Peter Cleary, Greg Chittick, and Richard Szydlowski, deserve a "job well done." The data management, analysis, and graphics was efficiently conducted using RS/1, a software package from Bolt Beranek and Newman, Inc. And of course, this study could not have been conducted without all the homeowners that volunteered to let strangers invade their homes and monitor their appliances.

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# APPENDIX A

# APPLIANCE TEST SAMPLE DESCRIPTION

The test sample of appliances used for the audit procedures small-scale field test was not randomly selected, and thus may be biased by the type of volunteer homeowners that were interested in participating. Table A.1 compares some selected attributes of 40 respondents from this study's test sample with the PG&E single family 1986 Residential Appliance Saturation Survey (RASS). The numbers show some clear differences between the households in the LBL sample and the PG&E single family 1986 RASS sample, which may affect generalization of the efficiency results to the population. The appliance sample also affects the audit analysis procedure because the algorithms used to normalize the refrigerator and air conditioner raw field data to rated conditions are based on a specific sample of appliances, not necessarily the same as our sample.

A short description of the parameters measured to calculate the appliance efficiency indicators is presented in this appendix. In addition, all of the data presented in this report is condensed into four tables for future reference. All appliance ages were based on 1986. The summary data enclosed in "()" or "[ ]" indicates measured value summaries for which corresponding ratings are available. Values enclosed in "<>" were determined to be outliers, and are not used in the averages enclosed in "()".

## Refrigerators

A distribution of refrigerator energy consumption without normalization (i.e. raw data) for all measured refrigerators (59 units) is presented in Figure A.1. The average energy consumption is 4.34 kWh/Day, but the range from minimum (2.01 kWh/Day) to maximum (8.57 kWh/Day) is vary large. This compares to an average of 5.22 kWh/Day for the normalized data.

The normalization of field measured refrigerator energy consumption to laboratory conditions is very sensitive to the actual refrigerator ambient air and compartment temperatures, and to occupant refrigerator use effects. Field measurements of the ambient air temperatures near the refrigerators are presented in Figure A.2. As shown, the average field temperature was 22.6 ° C, compared to the laboratory condition of 32.2 ° C. None of the field ambient air temperatures were as warm as standard laboratory test conditions. Field measurements of refrigerator fresh food and freezer compartment temperatures are presented in Figures A.3 and A.4. The fresh food compartment temperatures averaged 3.6 ° C, compared to a laboratory condition of 7.2 ° C. It is suspected that the reason for the three refrigerators with below freezing fresh food temperatures is that the temperature sensor was installed near the cooling vent from the freezer compartment. The freezer compartment temperatures averaged -15.4 ° C, compared to a laboratory condition of -15.0 ° C.

One measure of occupant effects on refrigerator energy consumption is the number of refrigerator compartment door openings. Figures A.5 and A.6 present refrigerator compartment door openings for the 13 winter study refrigerators that had door opening sensors installed. The average number of door openings is based on the total number of door openings counted for the one-week long-term test period. The fresh food compartment averaged 38.3 openings per day, and the freezer compartment averaged 6.8 openings per day. Both values are consistent with the limited refrigerator door opening data presented by other researchers. All of the refrigerator data presented in this report is given in Table A.2.

## Water Heaters

There is a lot of interest in the size of DHW heater pilot lights because of the pilot light's effect on standby loss rates. Figure A.7 presents a distribution of the pilot light energy consumptions found in this study. The average pilot light consumption was 584 Btu/h, but there was one DHW heater with a pilot light three times that size. A comparison of pilot light consumption with DHW heater age is presented in Figure A.9. A linear fit indicates a small, but significant, trend toward smaller pilot lights with newer DHW heaters.

A distribution of DHW heater main burner energy consumption, which averaged 34.1 kBtu/h, is shown in Figure A.11. It is interesting to compare measured gas input to rated gas input, as presented in Figure A.12. The measured gas input averaged 10% lower than the rated gas input value. Although there were very few measured gas input values greater than rated, there were many cases of measured values significantly lower than rated.

DHW heater standby loss rates are sensitive to both the hot water aquastat temperature setting and the ambient air temperature near the tank. The occupants involved in this study used a wide range of hot water temperature settings. Figure A.13 shows that although the average hot water setting was 54.7 ° C, they ranged from 43.5 to 70.2 ° C. The 70.2 ° C was for a DHW heater that was part of a solar system which included a down-stream tempering valve. Ambient air temperatures averaged 21.1 ° C, with temperatures ranging between 11.2 and 32.6 ° C. Although it was expected that the winter study DHW heaters would experience much lower ambient air temperatures than the summer study, that was not the case. The average summer ambient temperature was 24.2 ° C, compared with a winter temperature of 18.7 ° C, a difference of only 5.5 ° C. It had been hoped that lower air temperatures in the winter would provide higher standby losses, leading to more data collection. As a result, the amount of DHW heater standby loss information collected during the winter study was not as large as expected.

Measured recovery efficiencies for all measured DHW heaters (57 units) is presented in Figure A.14. The average recovery efficiency is 70.6%. All of the DHW heater data presented in this report is given in Table A.3.

## Air Conditioners

EER and SEER for all measured air conditioners (27 units) are presented as distributions in Figures A.15 and A.16. The average measured EER is 6.24 Btu/Wh. The average SEER is 5.72 Btu/Wh. All of the air conditioner data presented in this report is given in Table A.4.

## Furnaces

Figure A.17 presents a distribution of measured furnace pilot light consumption. Furnaces that were less that one year old used electronic ignition, and therefore did not have pilot lights. Pilot light energy consumption for furnaces without electronic ignition averaged 932 Btu/h.

Measured furnace gas consumption data is presented in Figure A.18. Although burners averaged 84 kBtu/h, there was one very large furnace at 173 kBtu/h. It is interesting to compare measured gas input to rated gas input, as presented in Figure A.19. The measured gas input averaged 6% lower than the rated gas input value. Although there were very few measured gas input values greater than rated, there were many cases of measured values significantly lower than rated.

Steady state and seasonal efficiencies for all measured furnaces (29 units) are presented as distributions in Figures A.20 and A.21. The average steady state efficiency is 78.3%. The average seasonal efficiency is 65.2%. All of the furnace data presented in this report is given in Table A.5.

TABLE A.1 COMPARISON OF SAMPLE CHARACTERISTICS

| | Single Family 1986 RASS | LBL Sample |
|---|---|---|
| Owners | 80% | 97% |
| Renters | 20% | 3% |
| **LENGTH OF OCCUPANCY** | | |
| Mean | 11.3 yrs | 6.6 yrs |
| 0-5 yrs | 39% | 59% |
| 6-15 yrs | 34% | 26% |
| 16 yrs or longer | 27% | 15% |
| **AGE OF RESIDENCE** | | |
| Mean | 28 yrs | 3.9 yrs |
| 0-2 yrs | 4% | 54% |
| 3-16 yrs | 34% | 43% |
| 17 years or older | 62% | 3% |
| **NUMBER OF RESIDENTS** | | |
| Mean | 3.0 | 2.92 |
| 1-2 | 46% | 42% |
| 3-5 | 48% | 53% |
| 6 or more | 6% | 5% |
| **SQUARE FOOTAGE** | | |
| Mean | 1,606 ft$^2$ | 2,022 ft$^2$ |
| Less than 1000 ft$^{f2}$ | 14% | 3% |
| 1000-2000 ft$^2$ | 65% | 45% |
| Greater than 2000 ft$^2$ | 21% | 52% |
| **NUMBER OF BEDROOMS** | | |
| Mean | 3.0 | 3.5 |
| 0-2 | 28% | 12% |
| 3-4 | 68% | 80% |
| 5 or more | 4% | 8% |
| **HOUSEHOLD INCOME** | | |
| Mean | $34,938 | $54,260 |
| Less than $20,000 | 29% | 0% |
| $20,000-$40,000 | 37% | 19% |
| Greater than $40,000 | 34% | 81% |
| **CONSERVATION FEATURES** | | |
| Ceiling Insulation | 81% | 97% |
| Wall Insulation | 58% | 65% |
| Weatherstripping | 63% | 44% |
| Water Heater Blanket | 44% | 44% |
| Low-Flow Showerhead | 46% | 66% |
| Caulking | 44% | 62% |
| Duct Wrap | 37% | 60% |

TABLE A.2 REFRIGERATOR RESULTS

| Site Code | Age [Yr] | Volume [ft3] | Compartment Temperatures Fresh [°C] | Freezer [°C] | Ambient [°C] | Door Openings Fresh [No./Day] | Freezer [No./Day] | Anti-Sweat Heater | Measured Consumption [kWh/Day] | Normalized Measured Consumption [kWh/Day] | Rated Consumption [kWh/Day] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Summer: | | | | | | | | | | | |
| CON01 | 17 | 19.5 | 4.7 | -13.4 | 24.2 | | | ON | 6.90 | 8.33 | 3.14 |
| CON02 | 17 | 23.5 | 5.8 | -15.7 | 23.9 | | | NONE | 3.41 | 3.80 | 5.17 |
| DAN01 | 12 | 22.5 | 4.1 | -16.7 | 26.4 | | | OFF | 4.95 | 4.85 | 3.70 |
| DAN02 | 9 | | 4.8 | -17.9 | 23.6 | | | NONE | 7.33 | 7.60 | |
| FRE01 | 18 | 19.2 | 4.6 | -13.8 | 22.3 | | | ON | 4.12 | 5.31 | 4.45 |
| FRE02 | 27 | | 3.4 | -13.7 | 22.4 | | | OFF | 6.50 | 8.37 | |
| FRE03 | | 18.6 | 4.2 | -13.6 | 22.1 | | | NONE | 2.25 | 2.95 | 3.23 |
| FRE04 | 10 | | 7.2 | -9.0 | 22.4 | | | OFF | 3.43 | 5.60 | |
| FRE06 | 20 | 19.1 | 4.6 | -14.4 | 25.5 | | | OFF | 2.91 | 3.20 | 4.12 |
| FRE07 | 3 | 21.8 | 3.3 | -16.0 | 23.1 | | | OFF | 3.62 | 4.11 | 4.44 |
| FRE08 | 11 | 16.6 | 6.3 | -15.2 | 21.4 | | | NONE | 2.48 | 3.12 | 3.01 |
| FRE09 | 30 | 22.0 | | | | | | NONE | | | 4.87 |
| LIV01 | 3 | 19.0 | 4.3 | -12.6 | 22.5 | | | OFF | 4.07 | 5.59 | 5.20 |
| LIV02 | 4 | 25.0 | 5.4 | -19.5 | 25.7 | | | OFF | 7.31 | 6.79 | 6.42 |
| MAR01 | 10 | 20.0 | 5.0 | -17.2 | 23.6 | | | OFF | 3.43 | 3.65 | 4.22 |
| PLN01 | 2 | | 3.7 | -11.7 | 24.6 | | | NONE | 4.99 | 6.37 | |
| SAC01 | 2 | 17.2 | 4.8 | -14.7 | 24.3 | | | ON | 3.90 | 4.44 | 2.85 |
| SAC02 | 15 | 22.1 | 5.0 | -9.1 | 23.0 | | | OFF | 4.59 | 7.21 | 4.61 |
| SAC03 | 1 | 23.6 | 3.8 | -16.2 | 24.4 | | | ON | 4.71 | 5.05 | 4.80 |
| SAC04 | 7 | 18.0 | 4.2 | -13.1 | 25.0 | | | OFF | 2.30 | 2.72 | 2.83 |
| SAC05 | 3 | 17.2 | 3.7 | -15.0 | 24.8 | | | ON | 2.50 | 2.76 | 2.50 |
| SAC06 | 5 | 19.6 | 2.1 | -16.9 | 24.5 | | | ON | 3.44 | 3.58 | 3.25 |
| SAC07 | 7 | 21.8 | 5.4 | -17.0 | 26.7 | | | NONE | 5.47 | 5.26 | 4.80 |
| SRM01 | 9 | 23.8 | 3.8 | -14.1 | 28.0 | | | ON | 8.14 | 8.27 | 4.75 |
| SRM02 | 1 | 19.6 | 4.0 | -12.7 | 25.8 | | | OFF | 2.74 | 3.19 | 2.99 |
| SRM03 | 9 | 19.2 | 3.9 | -18.8 | 24.7 | | | ON | 5.40 | 5.22 | 4.03 |
| SRM04 | 9 | 19.7 | 2.5 | -17.3 | 24.3 | | | OFF | 2.43 | 2.51 | 3.11 |
| SRM05 | 1 | 23.8 | -1.2 | -16.7 | 25.6 | | | NONE | 4.56 | 4.60 | 4.83 |
| SRM06 | 1 | 19.3 | 3.6 | -15.6 | 24.3 | | | OFF | 3.09 | 3.40 | 3.17 |
| SRM07 | 10 | 15.6 | 3.6 | -17.0 | 22.8 | | | OFF | 4.90 | 5.41 | 4.55 |
| SUN01 | 5 | 23.5 | -0.6 | -18.4 | 24.7 | | | OFF | 7.09 | 6.95 | 5.28 |

(Continued)

## TABLE A.2 REFRIGERATOR RESULTS (Continued)

| Site Code | Age [Yr] | Volume [ft3] | Compartment Temperatures Fresh [°C] | Compartment Temperatures Freezer [°C] | Compartment Temperatures Ambient [°C] | Door Openings Fresh [No./Day] | Door Openings Freezer [No./Day] | Anti-Sweat Heater | Measured Consumption [kWh/Day] | Normalized Measured Consumption [kWh/Day] | Rated Consumption [kWh/Day] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Winter: | | | | | | | | | | | |
| ALB01 | 1 | 17.7 | 5.1 | -18.3 | 19.9 | | | ON | 2.39 | 2.81 | 2.90 |
| CVY01 | 7 | 18.0 | 7.3 | -11.6 | 20.2 | 51.5 | 5.7 | NONE | 3.49 | 5.57 | 5.19 |
| CVY02 | 2 | 18.0 | 2.1 | -16.4 | 22.9 | | | NONE | | | |
| CVY03 | 25 | 25.7 | 3.5 | -15.5 | 21.2 | 36.3 | 7.9 | OFF | 3.43 | 4.30 | 4.60 |
| CVY04 | 1 | 21.1 | 5.3 | -11.8 | 20.0 | 22.9 | 7.0 | NONE | 3.00 | 4.79 | 4.67 |
| CVY05 | 7 | 18.0 | 6.0 | -9.6 | 19.9 | | | NONE | 2.57 | 4.70 | 5.19 |
| CVY06 | 20 | | 1.1 | -15.2 | 20.9 | | | NONE | 5.46 | 7.03 | |
| CVY07 | 1 | 27.8 | 3.1 | -15.6 | 21.1 | | | NONE | 4.54 | 5.69 | 5.20 |
| DUB01 | 6 | 18.5 | 1.9 | -17.1 | 22.7 | 32.8 | 8.3 | NONE | 2.78 | 3.07 | 3.23 |
| LIV04 | 1 | 21.0 | 1.8 | -17.7 | 20.4 | | | NONE | 2.98 | 3.52 | 3.29 |
| LIV05 | 1 | 17.0 | 3.7 | -13.4 | 18.7 | 63.8 | 7.5 | NONE | 3.38 | 5.30 | |
| LIV06 | 1 | 21.0 | 6.4 | -13.7 | 20.6 | | | OFF | 2.32 | 3.25 | 5.17 |
| LIV07 | 1 | 22.5 | 3.5 | -15.6 | 20.5 | | | ON | 4.26 | 5.49 | 3.70 |
| LIV08 | 21 | 20.0 | 2.8 | -12.7 | 20.5 | 23.0 | 2.9 | NONE | 4.56 | 6.75 | |
| LIV10 | 1 | 17.6 | 4.4 | -15.8 | 20.0 | | | NONE | 4.75 | 6.20 | |
| LIV11 | 4 | 12.0 | 2.4 | -15.2 | 21.1 | | | ON | 2.23 | 2.85 | 2.46 |
| MAR02 | 9 | 20.0 | -2.4 | -14 | 19.3 | 14.6 | 4.7 | OFF | 3.54 | 5.21 | 4.22 |
| PAC01 | 30 | | 3.6 | -13.1 | 17.5 | | | NONE | 2.01 | 3.43 | |
| PLN02 | 1 | 21.6 | 3.5 | -10.8 | 19.5 | 52.8 | 3.4 | ON | <7.62> | <13.26> | <6.38> |
| SRM09 | 1 | 23.5 | 3.0 | -18.1 | 21.7 | 56.9 | 5.8 | OFF | 5.94 | 6.56 | 5.17 |
| SRM10 | 1 | 19.4 | 4.1 | -16.3 | 19.1 | | | OFF | 5.05 | 6.72 | |
| TRA01 | 1 | 25.4 | 2.8 | -19.8 | 26.0 | 20.0 | 3.0 | OFF | 4.09 | 3.67 | 3.85 |
| TRA02 | 1 | | 4.6 | -21.9 | 23.7 | 31.0 | 11.3 | ON | 8.57 | 7.75 | |
| TRA03 | 1 | | 1.0 | -22.1 | 21.9 | 26.2 | 2.9 | OFF | 6.30 | 5.99 | |
| TRA04 | 1 | 25.0 | 3.0 | -16.4 | 21.7 | | | OFF | 4.91 | 5.80 | 5.10 |
| TRA05 | 1 | 22.5 | 3.6 | -18.5 | 23.7 | | | ON | 4.63 | 4.68 | 3.70 |
| TRA06 | 1 | 25.2 | 3.0 | -15.9 | 22.4 | 66.7 | 18.6 | OFF | 6.87 | 8.06 | |
| TRA07 | 1 | 25.8 | 1.8 | -17.9 | 21.4 | | | OFF | 3.46 | 3.90 | 4.12 |
| TRA08 | 1 | 21.8 | 2.9 | -13.2 | 17.9 | | | OFF | 3.88 | 6.44 | 4.80 |
| TRA09 | 1 | 24.7 | 1.5 | -17.1 | 21.6 | | | OFF | 4.21 | 4.86 | 4.58 |
| Average | 7.2 | 20.8 | 3.6 | -15.9 | 22.6 | 38.3 | 6.8 | | 4.34(3.99) | 5.22( 4.65) | (4.21) |
| Minimum | 1.0 | 12.0 | -2.4 | -22.1 | 17.5 | 14.6 | 2.9 | | 2.01(2.23) | 2.51( 2.51) | (2.46) |
| Maximum | 30.0 | 27.8 | 7.3 | -9.0 | 28.0 | 66.7 | 18.6 | | 8.57(8.14) | 13.26(8.32) | (6.42) |
| Std Dev | 8.0 | 3.1 | 1.8 | 2.8 | 2.3 | 17.8 | 4.3 | | 1.66(1.44) | 1.95( 1.48) | (0.93) |
| Number | | | | | | | | | 59 ( 45 ) | 59 ( 45 ) | ( 45 ) |

