Refrigerator Monitoring System Development and Field Testing Results

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Heretofore, tools for measuring refrigerator performance have been adapted from other generic data logging devices. Toward being able to recommend effective client education and assess cost effectiveness of various possible DSM and related conservation program designs, there is a need for appropriate tools for measuring refrigerator performance, allowing for a range of uses from quick audits to serious study of details affecting performance. This paper reports on an R&D project to develop analytical tools (