TABLE A.3 DOMESTIC HOT WATER RESULTS

| Site Code | Age [Yr] | Pilot Light [Btu/h] | Main Burner [Btu/h] | Tank Volume [Gallon] | Aquastat Setpoint [°C] | Ambient Temperature [°C] | Measured Steady State Efficiency [%] | Measured Recovery Efficiency [%] | Rated Recovery Efficiency [%] | Measured Standby Loss [%/h] | Rated Standby Loss [%/h] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Summer: | | | | | | | | | | | |
| CON01 | 17 | 731 | 40748 | 40 | 48.1 | 25.3 | 75.6 | 66.9 | | | |
| CON02 | 17 | 451 | 40699 | 40 | 67.5 | 21.9 | 74.9 | 68.7 | | | |
| DAN01 | 12 | 944 | 42332 | 50 | 43.5 | 26.6 | 73.7 | 60.6 | | | |
| DAN02 | 9 | 132 | 41810 | 50 | 47.0 | 21.0 | 76.4 | 66.3 | | | |
| FRE01 | 18 | 390 | 37840 | 40 | 46.7 | 26.1 | 74.9 | 70.1 | | | |
| FRE02 | 27 | 1032 | 29298 | 40 | 58.4 | 25.4 | 71.4 | 66.0 | | | |
| FRE03 | | | | | | | | | | | |
| FRE04 | 10 | 782 | 48812 | 40 | 59.6 | 20.3 | 73.9 | 67.6 | | | |
| FRE06 | 20 | 1301 | 27533 | 50 | 65.2 | 20.9 | 72.3 | 55.2 | | | |
| FRE07 | 3 | 855 | 32741 | 40 | 46.1 | 24.1 | 79.6 | 73.5 | 77 | | |
| FRE08 | 11 | 746 | 32278 | 40 | 51.7 | 23.3 | 82.3 | 80.6 | | | |
| FRE09 | 30 | 544 | 31004 | 40 | 59.0 | | 80.5 | 72.4 | | | |
| LIV01 | 3 | 560 | 23690 | 50 | 58.8 | 27.0 | 76.9 | 54.3 | 76 | | |
| LIV02 | 4 | 360 | 29700 | 40 | 48.6 | 23.4 | 80.4 | 74.2 | 76 | | |
| MAR01 | 10 | 609 | 38674 | 40 | 53.3 | 25.6 | 71.7 | 66.6 | | | |
| PLN01 | 2 | 445 | 34310 | 40 | 44.1 | 13.2 | 82.3 | 72.3 | 76 | | |
| SAC01 | 2 | 700 | 32400 | 50 | 52.0 | 25.9 | 78.8 | 69.0 | 76 | | |
| SAC02 | 15 | 702 | 28981 | 30 | 50.2 | 21.5 | 75.5 | 64.5 | | | |
| SAC03 | 1 | | 28651 | 50 | 46.9 | 26.3 | 83.1 | 77.6 | 76 | | |
| SAC04 | 7 | | | | | 26.4 | | | | | |
| SAC05 | 3 | | | | | 24.5 | | | 76 | | |
| SAC06 | 5 | 355 | 34245 | 40 | 49.0 | 25.8 | 81.4 | 71.3 | | | |
| SAC07 | 7 | 408 | 34387 | 50 | 58.6 | 25.4 | 79.3 | 70.5 | 76 | | |
| SRM01 | 9 | 782 | 39965 | 40 | 63.2 | 27.7 | 71.0 | 52.4 | | 5.77 | 3.90 |
| SRM02 | 1 | 548 | 37059 | 50 | 45.6 | 25.2 | 81.0 | 67.8 | 76 | | |
| SRM03 | 9 | 726 | 42574 | 40 | 53.6 | 25.4 | 75.1 | 56.2 | | | |
| SRM04 | 9 | 627 | 36162 | 40 | 56.2 | 24.3 | 72.7 | 53.2 | | 7.56 | 3.90 |
| SRM05 | 1 | 561 | 31735 | 50 | 57.9 | 22.4 | 81.0 | 76.2 | 76 | | |
| SRM06 | 1 | 513 | 30611 | 50 | 53.2 | 22.7 | 76.8 | 74.9 | 76 | | |
| SRM07 | 10 | 987 | 38761 | 40 | 58.8 | 21.1 | 75.5 | 60.6 | | | |
| SUN01 | 5 | | | | | | | | | | |

(Continued)

## TABLE A.3 DOMESTIC HOT WATER RESULTS

| Site Code | Age [Yr] | Pilot Light [Btu/h] | Main Burner [Btu/h] | Tank Volume [Gallon] | Aquastat Setpoint [°C] | Ambient Temperature [°C] | Measured Steady State Efficiency [%] | Measured Recovery Efficiency [%] | Rated Recovery Efficiency [%] | Measured Standby Loss [%/h] | Rated Standby Loss [%/h] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Winter: | | | | | | | | | | | |
| ALB01 | 1 | 576 | 32638 | 50 | 53.8 | 21.4 | 79.5 | 76.6 | 76 | | 3.69 |
| CVY01 | 7 | 600 | 30551 | 40 | 47.9 | 15.3 | 77.6 | 75.1 | 76 | | |
| CVY02 | 2 | 516 | 30931 | 40 | 58.7 | 28.4 | 78.5 | 70.3 | 76 | | |
| CVY03 | 25 | 703 | 51934 | 50 | 60.6 | 20.0 | 77.5 | 76.9 | | | |
| CVY04 | 1 | 339 | 35918 | 50 | 54.8 | 13.1 | 67.9 | 80.3 | 78 | 5.90 | 3.30 |
| CVY05 | 7 | 323 | 35521 | 40 | 55.5 | 19.4 | 80.1 | 72.6 | | 6.46 | 3.90 |
| CVY06 | 20 | 606 | 39791 | 40 | 49.0 | 15.2 | 75.9 | 70.0 | | | |
| CVY07 | 1 | 589 | 26929 | 40 | 48.3 | 14.1 | 80.0 | 81.5 | 76 | | 3.95 |
| DUB01 | 6 | | 28363 | 40 | 61.7 | 17.5 | 81.5 | 81.0 | | 8.33 | 3.90 |
| LIV04 | 1 | 396 | 28993 | 40 | 46.5 | 23.1 | 81.5 | 82.4 | 76 | | |
| LIV05 | 1 | 406 | 27967 | 40 | 56.5 | 13.2 | 81.9 | 73.0 | 76 | | |
| LIV06 | 1 | 388 | 29512 | 40 | 57.1 | 16.1 | 82.4 | 78.2 | 76 | | |
| LIV07 | 1 | 329 | 28925 | 40 | 57.7 | 20.0 | 80.1 | 79.2 | 76 | | |
| LIV08 | 21 | 684 | 34354 | 40 | 57.4 | 20.2 | 71.7 | 60.2 | | | |
| LIV10 | 1 | 378 | 29669 | 40 | 52.6 | 26.3 | 79.6 | 75.2 | 76 | | |
| LIV11 | 4 | 564 | 31342 | 40 | 60.8 | 14.2 | 79.4 | 63.0 | 76 | | |
| MAR02 | 9 | 550 | 37864 | 40 | 48.8 | 12.3 | 72.8 | 72.0 | | 5.73 | 3.90 |
| PAC01 | 30 | 780 | 48469 | 30 | 52.8 | 32.6 | 74.3 | 71.6 | | | |
| PLN02 | 1 | 366 | 37008 | 40 | 43.7 | 11.2 | 79.5 | 78.8 | 76 | 8.90 | 3.90 |
| SRM09 | 1 | 612 | 32210 | 50 | 59.6 | 11.2 | 80.1 | 78.4 | 76 | | |
| SRM10 | 1 | | 27398 | 40 | 54.1 | 14.5 | 75.1 | 68.7 | 76 | 5.85 | 3.69 |
| TRA01 | 1 | 535 | 31209 | 50 | 57.3 | 19.2 | 78.3 | 64.9 | 76 | | |
| TRA02 | 1 | 459 | 31330 | 50 | 70.2 | 20.2 | 79.5 | 75.7 | 76 | | |
| TRA03 | 1 | 687 | 34075 | 50 | 51.1 | 19.2 | 79.5 | 72.0 | 76 | | |
| TRA04 | 1 | 397 | 33312 | 50 | 61.7 | 18.8 | 76.5 | 70.5 | 76 | | |
| TRA05 | 1 | 545 | 30745 | 50 | 66.2 | 19.9 | 78.3 | 74.8 | 76 | | |
| TRA06 | 1 | 615 | 33397 | 50 | 56.6 | 19.7 | 79.5 | 76.5 | 76 | | |
| TRA07 | 1 | 473 | 31330 | 50 | 69.1 | 18.7 | 76.4 | 71.0 | 76 | | |
| TRA08 | 1 | 436 | 31857 | 50 | 58.4 | 13.7 | 78.9 | 76.8 | 76 | | |
| TRA09 | 1 | 869 | 32348 | 50 | 47.9 | 17.1 | 78.3 | 69.4 | 76 | | |
| Average | 7.2 | 583 | 34110 | 43.7 | 54.7 | 21.1 | 77.5 | 70.6(73.4) | (76.1) | 6.81 | 3.80 |
| Minimum | 1.0 | 132 | 23690 | 30.0 | 43.5 | 11.2 | 67.9 | 52.4(54.3) | (76.0) | 5.73 | 3.30 |
| Maximum | 30.0 | 1301 | 51934 | 50.0 | 70.2 | 32.6 | 83.1 | 82.4(82.4) | (78.0) | 8.90 | 4.95 |
| Std Dev | 8.0 | 209 | 5721 | 5.6 | 6.6 | 4.8 | 3.5 | 7.4( 5.7) | ( 0.4) | 1.27 | 0.20 |
| Number | | | | | | | | 57 ( 33 ) | ( 33 ) | | |

## TABLE A.4 AIR CONDITIONER RESULTS

| Site Code | Age [Yr] | Steady State Compressor [kW] | Inside Fan [kW] | Outside Ambient [°C] | Condenser Air Flow [m3/h] | Condenser Diff. Temp. [°C] | Measured EER [Btu/Wh] | Rated EER [Btu/Wh] | Measured SEER [Btu/Wh] | Rated SEER [Btu/Wh] |
|---|---|---|---|---|---|---|---|---|---|---|
| Summer: | | | | | | | | | | |
| CON01 | 15 | 4.65 | 0.38 | 30.0 | 2149 | 14.0 | 3.62 | | 3.26 | |
| CON02 | 17 | 5.75 | 0.38 | 30.7 | 2800 | 9.6 | 1.72 | | 1.30 | |
| DAN01 | 11 | 4.13 | 0.48 | 24.1 | 2150 | 8.0 | 1.39 | | 1.18 | 6.7 |
| DAN02 | 9 | 7.32 | 0.64 | 32.7 | 4848 | 12.7 | 5.54 | | 4.91 | 7.1 |
| FRE01 | 16 | 6.80 | 0.94 | 33.2 | 4800 | 10.2 | 3.83 | | 3.35 | |
| FRE02 | 15 | 5.56 | 0.46 | 23.5 | 4200 | 8.7 | 4.42 | | 3.93 | |
| FRE03 | 12 | 4.23 | 0.67 | 22.3 | 3250 | 11.7 | 6.95 | | 6.55 | |
| FRE04 | 14 | 5.24 | 0.70 | 22.4 | 4500 | 11.3 | 8.03 | | 7.62 | 7.1 |
| FRE06 | 20 | 3.59 | 0.33 | 27.5 | 5800 | 6.1 | 7.66 | 7.7 | 7.47 | 8.6 |
| FRE07 | 3 | 3.84 | 0.73 | 24.1 | 3500 | 9.6 | 6.35 | 8.1 | 6.00 | 8.6 |
| FRE08 | 10 | 4.56 | 0.66 | 25.9 | 4750 | 7.9 | 5.89 | | 5.57 | |
| FRE09 | 4 | 5.88 | 0.77 | 26.1 | 5000 | 9.1 | 5.18 | | 4.55 | 8.0 |
| LIV01 | 3 | 4.50 | 0.69 | 32.5 | 2948 | 10.4 | 3.54 | 7.3 | 3.26 | 8.0 |
| LIV02 | 24 | 4.43 | 0.37 | 29.5 | 3073 | 12.3 | 6.08 | | 6.09 | |
| MAR01 | 10 | 4.19 | 0.59 | 20.7 | | 8.3 | | | | 7.0 |
| PLN01 | 2 | 4.85 | 0.83 | 33.8 | 7100 | 6.5 | 6.01 | 7.6 | 5.39 | 8.1 |
| SAC01 | 2 | 4.17 | 0.64 | 33.1 | 6576 | 6.3 | 6.78 | 7.8 | 6.04 | 8.7 |
| SAC02 | 8 | 5.01 | 0.75 | 31.9 | 2950 | 12.5 | 4.32 | 6.0 | 4.13 | |
| SAC03 | 17 | 4.78 | 0.55 | 31.9 | | 11.1 | | | | |
| SAC04 | 1 | 2.85 | 0.55 | 25.1 | 4000 | 8.1 | 9.31 | | 8.74 | 9.0 |
| SAC05 | 3 | 4.44 | 0.66 | 31.8 | 5000 | 8.1 | 5.85 | | 5.16 | 8.1 |
| SAC06 | 5 | 4.28 | 0.52 | 35.6 | 3838 | 8.8 | 4.42 | 7.8 | 4.12 | 6.9 |
| SAC07 | 6 | 5.44 | 0.70 | 33.7 | 3700 | 11.7 | 4.58 | 7.7 | 3.99 | 7.0 |
| SRM01 | 1 | 3.58 | 0.73 | 31.3 | 5519 | 6.8 | 7.46 | | 7.23 | 8.6 |
| SRM02 | 1 | 3.38 | 0.71 | 21.2 | 6000 | 10.0 | 16.76 | | 14.96 | 8.6 |
| SRM03 | 9 | 4.70 | 0.70 | 31.4 | 5387 | 9.0 | 7.54 | | 7.30 | |
| SRM04 | 9 | 5.26 | 0.66 | 25.5 | 8000 | 8.9 | 12.08 | | 11.13 | |
| SRM05 | 1 | 2.43 | 0.38 | 25.4 | 3250 | 8.8 | 9.65 | 7.3 | 8.25 | 8.7 |
| SRM06 | 1 | 3.06 | 0.67 | 21.6 | 2500 | 8.9 | 4.81 | 7.7 | 4.35 | 8.6 |
| SRM07 | 10 | 3.26 | 0.64 | 31.0 | 1600 | 4.8 | | 6.4 | | |
| SUN01 | 5 | 5.77 | 0.58 | 32.6 | | 8.4 | | 7.6 | | 7.7 |
| Average | 8.5 | 4.57 | 0.61 | 28.5 | 4256 | 9.3 | 6.29(5.81) | (7.4) | 5.77[ 6.07] | [7.9] |
| Minimum | 1.0 | 2.43 | 0.33 | 20.7 | 1600 | 4.8 | 1.39(3.54) | (6.0) | 1.18[ 1.18] | [6.7] |
| Maximum | 24.0 | 7.32 | 0.94 | 35.6 | 8000 | 14.0 | 16.76(9.65) | (8.1) | 14.96[14.96] | [9.0] |
| Std Dev | 6.4 | 1.10 | 0.15 | 4.5 | 1574 | 2.1 | 3.14(1.86) | (0.6) | 2.88[ 3.00] | [0.8] |
| Number | | | | | | | 27 ( 10 ) | ( 10) | 27 [ 17 ] | [ 17] |

| TABLE A.5 FURNACE RESULTS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Site Code | Age [Yr] | Pilot Light [Btu/h] | Main Burner [Btu/h] | Fan Power [kW] | Measured Steady State Efficiency [%] | Rated Steady State Efficiency [%] | Measured Seasonal Efficiency [%] | Rated Seasonal Efficiency [%] |
| Winter: | | | | | | | | |
| ALB01 | 4 | 0 | 79389 | 0.47 | 79.1 | | 64.8 | |
| CVY01 | 10 | 734 | 118716 | 0.47 | 76.4 | | 56.9 | |
| CVY02 | 7 | 1044 | 68195 | | 80.3 | 75 | 58.9 | |
| CVY03 | 25 | 1436 | 172370 | 0.84 | 77.5 | 75 | 58.1 | |
| CVY04 | 18 | 1091 | 49759 | 0.23 | 75.3 | 75 | 51.3 | |
| CVY05 | 11 | 449 | 69858 | 0.30 | 75.6 | 75 | 54.0 | |
| CVY06 | 30 | 1357 | 54356 | 0.28 | 74.3 | 75 | 45.4 | |
| CVY07 | 22 | 668 | 114160 | 0.44 | 70.2 | 75 | 51.4 | |
| DUB01 | 24 | | 69660 | 0.24 | 71.5 | 75 | 50.1 | |
| LIV04 | 1 | 0 | 94299 | 0.50 | 83.7 | | 79.0 | 76.7 |
| LIV05 | 1 | 0 | 66751 | 0.49 | 84.5 | | 78.0 | 76.2 |
| LIV06 | 1 | 0 | 66734 | 0.48 | 83.3 | | 76.6 | 76.2 |
| LIV07 | 1 | 0 | 66574 | 0.50 | 84.2 | | 78.3 | 76.2 |
| LIV08 | 1 | 0 | 81134 | 0.60 | | | | |
| LIV10 | 1 | 0 | 90416 | 0.60 | 82.5 | | 77.2 | 76.7 |
| LIV11 | 20 | 927 | 91361 | 0.38 | 77.0 | 75 | 61.0 | |
| MAR02 | 9 | 1014 | 86544 | 0.62 | 76.1 | | 55.4 | |
| PAC01 | 8 | 406 | 65987 | 0.28 | 76.1 | | 51.5 | |
| PLN02 | 20 | 1133 | 105883 | 0.42 | 78.9 | 75 | 55.0 | |
| SRM09 | 1 | 0 | 76965 | 0.65 | 73.4 | | 67.7 | 71.8 |
| SRM10 | 1 | 0 | 97064 | 0.64 | 82.5 | | 77.4 | 72.6 |
| TRA01 | 1 | 0 | 74011 | 0.76 | 83.7 | | 72.6 | 73.1 |
| TRA02 | 1 | 0 | 75580 | 0.90 | 82.4 | | 71.0 | 73.1 |
| TRA03 | 1 | 0 | 77174 | 0.85 | 83.4 | | 72.2 | 73.1 |
| TRA04 | 1 | 0 | 68442 | 0.79 | 82.4 | | 69.8 | 73.1 |
| TRA05 | 1 | 0 | 58479 | 0.41 | 82.4 | | 73.3 | 74.2 |
| TRA06 | 1 | 0 | 107126 | 0.43 | 80.6 | | 76.2 | 75.0 |
| TRA07 | 1 | 0 | 67266 | 0.75 | 82.0 | | 72.3 | 73.1 |
| TRA08 | 1 | 0 | 105062 | 0.65 | 80.5 | | 74.4 | 75.0 |
| TRA09 | 1 | 0 | 100135 | 0.37 | 79.3 | | 75.0 | 75.1 |
| Average | 7.5 | 897 | 83981 | 0.53 | 79.3(75.6) | (75) | 65.9[74.7] | [74.5] |
| Minimum | 1.0 | 353 | 49759 | 0.23 | 70.2(70.2) | (75) | 45.4[67.7] | [71.8] |
| Maximum | 30.0 | 1436 | 172370 | 0.90 | 84.5(80.3) | (75) | 79.0[79.0] | [76.7] |
| Std Dev | 9.2 | 382 | 24509 | 0.19 | 4.0( 3.3) | ( 0) | 10.6[ 3.2] | [ 1.6] |
| Number | | | | | 29 ( 9 ) | ( 9) | 29 [ 16 ] | [ 16 ] |

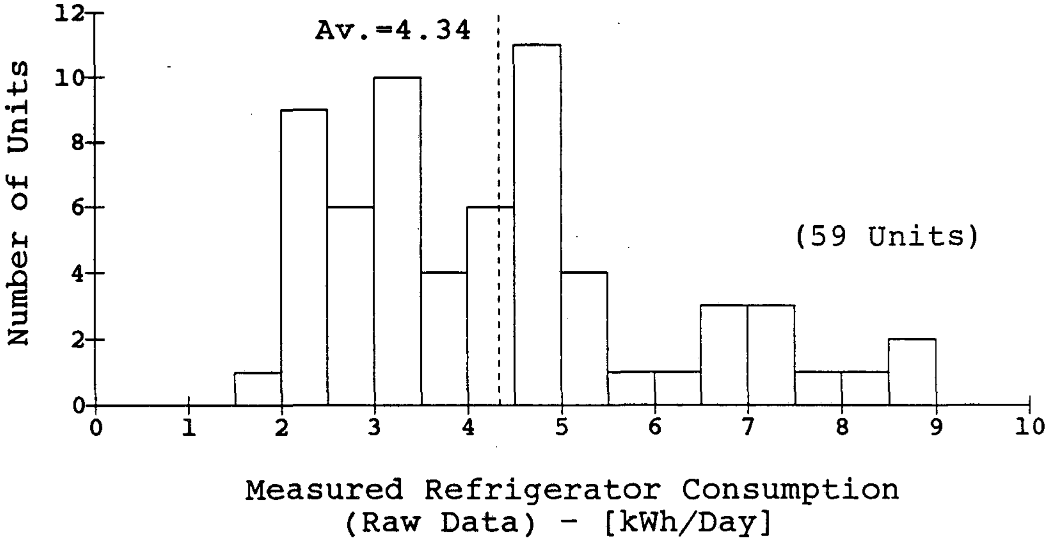

Figure A.1 Frequency distribution of measured refrigerator electricity consumption.

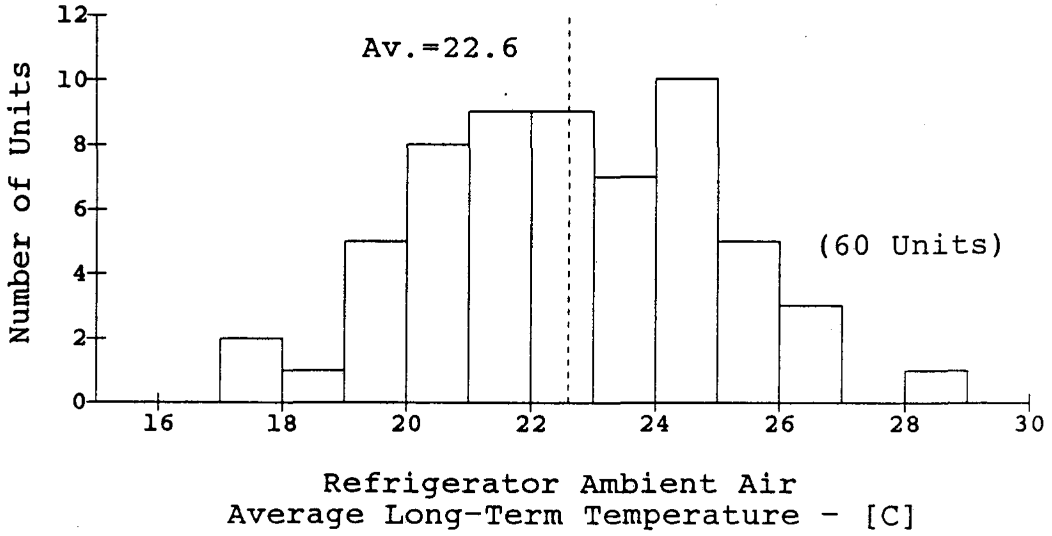

Figure A.2 Frequency distribution of refrigerator ambient air temperature.

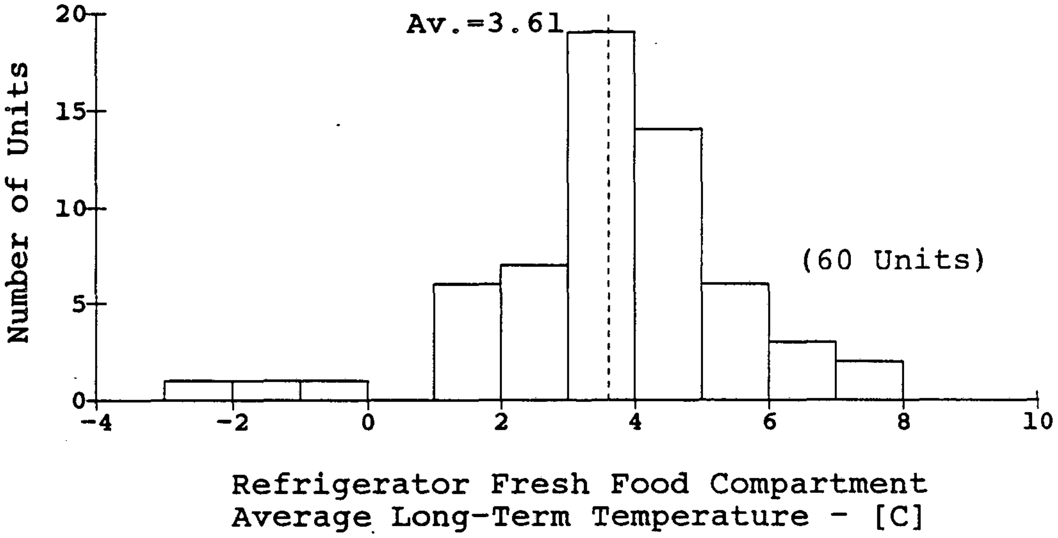

Figure A.3 Frequency distribution of refrigerator long term fresh food compartment temperature.

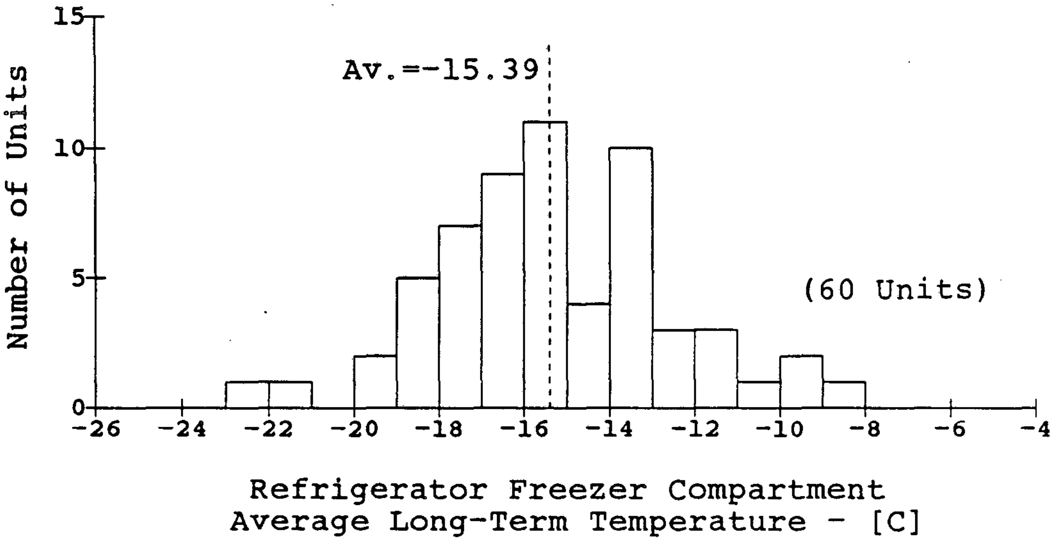

Figure A.4 Frequency distribution of refrigerator long term freezer compartment temperature.

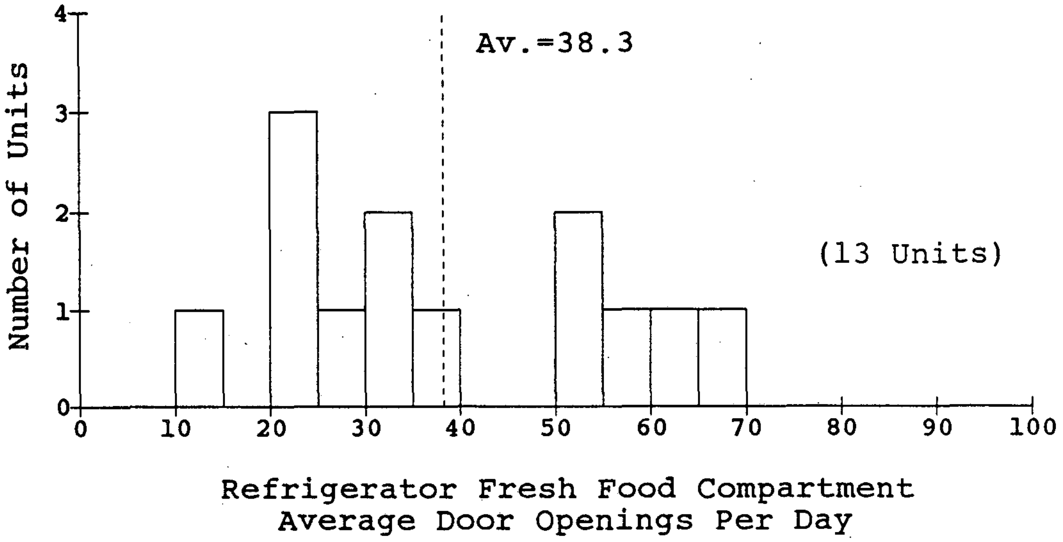

Figure A.5 Frequency distribution of refrigerator fresh food compartment door openings.

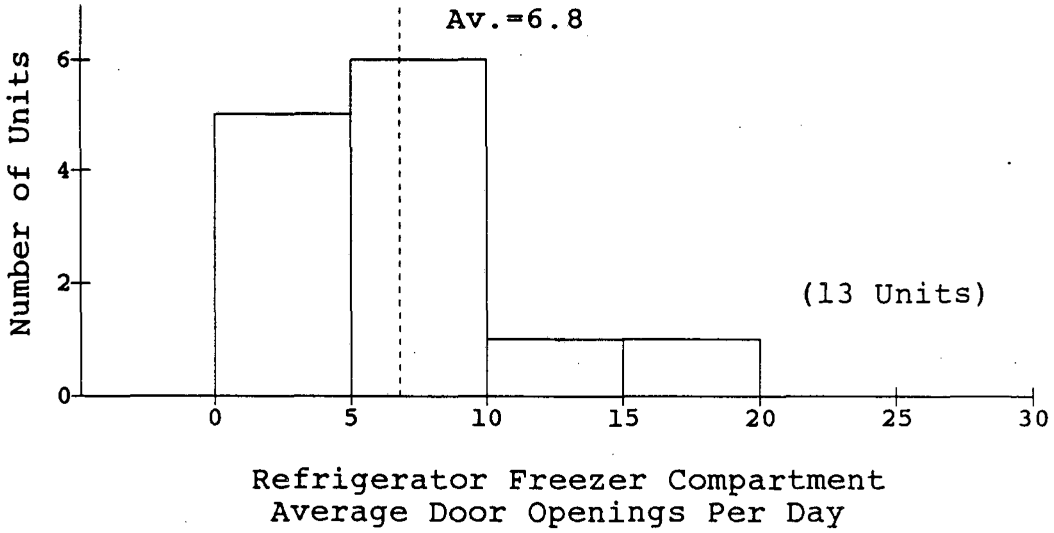

Figure A.6 Frequency distribution of refrigerator freezer compartment door openings.

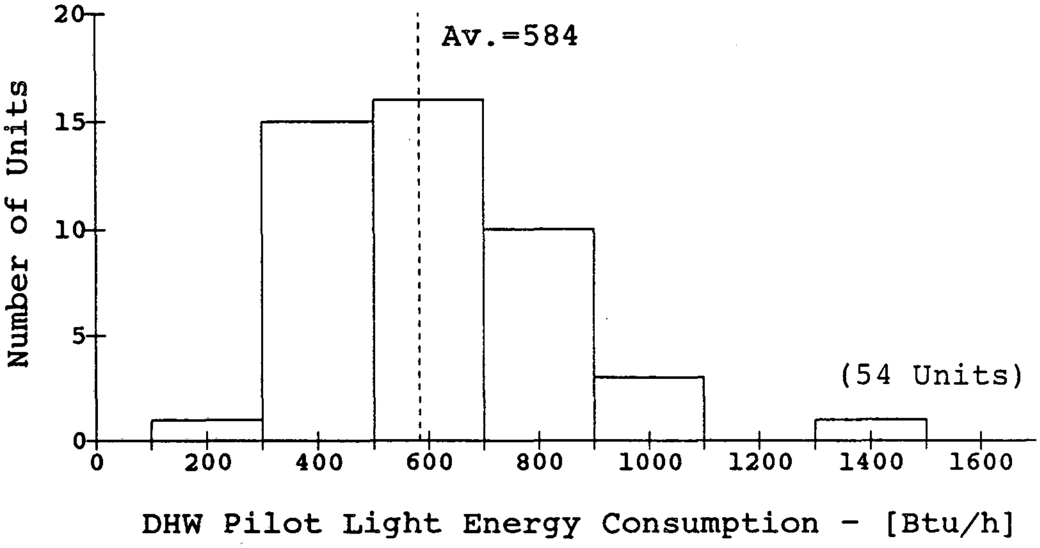

Figure A.7 Frequency distribution of DHW pilot light gas consumption.

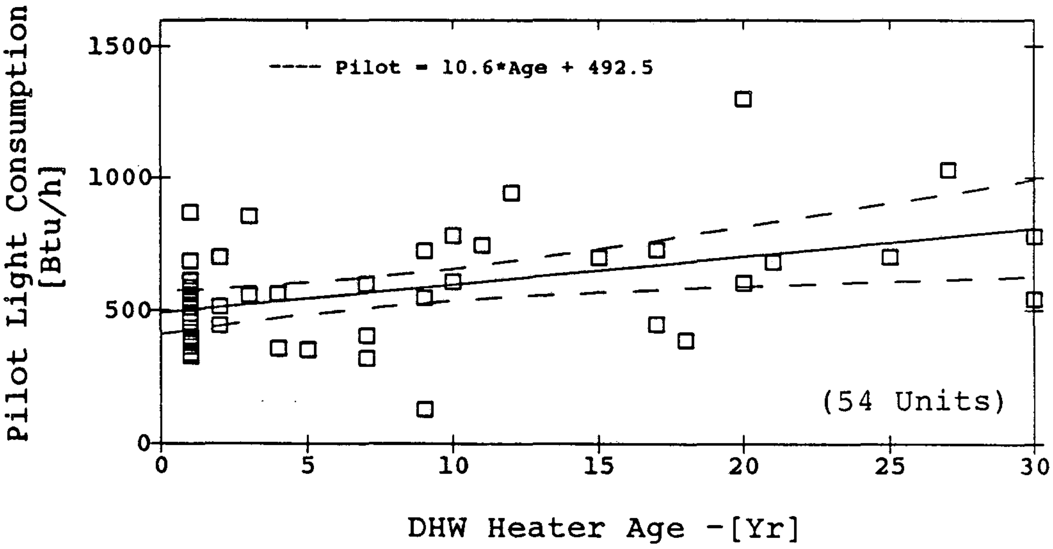

Figure A.8 DHW pilot light gas consumption as a function of unit's age.

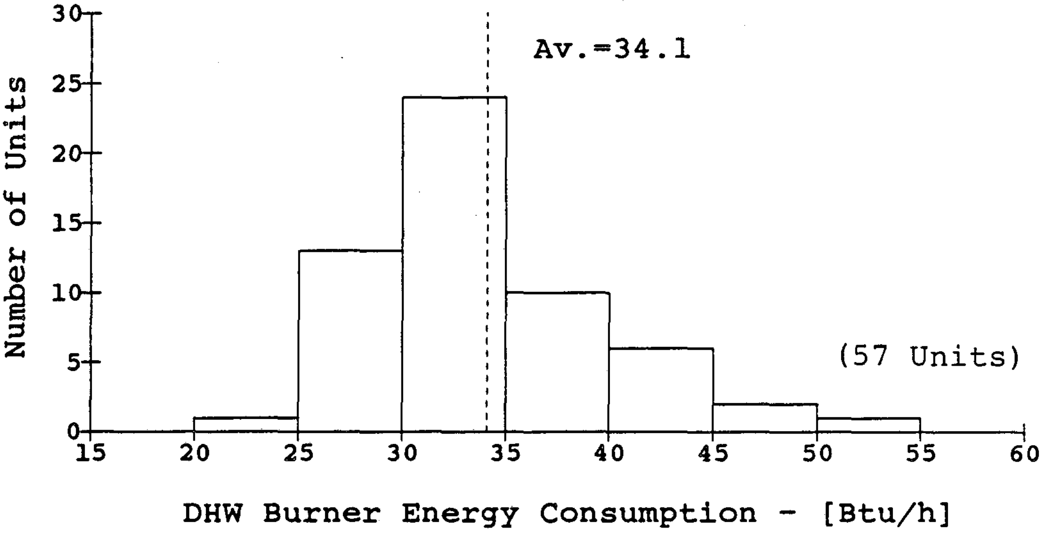

Figure A.9 Frequency distribution of DHW burner gas consumption.

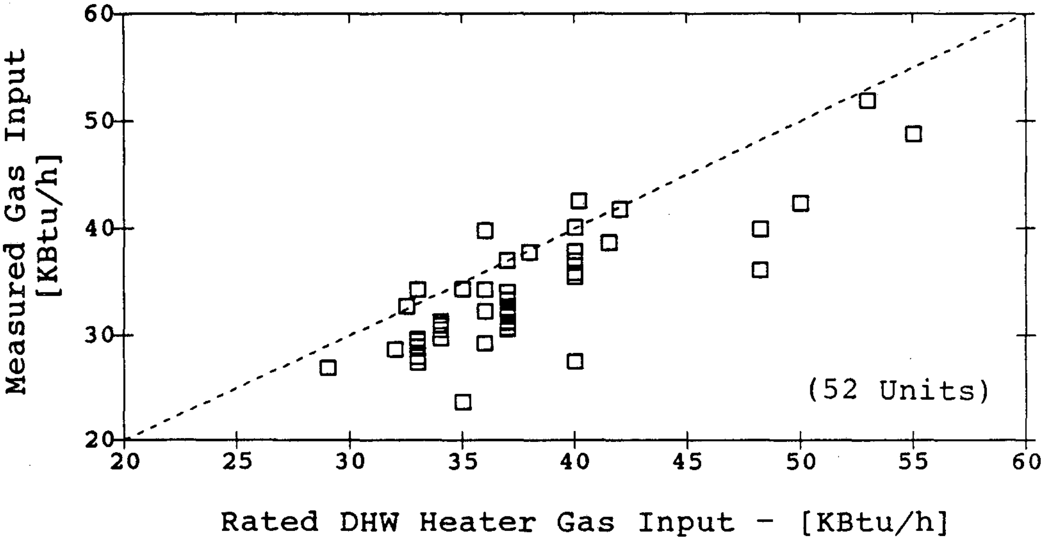

Figure A.10 Measured DHW burner gas input as a function of rated value.

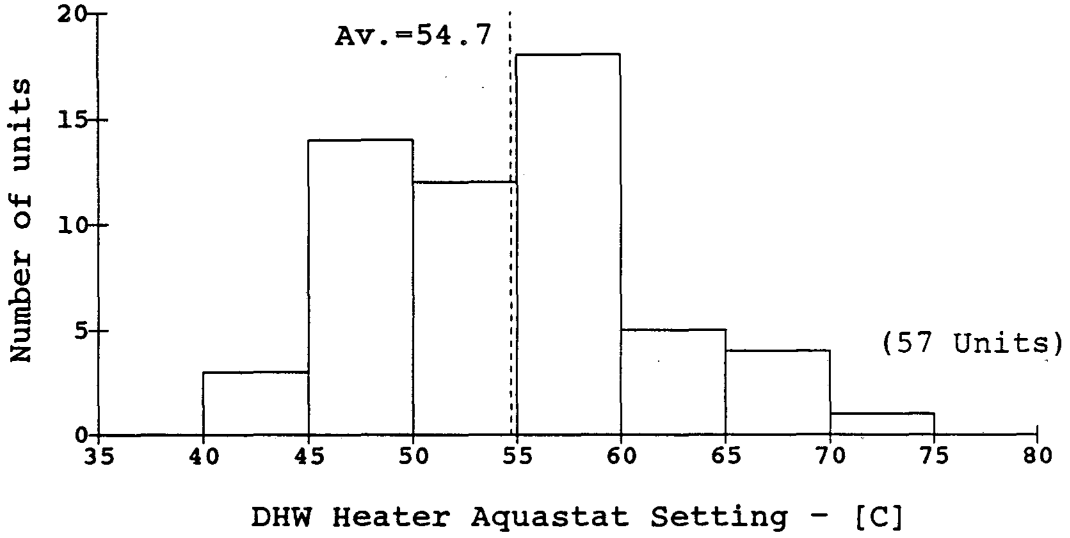

Figure A.11 Frequency distribution of DHW aquastat setting.

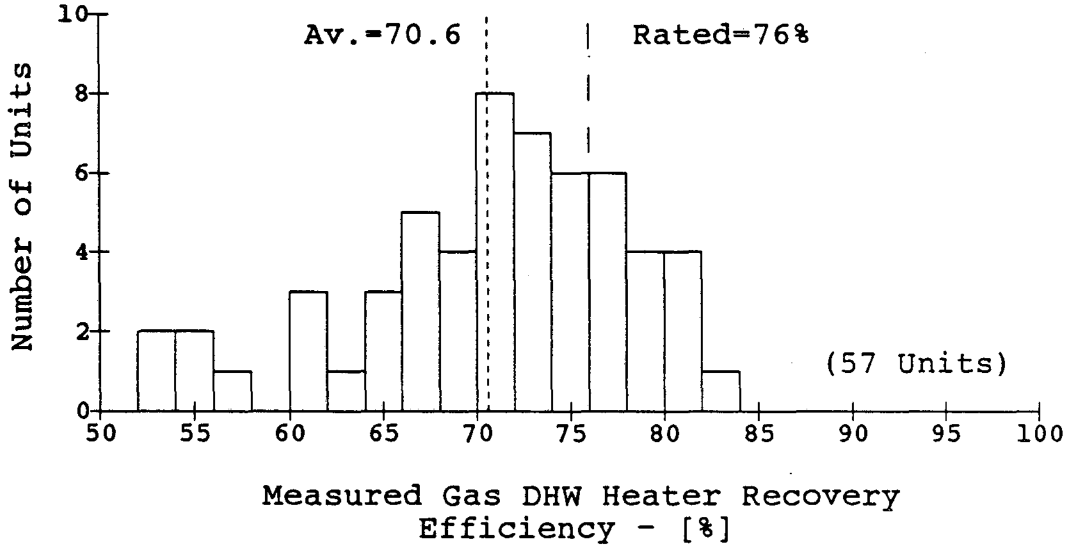

Figure A.12 Frequency distribution of DHW recovery efficiency.

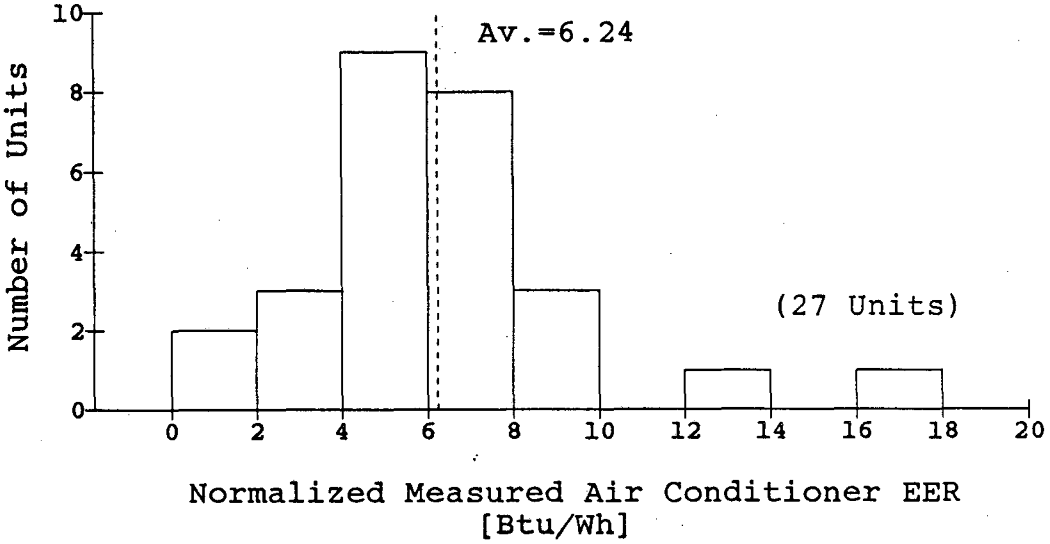

Figure A.13 Frequency distribution of normalized measured air conditioner EER.

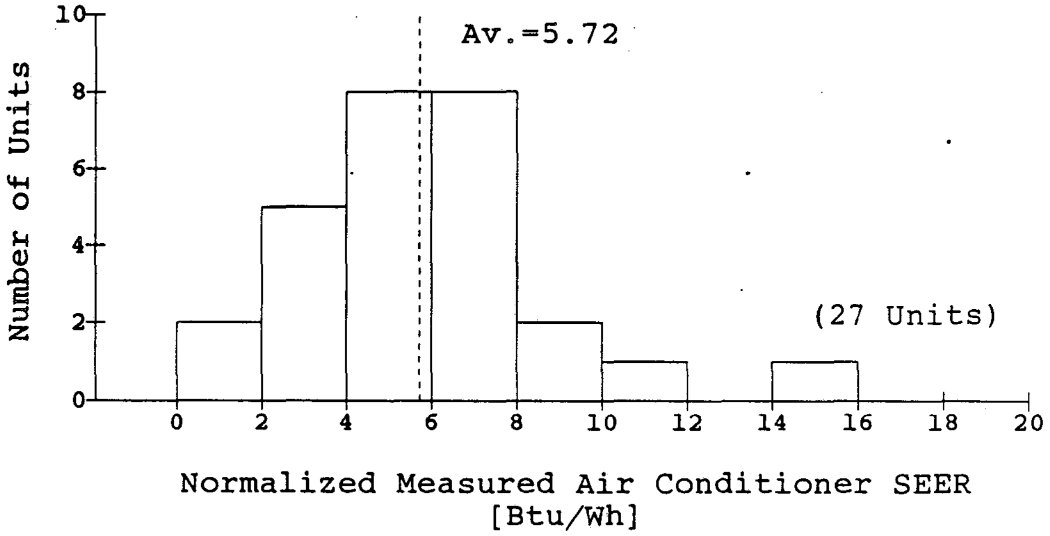

Figure A.14 Frequency distribution of normalized measured air conditioner SEER.

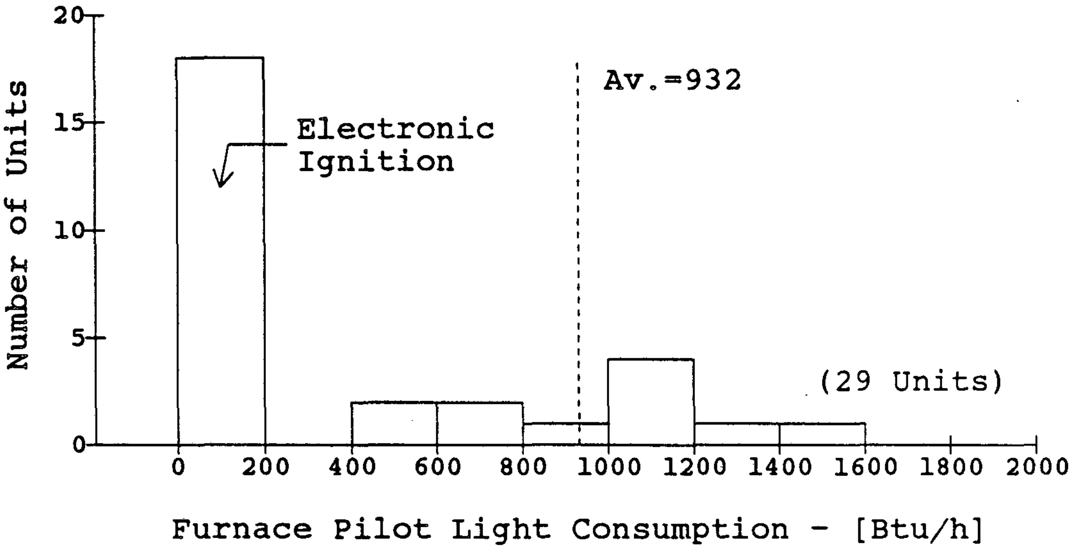

Figure A.15 Frequency distribution of furnace pilot gas consumption.

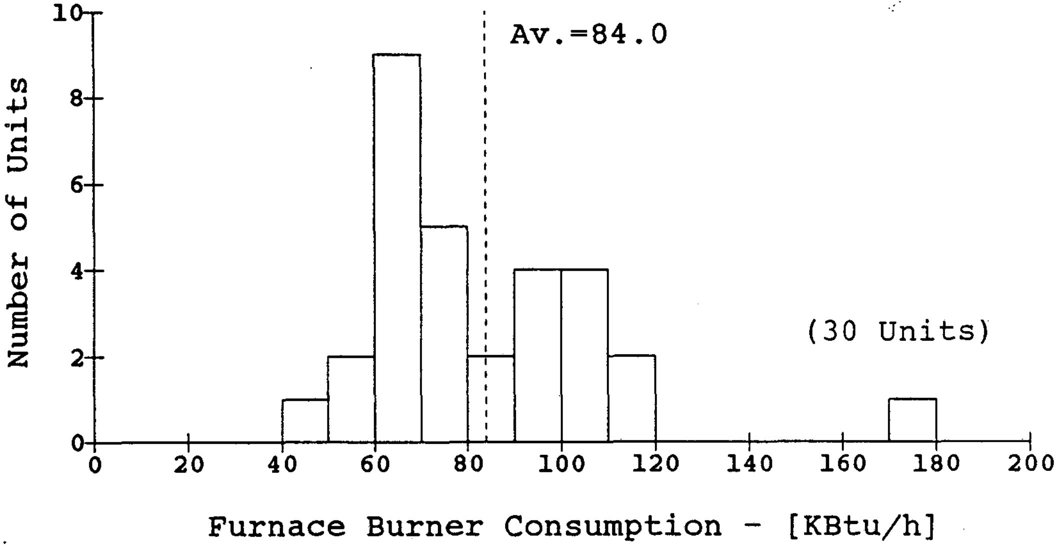

Figure A.16 Frequency distribution of furnace burner gas consumption.

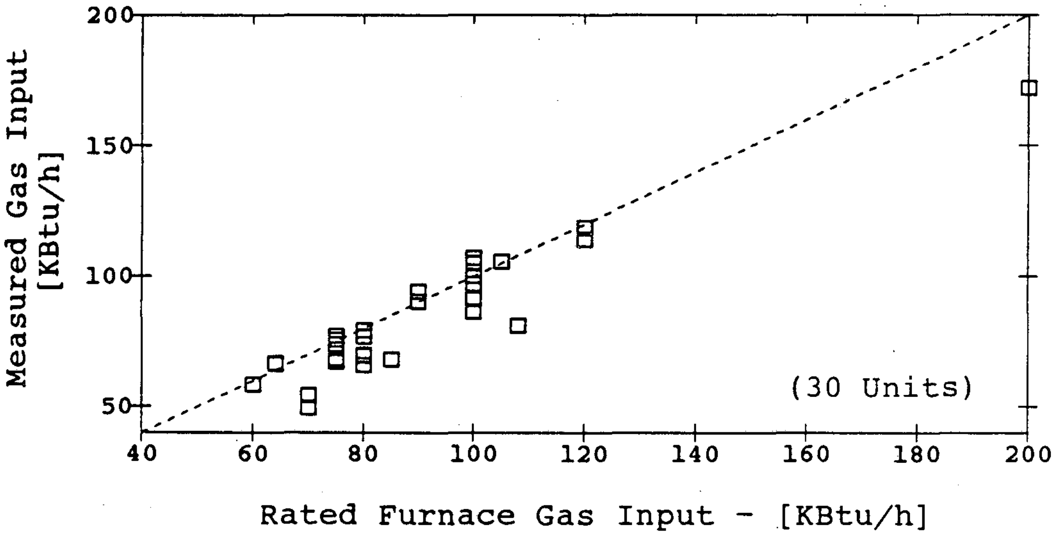

Figure A.17 Measured furnace gas input as a function of rated value.

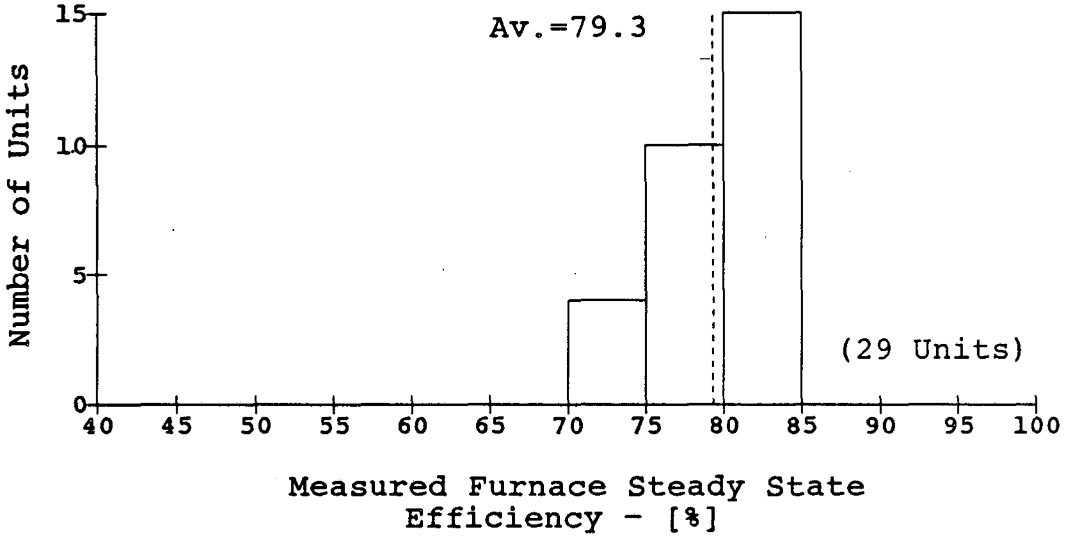

Figure A.18 Frequency distribution of furnace measured steady-state efficiency.

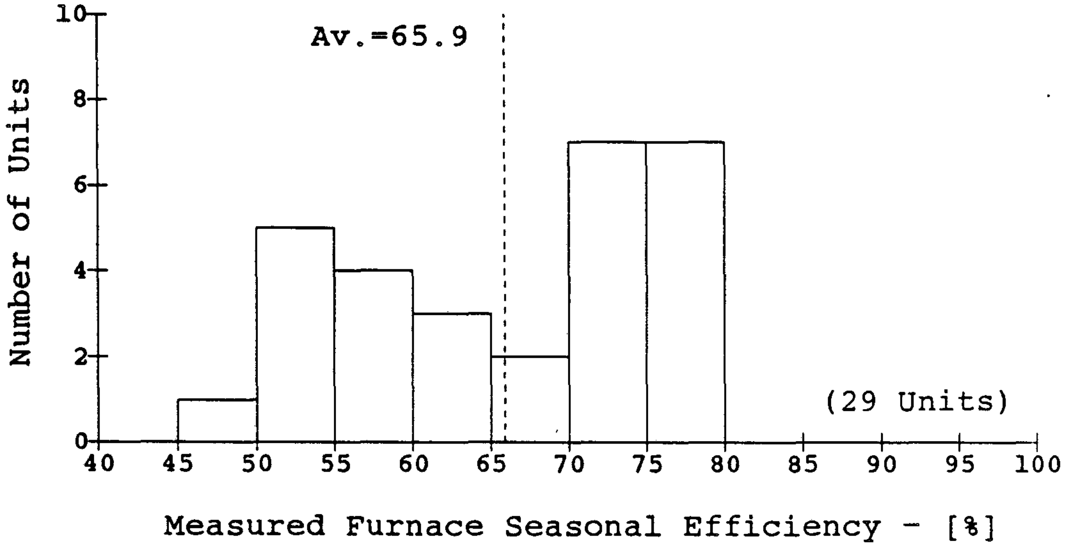

Figure A.19 Frequency distribution of furnace measured seasonal efficiency.

# APPENDIX B

# AUDIT PROCEDURES AND ANALYSIS

The audit test procedures developed for this study were designed to measure all of the performance indicators required by the California appliance efficiency standards. These procedures are an attempt to reproduce the laboratory test procedures in a field application. They also include a series of diagnostic tests to investigate suspected causes of discrepancy between field and laboratory indicators.

As it is impossible to create the specified laboratory test conditions in the field, field test results must be corrected to account for the differences. The corrections vary from appliance to appliance, sometimes requiring monitoring not included in the laboratory procedures.

## Refrigerators

For refrigerators, the laboratory indicators are based upon two tests, each 3 to 24 hours long, conducted after the unit has reached steady-state conditions. The efficiency indicator, the monthly energy consumption, is determined from these measurements. In the field, electricity consumed during the one-week period is used to estimate the monthly energy consumption. A one-week averaging period is needed because of fluctuations in refrigerator temperature and wide variations in the amount of food loading from day to day.

The laboratory tests are conducted at 32.2 °C (90 °F) ambient temperature, 7.2 °C (45 °F) refrigerator compartment temperature, and -15.0 °C (5 °F) freezer compartment temperature. The refrigerator and freezer compartments are empty, and the doors are kept closed throughout the test. As these conditions do not occur in the field, field results must be corrected for the temperature difference across the refrigerator/freezer walls, and for door openings and any food addition.

It was assumed that the energy use of a refrigerator varies with the temperature difference between the freezer and the surroundings according to the equation:

$$E = E_{40} ( 1 + b (\Delta T_F - 40)) \qquad \text{(B.1)}$$

where

| | |
|---|---|
| $E$ | is the energy consumption of the refrigerator [kWh/month] |
| $E_{40}$ | is the energy consumption of the refrigerator at 40 °C $\Delta T_F$, [kWh/month] |
| $b$ | is a constant for all refrigerators, [dimensionless] |
| $\Delta T_F$ | is the temperature difference between freezer and ambient, [ °C] |

Thus refrigerators increase their energy use by ”100 x b” percent of their use at 40 °C ΔT for every °C increase in ΔT. The value of ”b” was determined from linear least-squares fits of measured energy use, $E_m$, against ΔT. ”b” is equal to (slope divided by (Intercept + (40*slope)), as calculated from each least-squares fit. From those refrigerators with an $R^2 > 0.5$, an average value of ”b” was calculated. ”b” was found to be 3.8% per °C . This value was then used to adjust the energy use of the refrigerators to the standard $\Delta T_F$ of 47.22 °C. This value of ”b” compares with a value of 3.6% per °C that can be derived from a refrigerator study conducted by the National Bureau of Standards (NBS).[1] A study by Arthur D. Little Inc. (ADL)[2] gives a value of 3.6% per °C for changes in ambient temperature. For the units in this study, the temperature correction increased energy use by a factor that varied from 1.05 to 2.13, with a mean of 1.42. The 2.13 factor (a 113% increase in electricity consumption) was for a refrigerator which had a very high freezer temperature.

Door-openings and Food load

The laboratory tests include no door openings and no addition of food to the refrigerator. The houses tested in this study showed 3 to 19 freezer door openings and 15 to 67 fresh food door openings. The NBS and ADL studies referred to above showed 10 to 30 freezer door openings per day, and 18 to 70 fresh food compartment openings. It appears likely that the refrigerators in all three studies followed similar use patterns.

ADL estimated that door openings and food load accounted for 14% of electricity consumption. Data for five refrigerators from the NBS study showed 13% of energy use correlated with door openings; this presumably includes the effect of food load. However, there was no universal relationship between door openings and and the percentage of electricity that correlates with door openings. For example, one refrigerator showed 7% consumption correlated with 65 daily door openings, while another unit showed 10% for 27 openings. Therefore, we decided to apply the ADL figure, 14%, to all of the units in our study. This correction may be in error for any individual case, but on average we expect the correction to be accurate. The combined effect of both adjustments is shown in Figure B.1. The corrected values for energy consumption are:

$$E_{cor} = \frac{30.5 * 0.86 * E_m \ (1 + b\,(\Delta T_s - 40))}{(1 + b\,(\Delta T_m - 40))} \tag{B.2}$$

where

$E_{cor}$ is the corrected value of electricity use, [kWh/month]
$E_m$ is the measured value of electricity use, [kWh/month]
30.5 is the average number of days in a month
0.86 is the 14% reduction for door openings and food load
$\Delta T_s$ is the standard temperature difference, [47.22 °C]
$\Delta T_m$ is the measured temperature difference, [°C]
$b$ is a constant, 0.038 per °C, as explained in text

The refrigerators tested ranged in volume from a minimum of 12 $ft^3$ to a maximum of 27.8 $ft^3$. To compare all of these refrigerators to each other, an adjustment for volume was performed. The equation used was:

$$E_{spec} = \frac{E_{cor} - 40}{V} \tag{B.3}$$

where

$E_{spec}$ is the specific electricity consumption [kWh/month-$ft^3$]
$V$ is the volume of the refrigerator [$ft^3$]

This particular form was chosen because it allows a graphic presentation of whether or not a refrigerator meets the State of California standards. In the standards adopted 11/3/76, a specific consumption of 7 kWh/month-$ft^3$ was required effective November 3, 1977, and a specific consumption of 5 kWh/month-$ft^3$ was required effective November 3, 1979. Before the 1979 standard actually became effective, it had been reformulated in terms of kWh per year. As a consequence, the volume adjustment shown above should use 40.58 instead of 40.0 for all units after November 3, 1979. Also, the required specific consumption was restated as 4.58 kWh/month-$\text{ft}^3$ for units with anti-sweat heater switches, and 5.07 for those without. The small change from 40.0 to 40.58 was omitted from the calculation for the sake of clear graphics in the final figure.

## Domestic Hot Water Appliances

The efficiency indicators for gas domestic hot water (DHW) appliances are the recovery efficiency and the standby loss. The recovery efficiency is a measure of how much of the energy in the gas goes into heating the water while the burner is operating. The standby loss is a measure of how much energy is consumed to maintain a constant water temperature. For electric DHW appliances, for which the recovery efficiency is essentially unity, the only indicator is the standby loss.

The laboratory procedure for measuring recovery efficiency involves filling the tank with cold water, setting the aquastat to 71.1 °C (160 °F), and measuring the energy required to bring it to this temperature. Six temperature sensors immersed in the tank are used to determine the average temperature rise of the water. The audit procedure is designed to be similar to that used in the laboratory. The field test procedure is to create a tank of cold water and heat it to the water heater's maximum aquastat setting. The tank of cold water is created by turning off the burner and then drawing hot water from a faucet until the hot water temperature is within 1 °C of the cold water supply temperature, using the average of the hot and cold water temperature as the initial water temperature. The tank of cold water is then heated to the water heater's maximum temperature. The hot water's final temperature is determined by measuring the hot water temperature at a faucet after the aquastat turns the burner off. The recovery efficiency is then determined with the same equation used in the laboratory:

$$E_r = \frac{c * V * \Delta T_{tank}}{Q_{gas}} \qquad \text{(B.4)}$$

where

$E_r$ is the recovery efficiency of the unit [dimensionless].
c is the specific heat of water [Btu/gallon ° F];
V is the volume of the tank [gallons],
$\Delta T_{tank}$ is the change in temperature of the tank during the test period [° F],
$Q_{gas}$ is the total energy content of the gas consumed during the test period [Btu],

The standby loss is the energy consumed per hour expressed as a percentage of the energy stored in the tank. The laboratory procedure is the same for both gas and electric appliances. It involves measuring all the energy lost in a 48-hour period of normal aquastat operation. The energy loss is the total energy consumption during that period plus the loss in energy stored in the tank. The energy stored is calculated using the six temperature sensors inside the tank.

The audit procedure is similar, except that a 48-hour period without hot water demand is unlikely to occur, and installing six temperature sensors inside the tank is not possible. By monitoring the temperature of the flue for gas units, or monitoring the electric current to the heating elements of the electric units, the total energy consumed during a given period can be determined. For gas units it is determined from one-time measurements of the gas consumption of the pilot light and the main burner; the burner on-time is indicated by the flue temperature. By monitoring the cold water supply pipe temperature near the tank, it can be determined whether or not there was any hot water drawn during a given period. The standby energy losses can be determined for a period in which there was a burn and it is confirmed that no hot water was drawn (e.g. at night).

During a long period of no use, typically 14 hours, the tank slowly cools down, until its temperature reaches the lower aquastat set point. Then the main burner turns on again, and returns the tank to the upper setpoint temperature. The energy content of the tank is now equal to its value before cool down. The total standby loss is therefore the energy consumed in this burn plus the energy consumed by the pilot during the standby period. The average ambient temperature is required to normalize the energy lost. The equation used to determine the standby loss from laboratory data is:

$$S = \frac{Q_{gas}}{c \;*\; V \;*\; \Delta T_{ta} \;*\; t} - \frac{\Delta T_t}{\Delta T_{ta} \;*\; t \;*\; E_r} \quad . \tag{B.5}$$

where

| | |
|---|---|
| S | is the standby loss [1/h], |
| $Q_{gas}$ | is the total energy content of the gas consumed during the test period [Btu], |
| c | is the specific heat of water [Btu/gallon ° F], |
| V | is the volume of the tank [gallons], |
| $\Delta T_{ta}$ | is the average temperature difference between the tank and ambient air [° F], |
| $t$ | is the length of the test period [h], |
| $\Delta T_t$ | is the change in temperature of the tank during the test period [° F], |
| $E_r$ | is the recovery efficiency of the unit [dimensionless]. |

Changes in temperature of the hot water in the tank can not be detected from the hourly average data that was recorded during the long-term test, so the second term in Equation B.5 was assumed to be zero. The equations used for the field measurements are:

$$S_{meas} = \frac{(Q_{pilot}\;(\;H_{sby} - H_{burn}\;)) + (Q_{burner}\;H_{burn}\;)}{H_{sby} \;*\; 8.25 \;*\; V\;(\Delta T - \frac{T_{DB}}{2})} \tag{B.6}$$

where

| | |
|---|---|
| $S_{meas}$ | is the measured value of the standby loss [1/h] |
| $H_{sby}$ | is the length of the a standby period [h] |
| $H_{burn}$ | is the average length of a burn following a standby period [h] |
| $Q_{burner}$ | is the gas input to the main burner plus the pilot [Btu/h] |
| $Q_{pilot}$ | is the gas flow to the pilot [ Btu/h] |
| $T_{DB}$ | is the aquastat deadband [° F] |
| $\Delta T$ | is the difference between faucet hot water temperature and ambient [° F] |
| $V$ | is the volume of the water heater [gallons] |
| 8.25 | is the specific heat of water [Btu/gallon ° F] |

The faucet hot water temperature is the initial value measured during the short-term test. We assume that this is the upper aquastat setpoint. For the units with measured standby data, the aquastat deadband is:

$$T_{DB} = \frac{Q_{burner} * H_{burn} * E_r}{8.25 * V} \tag{B.7}$$

where

$E_r$ is the recovery efficiency [dimensionless]

During the procedure development process, it was noted that on some gas units the burner did not come on even during an entire summer week with no hot water use. This suggests that in those units the temperature of the water is dropping very slowly (or perhaps increasing). On only a few units was it possible to observe two operations of the main burner with no use of hot water in between. The quantity of standby loss data is therefore very limited.

### Central Air Conditioners

Depending upon the year of construction, the efficiency indicator for air conditioners is either the Energy Efficiency Ratio (EER), or the Seasonal Energy Efficiency Ratio (SEER).[3] Both indicators are ratios of heat removed in Btu/h, to electrical energy consumed in Watts. EER is a steady-state value, whereas SEER is a steady-state value corrected for cycling of the air conditioner. The laboratory procedures for both values are performed at specified indoor and outdoor temperature conditions (both wet- and dry-bulb inside and dry-bulb outside).

The laboratory procedure for determining EER involves a steady-state test in which readings taken at four consecutive 10-minute intervals are within specified tolerances of each other. The EER test conditions are: 35.0°C (95°F) outdoor dry-bulb, 26.7°C (80°F) indoor dry-bulb, and 19.4°C (67°F) indoor wet-bulb (ARI Test A). The SEER laboratory procedure involves three separate efficiency tests: 1) a steady-state test to determine EER at 28.8°C (82°F) outdoor dry-bulb, 26.7°C (80°F) indoor dry-bulb, and 19.4°C (67°F) indoor wet-bulb (ARI Test B), 2) a steady-state test to determine EER at 35.0°C (95°F) outdoor dry-bulb, 26.7°C (80°F) indoor dry-bulb, and 13.9°C (57°F) indoor wet-bulb (ARI Test C, dry-coil), and 3) a cyclic test to determine a transient EER at 35.0°C (95°F) outdoor dry-bulb, 26.7°C (80°F) indoor dry-bulb, and 13.9°C (57°F) indoor wet-bulb (ARI Test D, dry-coil). The specification of dry-coil cyclic tests stems from practical considerations, such as the difficulties of measuring the condensate or humidity changes during a cyclic test. The cyclic test for SEER (Test D) uses a 6-minute-on, 24-minute-off cycle, measuring the total heat removed and energy consumed during a cycle.

The main difficulty in reproducing the laboratory tests in the field is that ambient temperatures differ from those in the laboratory. However, algorithms to adjust EER for indoor wet-bulb temperature and outdoor dry-bulb temperature have been developed. We utilize an algorithm in the DOE-2 program to correct from field conditions to standard laboratory conditions.[4] This algorithm (Equation B.8) represents an average value for a number of different air conditioners. The algorithm assumes that the interior coil is wet, which it was in all tests performed in this study.

$$R^{EER} = -0.9617787 + 0.04817751*WB - 0.0002311*WB^2 + 0.00324392*TO + 0.00014876*TO^2 - 0.0002952*WB*TO \tag{B.8}$$

where

| | |
|---|---|
| $R^{EER}$ | EER correction factor [dimensionless], |
| WB | is the indoor wet-bulb temperature [° F], and |
| TO | is the outdoor dry-bulb temperature [° F]. |

Equation B.8 can be used to correct the EER directly, both for the EER indicator and SEER indicator. However, studies have shown that the effects of cycling are relatively independent of indoor or outdoor temperature, or condensation on the indoor coil.[5,6] Thus only the steady-state tests (ARI Test B and ARI Test A) must be corrected for indoor wet-bulb and outdoor dry-bulb temperatures. ARI Test C need only be corrected if it is not performed under the same temperature conditions as ARI Test D.

Another difference between the laboratory procedure and the audit procedure is that the heat removed is determined directly on the indoor side in the laboratory, whereas it is determined indirectly from the heat rejected at the condenser in the field. From the field measurements, the EERs are determined as:

$$EER_A = \frac{\dot{V}_{cond} * \rho_{out} * c_p * \Delta T_c * 60 - (E_{comp/c} + E_{fan}) * 3.414}{E_{comp/c} + E_{fan}} * R^{EER}_{WB/TO} \tag{B.9}$$

$$EER_B = \frac{\dot{V}_{cond} * \rho_{out} * c_p * \Delta T_c * 60 - (E_{comp/c} + E_{fan}) * 3.414}{E_{comp/c} + E_{fan}} * \frac{R^{EER}_{WB/TO}}{R^{EER}_{67/82}} \tag{B.10}$$

$$EER_C = \frac{\dot{V}_{cond} * \rho_{out} * c_p * \Delta T_c * 60 - (E_{comp/c} + E_{fan}) * 3.414}{E_{comp/c} + E_{fan}} \tag{B.11}$$

$$EER_D = \frac{\dot{V}_{cond} * \rho_{out} * c_p * \int \Delta T_c \, dt * 60 - (E_{comp/c} + E_{fan}) * 3.414 * 0.1}{(E_{comp/c} + E_{fan}) * 0.1} \tag{B.12}$$

where

| | |
|---|---|
| $EER_A$ | is the energy efficiency ratio at 19° C (67° F) wet-bulb inside, and 35° C (95° F) dry-bulb outside [Btu/W h], |
| $EER_B$ | is the energy efficiency ratio at 19° C (67° F) wet-bulb inside, and 28° C (82° F) dry-bulb outside [Btu/W h], |
| $EER_C$ | is the energy efficiency ratio measured under steady-state field-test conditions [Btu/W h], |
| $EER_D$ | is the energy efficiency ratio measured under cyclic field-test conditions [Btu/W h], |
| $\dot{V}_{cond}$ | is the volumetric flow rate across the condenser [cfm], |
| $\rho_{out}$ | is the density of the air flowing through the condenser [$lb/ft^3$], |
| $c_p$ | is the specific heat of air at constant pressure [Btu/lb ° F], |
| $\Delta T_c$ | is the air temperature rise across the condenser [° F], |
| $\int \Delta T_c \, dt$ | is the integrated temperature rise [°F h], |

| | |
|---|---|
| 60 | is the number of minutes per hour [min/h], |
| $E_{comp/c}$ | is the electrical consumption of the compressor and condenser fan [W], |
| $E_{fan}$ | is the electrical consumption of the inside duct fan [W], |
| 3.414 | is the conversion from watts to Btu/hour [Btu/h W], |
| $R^{EER}_{WB/TO}$ | is the efficiency correction factor for the test conditions [dimensionless], |
| $R^{EER}_{67/82}$ | is the efficiency correction factor for Test B conditions [dimensionless], |
| 0.1 | is the number of hours of integration (compressor operation) in the cyclic test [h]. |

$EER_A$ is the efficiency indicator used for appliances built when the California standard specified EER as the indicator. $EER_B$, $EER_C$, and $EER_D$, are used to compute the SEER for newer appliances. The equation used to calculate SEER is:

$$SEER = EER_B * \left[ 1 - 0.5 * \left( \frac{1 - \dfrac{EER_D}{EER_C}}{1 - \dfrac{EER_D}{5 * EER_C}} \right) \right] \tag{B.13}$$

## Gas Forced-Air Furnaces

The efficiency indicator for forced-air gas furnace is the seasonal efficiency. This indicator includes the effect of latent losses, steady-state efficiency, electricity use by fans, cycling losses, and flue losses. It is found from the equation:

$$SE = 100 * \frac{(E_r * (AFUE/100)) + (E_{AKH} * 3412)}{E_r + (E_{AK} * 10236)} \tag{B.14}$$

where

| | |
|---|---|
| $SE$ | is the seasonal efficiency, [%] |
| $E_r$ | is annual gas energy consumption [Btu/year] |
| $AFUE$ | is the annual gas utilization efficiency, [%] |
| $E_{AKH}$ | is the annual auxiliary electrical energy which provides space heat, [kWh/year] |
| $E_{AK}$ | is the total annual auxiliary electrical energy, [kWh/year] |

The AFUE is defined as:

$$AFUE = \frac{5200 * \eta_{ss} * \eta_{s} * Q_{IN}}{5200\, \eta_{ss} * Q_{IN} + 2.5(1+0.7)(4600)\eta_{s} * Q_P} \tag{B.15}$$

where

| | |
|---|---|
| $\eta_{ss}$ | is $Effy_{ss}$ defined in ASHRAE standard 103-82, [%] |
| $\eta_{s}$ | is $Effy_{hs}$ defined in ASHRAE standard 103-82, [%] |
| 5200 | is the average annual heating degree days, [°F-day] |
| 4600 | is the average non-heating season hours per year, [hours] |
| $Q_{IN}$ | is the steady-state heat input, [Btu/hour] |
| $Q_P$ | is the pilot gas input, [Btu/hour] |
| 0.7 | is the average oversizing factor, [dimensionless] |

For the laboratory measurement of $Effy_{hs}$ and $Effy_{ss}$ flue and stack temperatures are measured with thermocouple grids 30 seconds and 2 minutes 30 seconds after burner start-up for a cold furnace, and again 2 minutes 30 seconds, and 9 minutes after burner shut-down after the furnace has reached steady-state. The delay between burner-on and distribution-fan-on and between burner-off and fan-off are also measured. Measurements are also made of flue and stack gas carbon dioxide content. The power to fans is measured, as is the gas flow rate for the main burner and the pilot light.

The audit procedure is similar the laboratory procedure. Flue and stack temperatures are measured at the designated times with individual thermocouples rather than thermocouple grids. Electrical power is measured with a clamp-on ammeter. Flue gas analysis is performed with an oxygen sensor, and the carbon dioxide content calculated on the assumption that the gas burned is pure methane. The gas flow rates are calculated based on timing the utility gas meter. The calculation procedure defined in ASHRAE standard 103-1982 is followed to find the values of the parameters in equations B.14 and B.15.

## DIAGNOSTICS

The audit test procedures included a series of diagnostic tests to investigate suspected causes of discrepancy between field and laboratory indicators. Additional diagnostics were performed to explore why indicators might not be representative of actual field performance. Table B1 contains a summary of the diagnostic tests performed.

**TABLE B.1: Diagnostics for Isolating Causes of Discrepancies between In-Situ and Laboratory Performance**

| *End Use* | *Cause of Discrepancy* | *Diagnostic* |
|---|---|---|
| Air Conditioner | Improper Refrigerant Charge | Refrigerant pressure measurement |
| | Dirty Coils | Visual inspection |
| | Improper Air flow Across Coils | Air flow measurements |
| | Duct System Losses | Leakage and operating pressure measurements (not performed) |
| | Thermostat Cycling Differences | Week-long test |
| | Worn Compressor | Pressure and power measurements |
| | Disadvantageous Location | Visual inspection, week-long measurements |
| DHW Heater (Gas) | Dirty Tank | Questioning |
| | Improper Air/Fuel Ratio | Combustion Gas Analysis ($O_2$,$CO_2$) |
| | Degraded Insulation | Week-long test |
| | Incomplete Combustion | Combustion Gas Analysis (CO) |
| | Thermostat Cycling Differences | Week-long test |
| | Disadvantageous Location | Visual inspection |
| DHW Heater (Electric) | Degraded Insulation | Week-long test |
| | Disadvantageous Location | Visual inspection |
| Refrigerator | Worn Compressor | (no specific diagnostic performed) |
| | Disadvantageous Location | Visual inspection |
| | Dirty Coils | Visual inspection |
| | Non-Standard Use Patterns | Questioning, week-long measurement |

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2. Study of energy-saving options for refrigerators and water heaters. Prepared for the Office of Transportation and Appliance Programs, Federal Energy Administration, by Arthur D. Little, Inc., Cambridge, MA 02140. May, 1977.

3. ARI Standard 210-81, Appendix A, Uniform Test Method for Measuring the Energy Consumption of Central Air Conditioners. This appendix was copied from Federal Register Vol 44, No 249, Thursday December 27, 1979, pages 76707-76723 (Appendix M).

4. DOE-2 Supplement Version 2.1C, LBL-8706 Rev. 4.Suppl., May 1984, Section 3 page 27.

5. D.A. Didion, G.E. Kelly, "New testing and rating procedures for seasonal performance of heat pumps", ASHRAE Journal, September, 1979.

6. W.H. Parken, D.A. Didion, P.H. Wojciechowski, L. Chern, "Field performance of three residential heat pumps in the cooling mode" NBSIR 85-3107, March 1985.

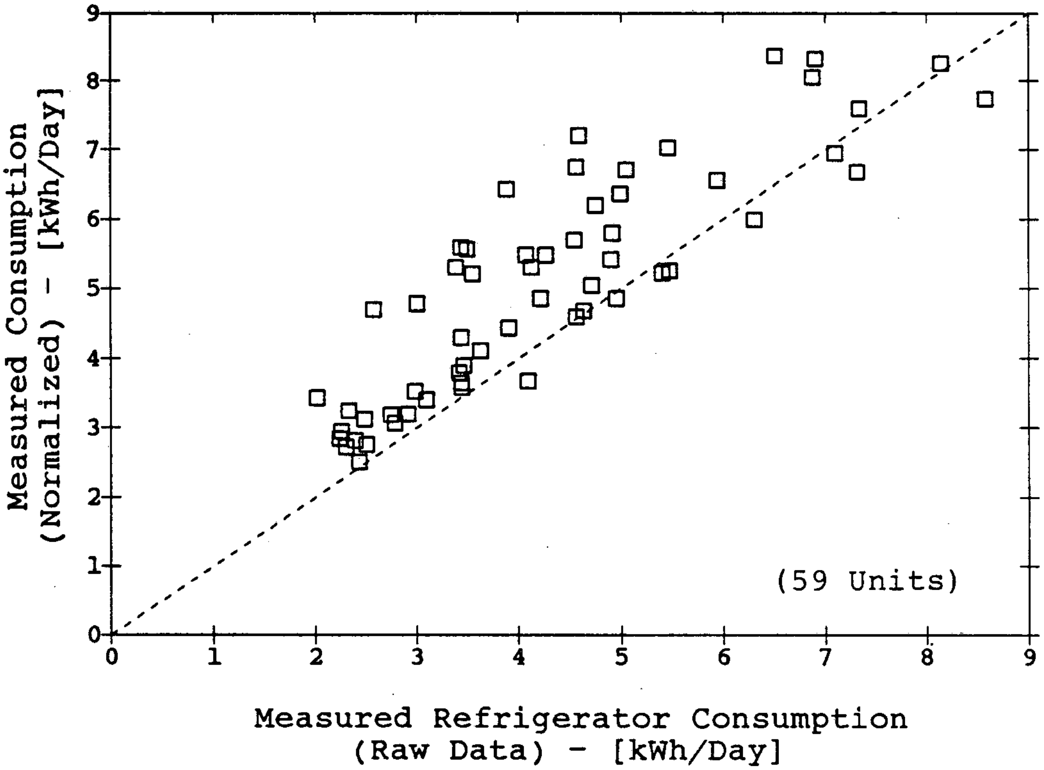

Figure B.1 Normalized measured refrigerator electricity consumption as a function of raw measured consumption.

# APPENDIX C

# PROBLEMS AND UNCERTAINTIES WITH FIELD MEASUREMENTS

As with any measurement procedure, there are uncertainties associated with each of the individual field measurements which propagate into an overall uncertainty in the parameter to be estimated. In our case, the parameters to be estimated are the indicators of appliance efficiency. The uncertainty associated with our field measurement techniques will be based upon standard uncertainties (i.e. for the particular sensors used), field experience with the measurement techniques, and uncertainties in the underlying assumptions.

It is important to note that "uncertainty" is the random deviation of a measurement from the average of a large number of sequential readings. These random deviations are a function of changes in sensor installation, measurement equipment uncertainties, technician error in operating the equipment, or random instabilities of the quantity being measured. The average of a large number of sequential readings may also have a bias, which means that the average has a constant offset from the correct value. Measurements which had a known bias were corrected before the indicators were calculated, the others are assumed to have no bias. Since uncertainties are random in nature, any individual measurement can not be corrected for uncertainty. The California Energy Commission's (CEC) specified measurement uncertainty tolerance limits for laboratory ratings tests, along with the in-situ audit measurement uncertainty and CEC specified target uncertainties are summarized in Table C.1 below. The following sections provide details for each of the appliance procedures.

Table C.1: Measurement and Target Uncertainties[a]

| Indicator | Laboratory Measurement Uncertainty [%] | Audit Measurement Uncertainty [%] | Audit Target Uncertainty [%] |
|---|---|---|---|
| Refrigerator Consumption | 10 | 20[b] | 10 |
| DHW Recovery Efficiency | 2.5 | 7 | 15 |
| DHW Standby Losses | 2.5 | 9 | 15 |
| Air Conditioner SEER | 5 | 25 | 15 |
| Furnace Seasonal Efficiency | 5 | 14 | 15 |

[a] See individual appliance sections for assumptions associated with each procedure.

[b] Most of the uncertainty is associated with the temperature and door opening normalization algorithms and cannot be reduced with improved field measurements.

## Refrigerators

The uncertainties associated with the refrigerator energy consumption indicator stem from several sources (see Equation B.2), including uncertainties in: 1) the electrical energy consumption during the test, 2) the compartment and ambient air temperatures, 3) normalization of in-situ temperature conditions to laboratory conditions, and 4) the correction for door openings and food loads.

The electricity consumption is measured with a standard utility kilowatt-hour meter, which is uncertain to better than 3%. The freezer compartment to ambient air temperature difference, which is calculated from separate compartment and ambient temperature measurements, has a 7% uncertainty. This uncertainty only affects the temperature correction factor in Equation B.2.

In addition to the measurement uncertainty, there are uncertainties in the methods used to normalize the results for door openings and temperature differences. It was assumed that the electricity consumption follows Equation B.2; the uncertainty in this assumption can be estimated as follows. The value that should be used for the parameter "b" is not clear; the values obtained from the curve fits for individual refrigerators in this study ranged from 0.024 to 0.054, with a mean of 0.038. When this range of values is included with the possible uncertainty in the temperature measurement (assuming a 35.0 °C (63 °F) $\Delta T$ ), this corresponds to a range in the correction factors from 2.06 to 1.21, with a mean of 1.57. The resulting temperature normalization uncertainty is 32%. The uncertainty in adjusting for door openings can be estimated from the NBS study. The authors found correction factors from 1.07 to 1.25, with a mean of 1.13. The resulting uncertainty is 8%. Although the overall instrument measurement uncertainty is only 8%, the temperature and door opening normalization algorithms increase the normalized energy consumption uncertainty to 20%. The refrigerator procedure measurement uncertainties are summarized in Table C.2.

Table C.2: Measurement Uncertainties for Refrigerator Procedure

| Indicator | Uncertainty [%] | Measurement | Overall Measurement Uncertainty [%] |
|---|---|---|---|
| kWh per month | 3 | Electricity meter | |
| | 7 | Temperature diff. | |
| | 32 | Temperature normalization | |
| | 8 | Door openings normalization | |
| | | | 20 |

Major calculation assumptions and correction methods:

- LBL temperature correction algorithm
- ADL door opening factor

## Water Heaters

### (a) Recovery Efficiency

The uncertainties associated with the recovery efficiency measurement stem from several sources (see Equation B.4), including uncertainties in: 1) the volume of the tank, 2) the gas energy consumed during the test, and 3) the temperature rise experienced by the water in the tank.

According to a study by Arthur D. Little Inc. (ADL)[1] tank volume for a nominal 40-gallon tank is usually between 38.5 and 39.5 gallons. The nominal values for tank volume were used in the calculations; but if it is assumed that tank volume is 40 ±1 gallon, this is an uncertainty of ±3%. In some cases, we found thermosiphon loops in the hot water systems, which would increase the effective heated volume of water an indeterminate amount.

The uncertainty associated with measuring the gas energy consumed stems from several sources: the measurement of the burner gas volume consumption, the heating value of the gas, and timing the length of burn required. The burner gas volume consumption uncertainty involves the accuracy of the utility gas meter, in reading the gas meter, and in reading the stopwatch. These effects yield a total uncertainty of approximately 5%. The uncertainty in the heating value of the gas should be less than 1%, and the uncertainty in timing the burn should be less than 0.5%. The resulting uncertainty in the gas energy consumption measurement is therefore less than 5%.

The uncertainty in the temperature rise experienced by the water in the tank stems from two sources, the uncertainty associated with the temperature sensors, and the uncertainty associated with estimating the average tank temperature based on a measurement of the hot water supply pipe rather than at six levels within the tank. The former source of uncertainty is small, as the thermocouple temperature measurements should be accurate to within 1.5 °C, which represents a 3% uncertainty in the average temperature rise of 45 °C. The uncertainty associated with measuring only the hot water supply pipe temperature was tested with an additional experiment in one house. By installing temperature sensors at five levels in a standard domestic hot water tank, the temperature of the water at different levels was compared with the hot water faucet temperature. The comparison (Figure C.1) indicates that the uncertainty is less than 4%. Thus the total uncertainty in the temperature measurement is less than 5%.

The uncertainty in the recovery efficiency measurement is 7%.

### (b) Standby loss

The standby loss is calculated by measuring the on-time for the main burner to return the tank to its aquastat set-point after a period of no use. It is assumed that the sequence of events is as follows: Following main burner operation, the tank is well mixed and at a uniform temperature at the upper end of the aquastat deadband. During a period of no use, the tank slowly and uniformly cools, until its temperature reaches the lower end of the aquastat deadband. Then the main burner turns on again, and returns the tank to the upper end of the aquastat deadband.

The standby loss calculation assumes that the average temperature of the tank falls linearly during the standby period, and that the total energy consumed by the pilot light and the main burner during the total standby period is the energy lost by the water. The accuracy of this set of assumptions has a major influence on the accuracy of the measured standby loss.

The measurement has several uncertainties associated with it (see Equation B.6), including uncertainties in: 1) the volume of the tank, 2) the gas energy consumption during the standby period, 3) the length of a standby period, and 4) the tank-ambient temperature difference.

The uncertainty of the tank volume is 3%, as noted above. Uncertainty in the gas energy consumption during standby results from uncertainty in the utility gas meter, in reading the gas meter, in reading the stopwatch, in long-term variations in burner flow rate, and in estimating the burner on-time from the flue-gas temperature. The length of the standby period is measured with an accuracy of less than 1 minute in the total period, typically 14 hours, an uncertainty of less that 1%. The resulting uncertainty in the gas energy consumption measurement is less than 5%. The temperature of the water inside the tank cannot be measured during the standby test period. As the water cools, the water temperature at the aquastat drops through the deadband, which is typically 11 ° C (20 ° F). Depending on the rate at which it cools, the uncertainty in the tank-ambient temperature could be 5%.

However, the problem with most test sites was that water use occurred between two subsequent operations of the main burner. Field tests showed that only 10% of the houses with gas water heaters had hot water non-use (standby) periods long enough to induce main-burner operation.

The uncertainty in the standby loss calculation should be less than 9%. However, violation of the assumptions used in the standby loss calculations are a potential large source of hidden error. (Examples: low water usage during the test is difficult to detect without an in-line water meter; losses by convective water flow would also remain undetected by the techniques used in this study; water temperatures in the tank were not measured, and may not vary according to the above assumptions.) The DHW procedure measurement uncertainties are summarized in Table C.3.

### Air Conditioners

The uncertainties associated with the SEER and EER measurements stem from several sources (see Equations B.8-13), including uncertainties in: 1) the electrical energy consumed by the air-conditioner, 2) the air volume flow rate through the condenser, 3) the temperature rise of the air passing through the condenser, and 4) the density of the air passing through the condenser.

The energy consumed by the air conditioner is not a major source of uncertainty, as the kilowatt meter used during the summer survey is uncertain to better than 3%, and the timing of the cycle is uncertain to better than 0.5%.

The major source of uncertainty is the measurement of the airflow through the condenser. A comparison of results from several tracer gas measurements on selected units and comparison to anemometer traverse measurements on the same units provided a basis for determining the air flow measurement uncertainty. Repeated measurements of air flow without sensor changes produced an uncertainty of 15%, but when measurements were taken on different days they were repeatable to only 25%. No equipment was available for comparing the tracer gas air flow measurements to a known accurate air flow measurement, so measurement bias is unknown.

Table C.3: Measurement Uncertainties for DHW Procedure

| Indicator | Uncertainty [%] | Measurement | Overall Measurement Uncertainty [%] |
|---|---|---|---|
| Recovery Efficiency | 3 | Tank volume | 7 |
| | 5 | Gas consumption | |
| | 5 | Water temperature | |
| Standby Loss | 3 | Tank volume | 9 |
| | 5 | Gas consumption | |
| | 1 | Time of standby | |
| | 5 | Water/air temp. diff. | |

Major calculation assumptions and correction methods:

- No hot water usage during standby
- No conductive or convective losses in water pipes during standby
- Average temperature of the tank falls linearly during standby
- Tank is well-mixed, or returns to initial state after a burn

The uncertainty in the temperature rise across the condenser stems from two sources: 1) the uncertainty associated with the thermopile (10 junction differential thermocouple), and 2) the uncertainty associated with the non-uniform velocity profiles in which the temperature sensors are placed. The thermopile itself yields an uncertainty of only 1% (0.1 °C uncertainty in a 10 °C measurement). It was assumed that the temperature and velocity profiles were uniform. The uncertainty in the density of air going through the condenser should be small; an error of 3 °C in the air temperature yields an error of 1% in the density.

The overall instrument uncertainty, when propagated through the equation to calculate air conditioner efficiency, is approximately 25%, depending on the actual EER. (The uncertainty is 25% for units with an EER of 5.8, the average measured value from the study. It is less for higher-EER units.) The air conditioner procedure measurement uncertainties are summarized in Table C.4.

### Furnaces

The uncertainties associated with the furnace efficiency measurement stem from several sources (see Equations B.14-15) including uncertainties in: 1) the flue and stack temperatures at the specified times, 2) the flue and stack oxygen contents, 3) the fan on and off times, and 4) the gas energy consumption during the test.

The uncertainty in the temperatures in the flue and stack stem from 1) the uncertainty associated with the temperature sensors, 2) the time at which the measurements were made, and 3) spacial variation of flue or stack temperatures. The first source of error is small, as the thermocouple temperature measurements should be accurate to

Table C.4: Measurement Uncertainties for Air-Conditioner Procedure

| Indicator | Uncertainty [%] | Measurement | Overall Measurement Uncertainty [%] |
|---|---|---|---|
| SEER | 3 | Electrical consumption | 25 |
| | 15 | Air flow | |
| | 1 | Temperature | |
| | 1 | Air Density | |

Major calculation assumptions and correction methods:

- Uniform temperature across faces of heat exchanger
- DOE 2.1 temperature correction algorithm

within 1.5 ° C, which represents a less than 1% uncertainty in the typical temperature rise of 200 ° C. A 0.5 second error in timing would produce an error of approximately 1 ° C, an uncertainty of 1%. The third source of uncertainty is larger. The temperatures in a flue or stack are non-uniform, and vary by 10% from point to point. The error in sampling is avoided in the laboratory test by using a thermocouple averaging grid.

The uncertainty associated with measuring the gas energy consumed stems from several sources: the measurement of the burner gas volume consumption, the heating value of the gas, and timing the length of burn required. The burner gas volume consumption uncertainty involves the accuracy of the utility gas meter, reading the gas meter, and reading the stopwatch. These effects yield a total uncertainty of approximately 5%. The uncertainty in the heating value of the gas should be less than 1%, and the uncertainty in timing the burn should be less than 0.5%. The resulting uncertainty in the gas energy consumption measurement is therefore less than 5%.

The fan power is measured to an accuracy of 3% with a kilowatt meter. The fan on- and off-times affect the seasonal efficiency only as minor adjustment terms; their measurement uncertainty is 0.5% The overall result of the seasonal efficiency calculation uncertainty is 14%. The furnace procedure measurement uncertainties are summarized in Table C.5.

Table C.5: Measurement Uncertainties for Furnace Procedure

| Indicator | Uncertainty [%] | Measurement | Overall Measurement Uncertainty [%] |
|---|---|---|---|
| Seasonal Efficiency | 10 | Temperatures | 14 |
| | 1 | Times for temperatures | |
| | 5 | Flue gas analysis | |
| | 1 | Fan on and off times | |
| | 5 | Gas consumption | |
| | 3 | Fan power | |

Major calculation assumptions and correction methods:

- None

# References

1. Study of energy-saving options for refrigerators and water heaters. Prepared for the Office of Transportation and Appliance Programs, Federal Energy Administration, by Arthur D. Little, Inc., Cambridge, MA 02140. May, 1977.

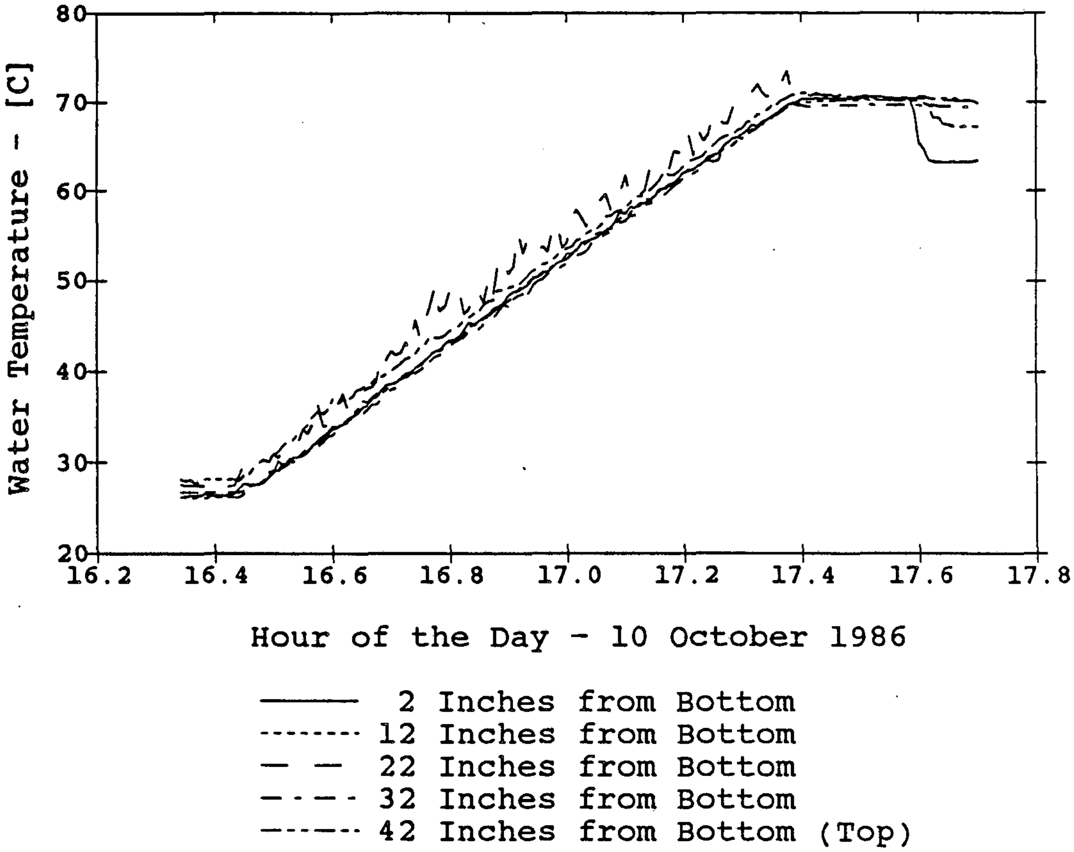

**Figure C.1** Water temperature at five equally-spaced points inside a field-installed DHW tank during a recovery efficiency test.

# APPENDIX D

## DIFFERENCES BETWEEN RATED AND MEASURED DATA

This section presents an analysis of the data to determine if there are any trends in the percentage difference between rated and measured efficiency indicators as a function of (i) rated indicator and (ii) age of appliance. In almost all cases, no significant trend was observed at the 95% confidence level. This may be seen by noting that in all cases where confidence intervals could be drawn, these intervals include much of the zero difference line. In some cases, a very weak correlation can be seen in the plots. The statistical significance of this correlation was not investigated.

Figures D.1a and D.1b show the data for normalized refrigerator electricity consumption. Figures D.2 shows the data for DHW recovery efficiency versus age; the data versus rated value are not presented because all rated values are almost identical, so the data is all bunched at one point.

Figure D.3 shows the data for domestic hot water standby loss; there are so few points that a confidence interval is not drawn. Again, the rated values are very bunched and are not presented.

Figures D.4a and D.4b show the data for air conditioner EER as a function of rated value and as a function of age. The 95% confidence limits are very broad because of the experimental errors, and once again no trend is observed. Figures D.5a and D.5b show the same data for SEER, and the same conclusions may be drawn.

Finally, Figures D.6a and D.6b show the data for difference in seasonal efficiency as a function of rated efficiency and of age. In the former, there is no significant trend; in the latter, a computational problem prevented the calculation of confidence limits, but visual observation of the data suggests that no trend is present.

### Confidence Interval Discussion

A short discussion of the confidence intervals used in many of the figures in this report will help to interpret their significance. The confidence intervals in this report are intervals constructed from the measured values in such a way that they have a 95% probability of containing the true linear line fit (linear regression) of the population of all appliances. This implies that there is **only** 5% probability of the true line fit existing outside the confidence intervals. The confidence interval can be used to establish whether or not the data is inconsistent with a particular hypothesis about the relationship between the variables (e.g. measured equals rated efficiency, or rated-minus-measured equals a constant with respect to appliance age).

If the hypothesis is not totally enclosed by the confidence interval, as in Fig. D.7a, then there is only a 5% probability that the data is consistent with the hypothesis and we reject the hypothesis. If the hypothesis is totally enclosed by the confidence interval, as in Fig. D.7b, the data is not inconsistent with the hypothesis of rated efficiency equals measured efficiency, and the hypothesis is accepted.

A narrow confidence interval implies robust data which allows many hypothesis to be rejected, whereas a wide interval suggests that only tentative conclusions can be supported. A wide interval can often be narrowed by reducing the uncertainties in the measurements and/or by taking more measurements. Fig. D.7c shows a narrow confidence interval, which contains a small range of linear relationships which are consistent with the data . The possible relationships for Fig. D.7c are:

$$\text{measured efficiency} = (0.9 \pm 0.1)^{*}\text{rated efficiency}.$$

In comparison, the wide confidence interval shown in Fig. D.7d can contain a very large range of linear relationships which are consistent with the data (i.e. can not be rejected), with no indication of which is the true relationship. The possible relationships in Fig. D.7d are:

$$\text{measured efficiency} = (0.9 \pm 0.3)^{*}\text{rated efficiency}.$$

Since the confidence intervals are calculated based on an assumption of normally distributed measurements and errors, the actual confidence intervals may vary depending on the actual statistical distribution of the data. More details of confidence intervals may be found in chapters 8 and 12 of Wonnacott and Wonnacott.[1]

Reference

1. T.M. Wonnacott and R.J. Wonnacott, Introductory Statistics for Business and Economics, Second Edition, 1977, John Wiley and Sons.

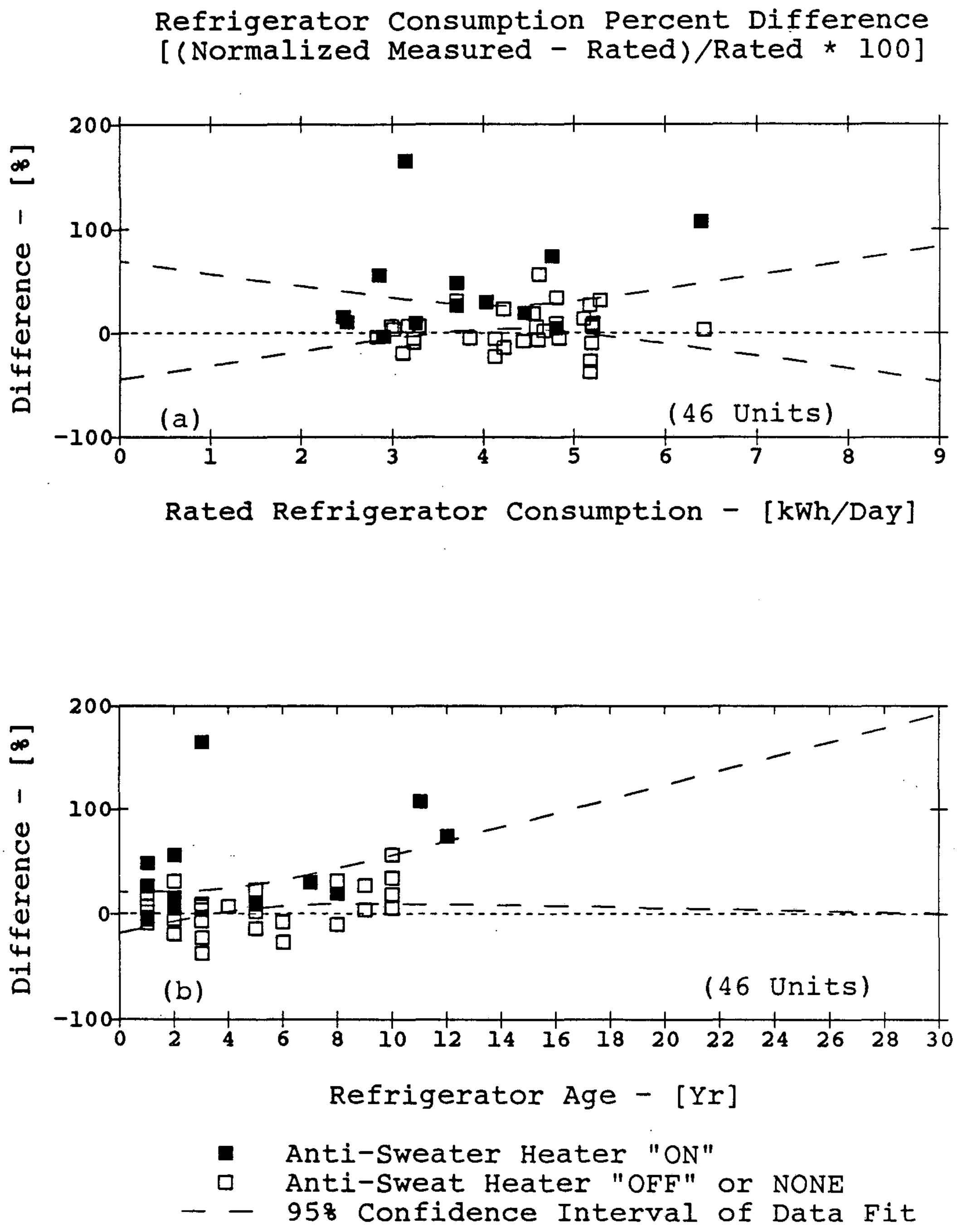

Figure D.1 Percentage difference between normalized measured and rated refrigerator electricity consumption as a function of (a) rated consumption, and (b) age of unit.

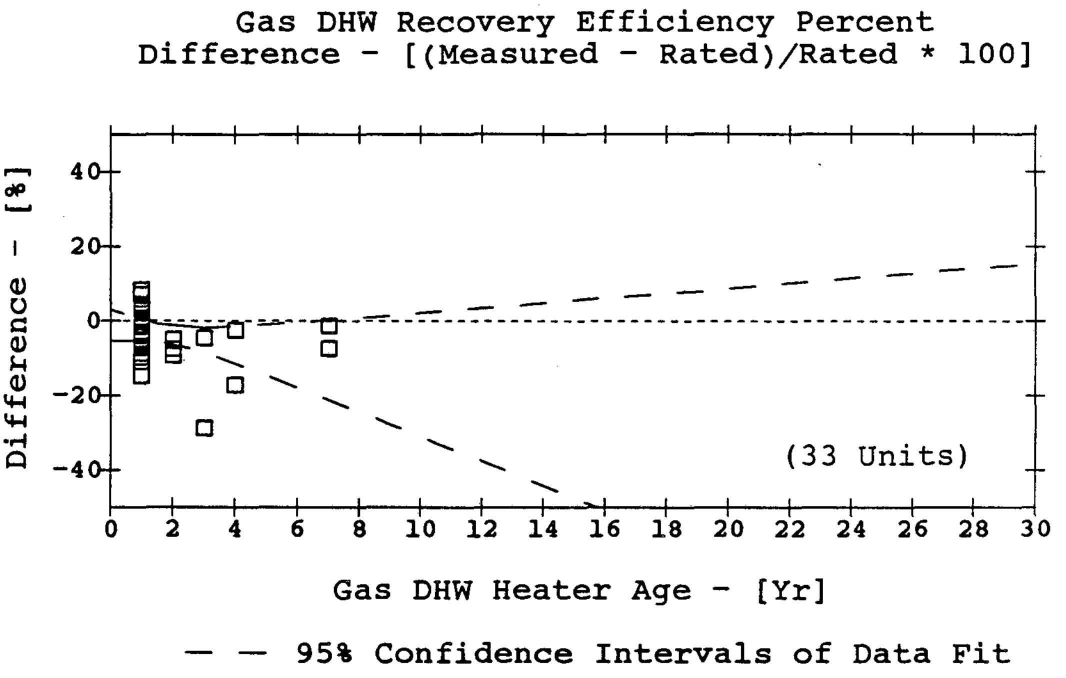

Figure D.2 Percentage difference between normalized measured and rated DHW recovery efficiency as a function of age of unit.

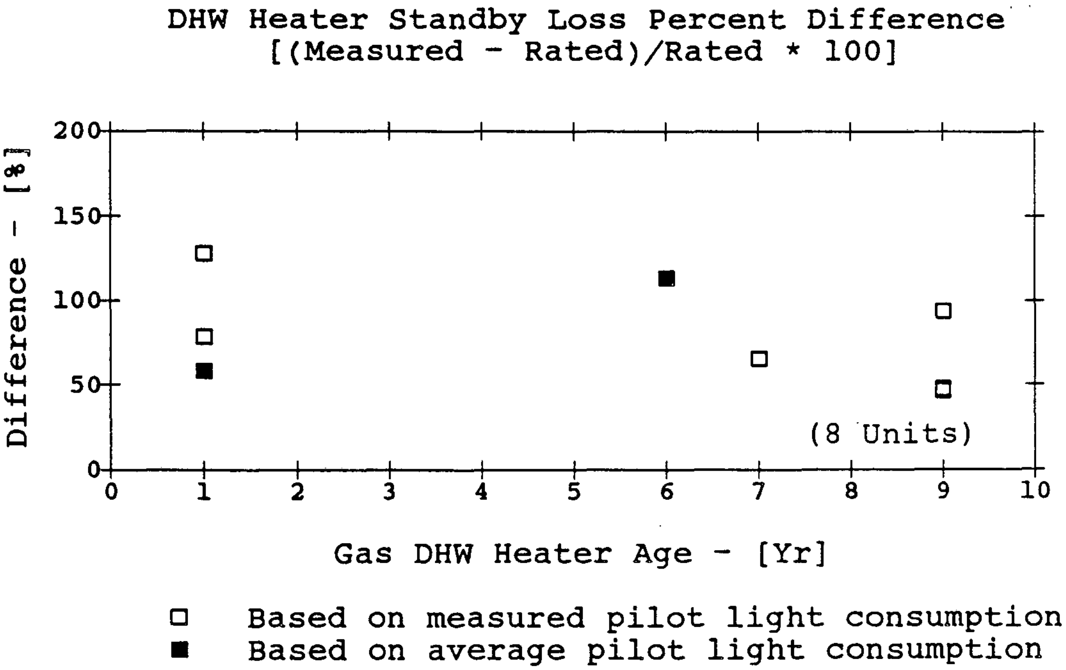

Figure D.3 Percentage difference between normalized measured and rated DHW standby loss rate as a function of age of unit.

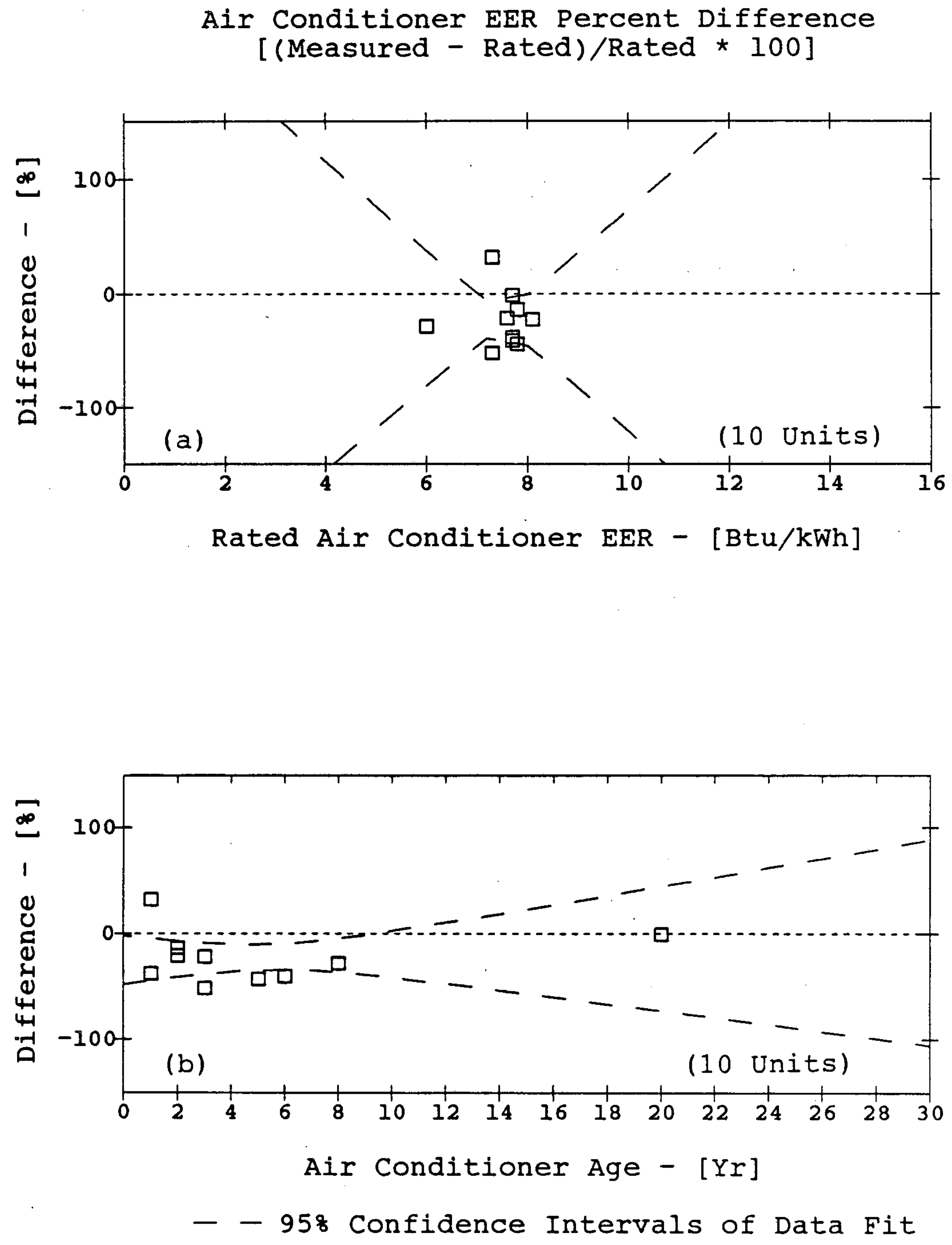

Figure D.4 Percentage difference between normalized measured and rated air conditioner EER as a function of (a) rated EER, and (b) age of unit.

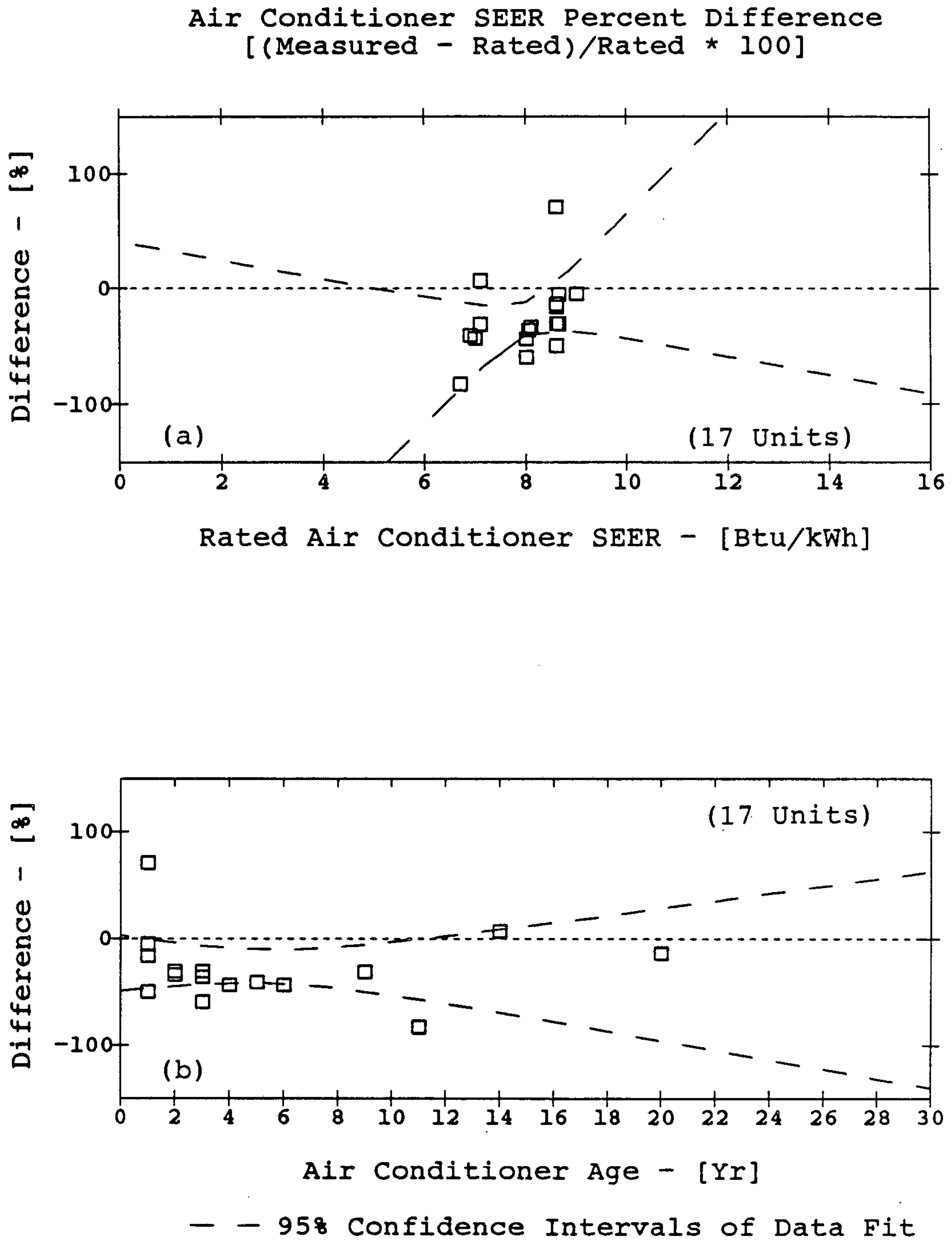

**Figure D.5** Percentage difference between normalized measured and rated air conditioner SEER as a function of (a) rated SEER, and (b) age of unit.

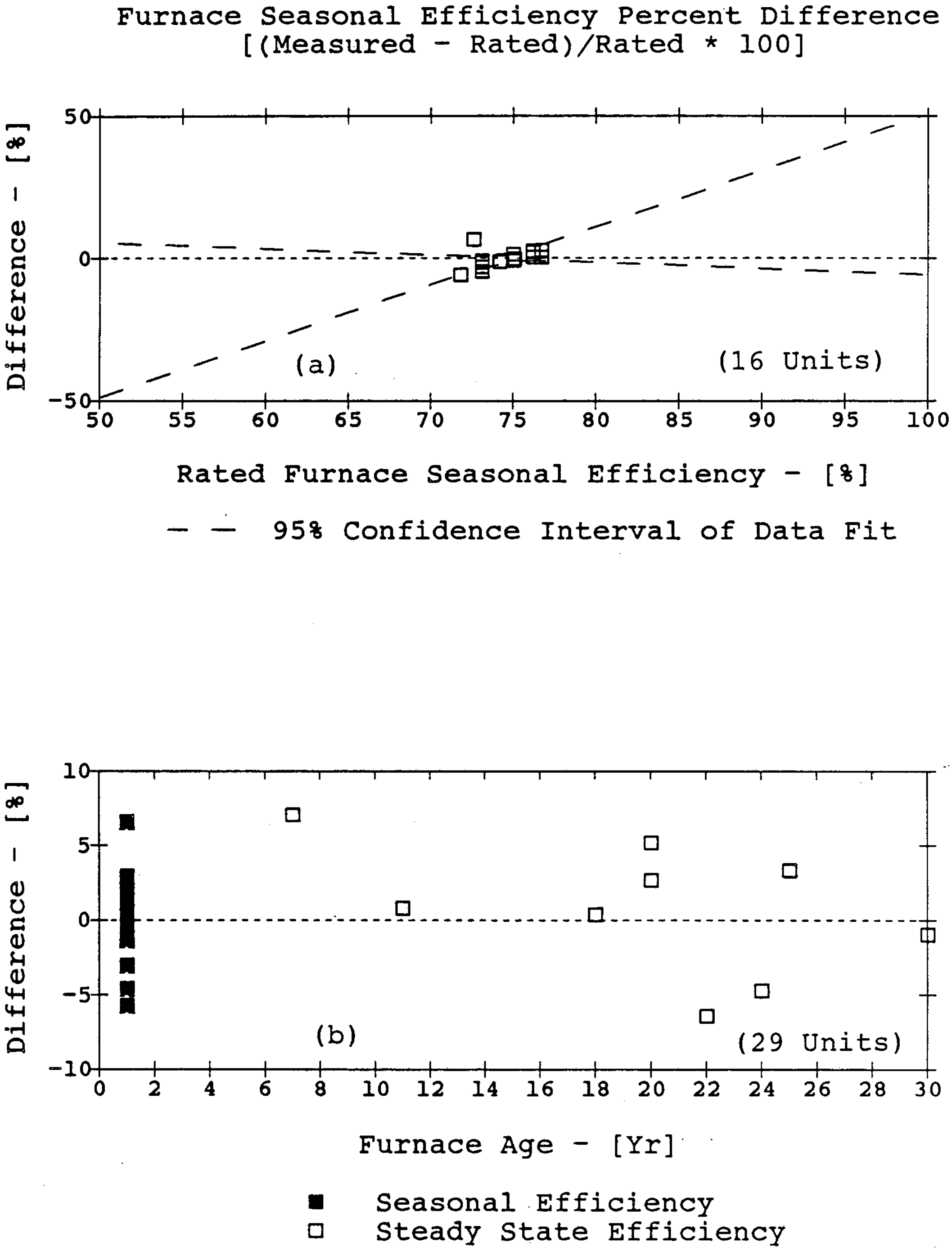

Figure D.6 Percentage difference between normalized measured and rated furnace seasonal efficiency as a function of (a) rated efficiency, and (b) age of unit.

Fig. D.7a Hypothesis Rejected

Fig. D.7b Hypothesis Accepted

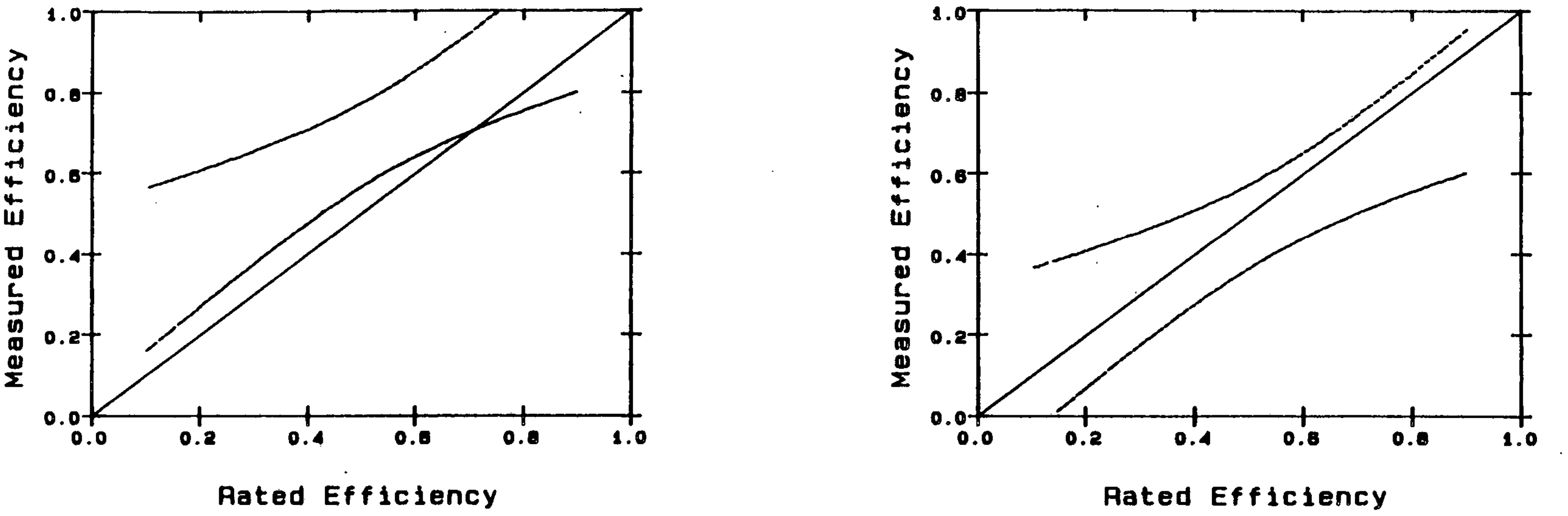

Fig. D.7c Narrow Conficence Interval

Fig. D.7d Wide Confidence Interval

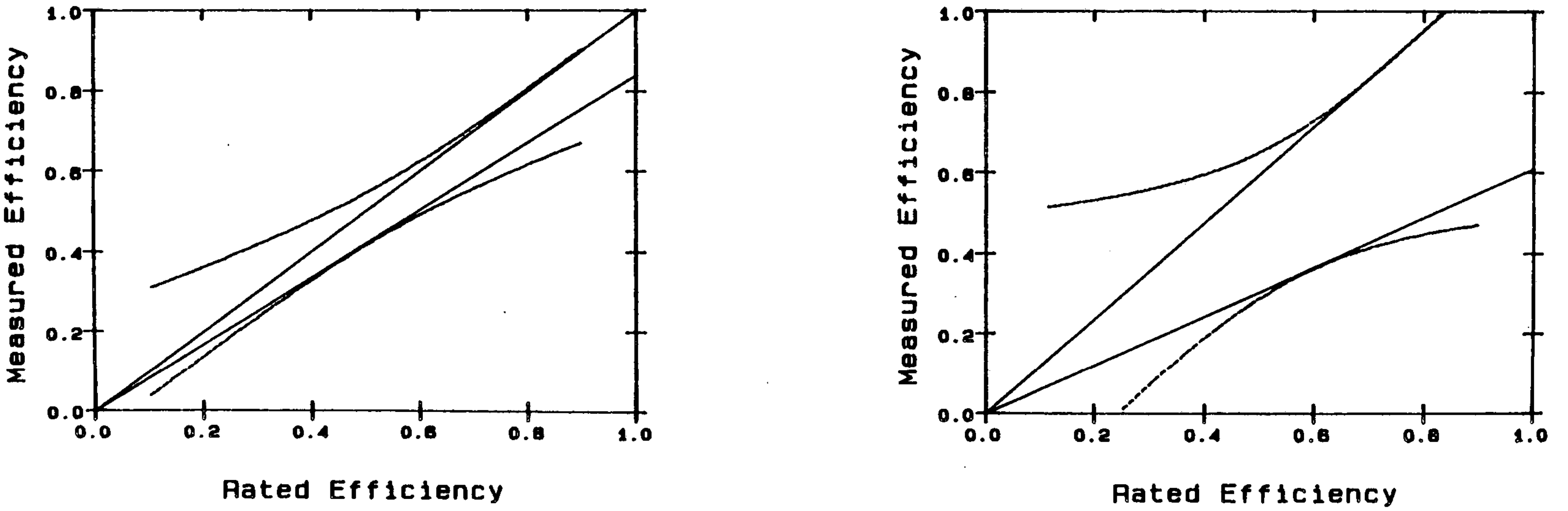

Figure D.7 Confidence interval interpretation examples.

# APPENDIX E

# ALTERNATIVE PROCEDURES

Over the course of the study, a number of potential modifications to the test procedures, as well as a number of replacement procedures, were examined. Some of these improvements or alternatives are focused on developing simpler, less expensive audit tools, while others are focused on improving the weak points of the present audit procedures.

## Refrigerators

Prior to this study, there was inadequate data for determining the minimum monitoring time period for accurately determining refrigerator compartment temperatures and electrical consumption. Therefore, there was no alternative to conducting one-week long-term monitoring of refrigerator temperatures and energy consumption. The data collected during the study provides insight into alternatives. The possibility of using short-term electrical consumption data was examined, but the uncertainty in the electrical consumption was unacceptably high for 2, 6, or 24-hour measurements, which were considered reasonable one-day test time periods.

Two possible alternatives for measuring refrigerator temperatures merit further investigation. First, because only the freezer compartment temperature is used in the refrigerator indicator calculations, there is no need for a fresh food compartment temperature. In addition, since only the average temperatures are used in the indicator calculations, integrating stand-alone temperature sensors for measuring the freezer compartment and ambient temperatures, costing approximately $400 each, could be substituted for the data acquisition system. This would greatly simplify the equipment and installation requirements.

The second alternative is to make temperature measurements during the 4-6 hour site visit period, and to use these short-term values to calculate the indicator. Analysis of the hourly temperature data from the study indicates that it may be practical to assume that the refrigerator fresh food and freezer compartment temperatures need only be measured for a short-term period. This alternative has been examined briefly, and the results plotted in Figure E.1. In this figure, it is evident that the 2-hour short-term data tracks the one-week long-term average data rather well. A slightly longer monitoring period, 4 hours, should improve the results considerably.

Although refrigerator fresh food and freezer compartment door openings were monitored in 13 houses during the winter study, it was concluded that individual corrections for each refrigerator would not provide accurate electrical consumption normalization. The door opening data did show that this test sample was similar to the populations of other reported monitoring projects. Additional data which correlates electrical consumption with door openings and ambient temperatures is required to establish a normalization algorithm based upon individually measured door openings.

## Water Heaters

The short-term recovery efficiency measurement procedure for gas hot water heaters is straightforward, and appears to have an acceptable uncertainty. Its major disadvantage is the time required to perform the test (2 to 3 hours).

An alternative procedure for determining the recovery efficiency is to use an adjusted steady-state efficiency, which is much simpler and quicker to measure (0.5 hour compared to 2.5 hours). The only equipment requirement for this procedure a stack-gas analyzer for measuring flue temperature and oxygen. As part of the diagnostics for gas hot water heaters, the stack gas was analyzed during the recovery test. The efficiencies measured by the stack-gas analyzer are compared with the recovery efficiency measurements in Figure E.2.

Figure E.2 shows that stack-gas efficiency is correlated with, but is consistently higher than, the recovery efficiency. The fact that the recovery efficiency is consistently lower than the stack efficiency is not surprising, as the stack-gas efficiency measurement does not take into account radiation losses from the burner flame to the ground, heat gain by the mass of the tank and insulation, losses from the tank walls, or heat conduction and convection losses associated with the attached pipes (such as thermosyphoning of the water). Stack-gas efficiency also varies within a much smaller envelope, generally between 70 and 82%, relative to recovery efficiency, which varies between 50 and 82%. Although it should be noted that the larger measurement uncertainty associated with the recovery efficiency measurement contributes to the larger range (scatter) for the recovery efficiencies, the additional losses included in the recovery efficiency imply that the scatter is meaningful, and should not be eliminated from efficiency analyses. It was concluded that the bias associated with measuring stack rather than recovery efficiency, and the costs associated with quantifying that bias (and its standard error), were not justified by the 1-2 hour time savings achieved with the stack efficiency test.

The standby-loss test proved to be problematic for many of the gas DHW heaters in this study due to the lack of main burner operation during hot-water non-use periods. This stems from the fact that the houses were occupied, which limits the length of the hot water non-use periods available for the standby test. Although the measurement technique itself worked well, the short non-use periods resulted in standby-loss measurements in only 8 of the 57 test sites in the study.

Some alternative techniques for calculating standby loss were investigated, which included: 1) limiting the tests to unoccupied houses, 2) developing estimates of the standby losses from other available data, and 3) developing measurement methodologies to measure standby losses directly. The first alternative greatly increases the logistical complications of any survey, and does not insure that the required data will be obtained (at one house the main burner did not cycle during an entire week without occupancy).

The second alternative, to estimate the standby losses from other available data, has been examined in detail. The procedure is to obtain standby loss estimates based upon the data collected and some assumptions about the operation of the DHW heater. The first estimated value was calculated assuming that the water in the tank remained at constant temperature during standby periods, the only loss being the pilot light. The calculation is:

$$S_{pilot} = \frac{Q_{pilot}}{8.25\ V\,\Delta T} \tag{E.1}$$

where

| | |
|---|---|
| $S_{pilot}$ | is the estimate of the standby loss based on the pilot light [$h^{-1}$] |
| $Q_{pilot}$ | is the fuel consumption rate of the pilot light [Btu/h] |
| 8.25 | is the specific heat of water [Btu/gal °F] |
| $V$ | is the volume of the water heater [gallons] |
| $\Delta T$ | is the difference between hot water setpoint temperature and ambient [°F] |

The second estimate was a value based upon the maximum observed length of time between operation of the main burner and the next draw of hot water (longest observed non-use period). This assumes that the burner would have operated in the next minute if there had not been a draw of hot water, i.e. that the water temperature was at precisely the lower aquastat deadband temperature when the hot water use occurred. The equations used are as follows. The calculation is:

$$S_{use} = \frac{(Q_{pilot}\,H_{no}) + \dfrac{T_{DB}\,8.25\,V}{E_{REC}}}{H_{no}\,8.25\,V\,(\,\Delta T - \dfrac{T_{DB}}{2})} \qquad \text{(E.2)}$$

where

| | |
|---|---|
| $S_{use}$ | is the estimate of the standby loss based upon the longest period between a burn and hot water use [$h^{-1}$] |
| $T_{DB}$ | is the estimated deadband of the thermostat [°F] |
| $E_{REC}$ | is the measured recovery efficiency of the unit [fraction] |
| $H_{no}$ | is the maximum length of time between the end of a main burner operation and the next hot water draw [hours] |

The second estimate was found to be as much as two or three times greater that the first estimate. If the mean value is used as a measure of the standby loss, this result implies potential errors on the order of 100%. In addition, we cannot conclude that the second estimate represents an upper bound on the standby loss. In the four houses for which both measured standby loss data and $S_{use}$ were available, $S_{use}$ was equal to the measured standby in two cases, and significantly lower than measured standby in two cases. This result is attributed to variable tank stratification conditions during use and non-use periods. It is also clear that the observed value for the $S_{use}$ estimate depends upon occupant behavior, as the length of burn-to-use periods is occupant controlled. For electric water heaters, the only applicable estimate is $S_{use}$.

The third alternative, direct measurement of standby losses, involves three separate measurements, including pilot energy consumption, flue heat loss, and jacket heat loss. The pilot energy consumption measurement is similar to that in the present measurement procedure. The flue heat loss must be measured over an extended period of time, and must include both air flow and temperature measurements. Continuous air flow measurements are expensive and impractical, implying that an additional procedure development effort would be required to develop a simple method of calculating flow from other measurements. This might be accomplished by developing a correlation between continuous tracer gas air flow measurements and flue temperature. The jacket heat loss measurement would also require some additional procedure development, as it would most likely involve the use of heat flux sensors. This measurement is inherently difficult to make in the field, as the appropriate location for the heat flux sensor may vary from one installation to another. This measurement will be further hampered on hot water heaters that have been retrofitted with an insulation jacket.

In conclusion, all alternative standby loss measurement techniques investigated to date require additional effort before field implementation, and are more complicated or more expensive than the present technique. If measurements for standby loss calculations are not conducted in future studies, then there is no need to conduct long-term monitoring for water heaters.

### Air Conditioners

The air-conditioner measurement procedure, in particular the air flow measurement procedure, is clearly the weak point of the field efficiency measurement procedure. Three techniques for measuring air flow were utilized during the study. The simplest method was to use a standard commercial flow hood with air flow straighteners and averaging pitot tube array. It was found that the air-flow resistance caused by the flow hood was excessive for the type of fan used in most residential condenser coil units, which rendered this technique unacceptable.

The second method was to measure air-speed profiles across the inlet and outlet of the condenser coil unit with hot-wire anemometers. The air speed profile results for the outlet were inconsistent due of the turbulent and three-dimensional nature of the air flow leaving the fan. Uncertainty in measurement of the cross-sectional flow area made the inlet measurements imprecise. Accurate measurements can be made only with extensive velocity profiling and precise cross-sectional area measurement, which was too time consuming to be useful as a field procedure.

The third method, which use the most complicated and expensive equipment, is a tracer gas technique. This technique involves injecting a tracer gas at a constant rate into the condenser fan inlet while the fan's outlet tracer gas concentration was monitored. The short mixing length associated with a condenser fan/coil unit resulted in incomplete or unstable mixing. A four-foot-long mixing tube was added to the fan outlet to improve the gas mixing length, but such a mixing tube was impossible to install on many air conditioners with rectangular outlets or on units mounted on roof-tops or in tight quarters.

Due to the lack of success with all three air flow measurement techniques, and the critical nature of this measurement, several additional procedures may merit further investigation. These alternatives are: 1) more-sophisticated tracer injection and sampling techniques, 2) a flow measurement technique based on inflating a large bag with the condenser fan, and 3) evaporator coil (indoor) flow measurements in combination with air temperature and humidity or condensate measurement apparatus.

The first alternative, using more sophisticated tracer injection and sampling, is probably not applicable to a large field survey of appliance performance. Standard tracer-gas equipment is too expensive and delicate for such a field survey.

The second alternative, using a very large bag (i.e. around 4 cubic meters) to measure the air flow through the condenser, merits further consideration. This technique involves measuring the time it takes to fill a large bag of known volume. The advantages of the technique are that it is quick, requires inexpensive equipment, and should not affect the flow through the unit since it has a low flow resistance. The disadvantages of the technique are that the bag size may cause physical installation difficulties in some instances (e.g. rooftops or restricted access situations), and that the bag may not be very durable.

The third alternative, making evaporator-side measurements, was considered and rejected at the initiation of this project due to the costs associated with accurately measuring air moisture content. Several techniques for measuring the air flow through the indoor air conditioner duct system were used during the summer study, including flow hoods, anemometer traverses, and tracer gas measurements. The uncertainty of the indoor air flow tracer gas measurements was much better than for the outdoor (condenser) fan-coil units. Although the tracer gas technique is reliable in this case, the simpler and cheaper commercially available air flow measurement techniques that would be applicable to a large-scale survey have several difficulties. Flow hood techniques have flow resistance problems when a house has more than one return register, and both the flow hood and anemometer traverse suffer inaccuracies whenever the return duct system has leaks. Anemometer traverses have the additional disadvantage that it is sometimes difficult to estimate the flow area without affecting the flow through the system (e.g. when returns have screens or slanted grilles).

The additional disadvantage of using indoor air flow measurements is the expense and difficulty of measuring temperature and air moisture before and after the evaporator coil, or measuring the condensate (particularly under short-term cyclic conditions). Experience with the duct temperature measurements made during this study showed that it is very difficult to accurately measure the average air temperature without significant intrusion into the ducts. On the other hand, indoor measurements have the advantage that the heat removed is measured directly, rather than by calculating heat removed from a subtraction of condenser heat rejection and electric consumption.

Two additional alternatives were discussed but not examined in detail. The first is to determine the EER by measuring temperatures and pressures in the refrigerant lines. Preliminary examinations of refrigerant-side measurements have been made at several universities, however a practical field measurement technique has not been developed. The second alternative is to use known electrical energy input (e.g. hot air injection) as a tracer for measuring air flow and as a means for determining the energy removed by the evaporator coil. This alternative may merit further investigation, as the use of heat as a tracer is a technique which has been utilized successfully in other applications.

One final point on the subject of alternative procedures for air conditioners is that it is not necessary to perform one-week long-term monitoring to measure the SEER or EER indicator, although such measurements are required to measure the actual cyclic characteristics of the system.

### Furnaces

The furnace measurement procedure proved to be one of the most reliable in the study. The field test for furnaces reproduces the laboratory test more closely than any of the other field procedures. However, an alternate technique for measuring the flue and stack temperatures would reduce the error associated with significant temperature stratification in the flue and stack. An averaging thermocouple grid would provide a measurement with less uncertainty, but would be harder to install in the field.

The long-term measurements were used to determine actual field cyclic characteristics of the system, which may differ from the assumed ASHRAE standard value, and are not required to determine the furnace indicators.

Although not an alternative procedure, one measurement related to both furnaces and air conditioners merits some discussion. Namely, as part of the furnace and air conditioner procedures, duct system flow measurements showed that the return ducts in a number of houses were leaky. This result is consistent with other studies which have shown that both return and supply ducts, particularly in California houses, are often leaky. Although duct leakage does not affect the performance indicators, it can have an important effect on actual system performance, implying that duct leakage measurements may have a role in future appliance efficiency field studies.

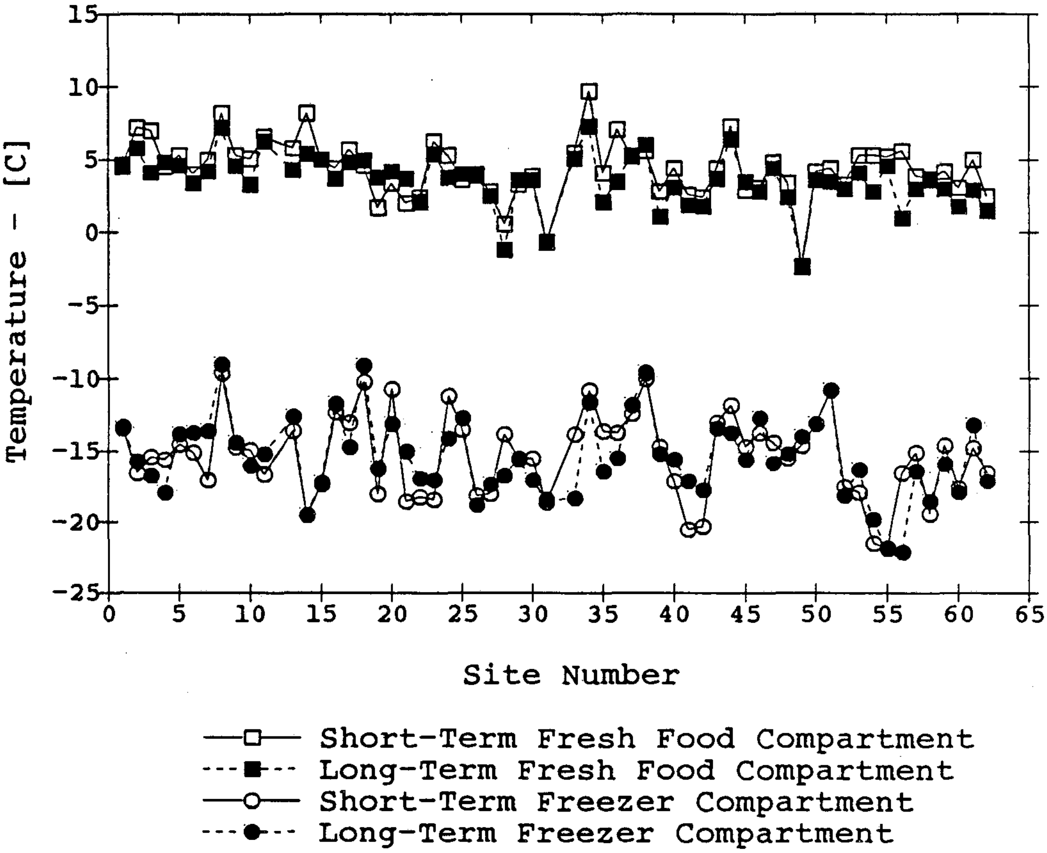

Figure E.1 Average temperatures in the fresh food and freezer compartments, as measured during the long- and short-term tests.

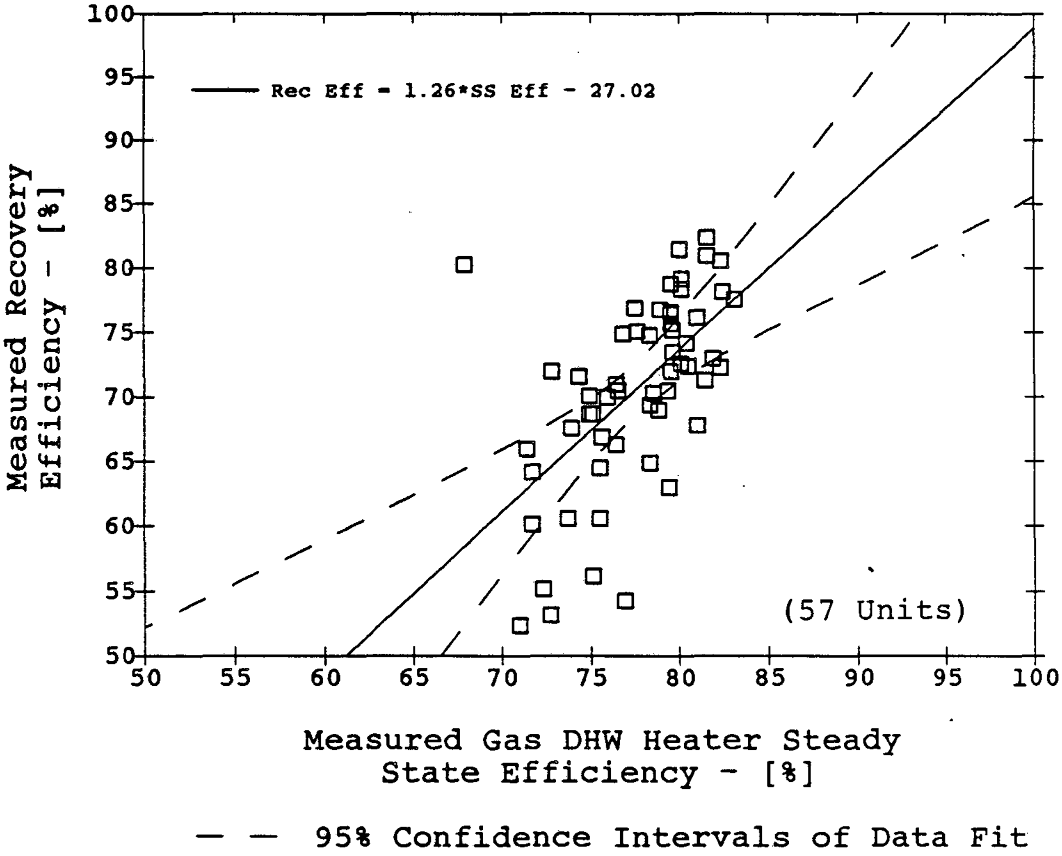

Figure E.2 Measured DHW recovery efficiency as a function of measured steady state efficiency.

*LAWRENCE BERKELEY LABORATORY*
*TECHNICAL INFORMATION DEPARTMENT*
*UNIVERSITY OF CALIFORNIA*
*BERKELEY, CALIFORNIA 94720*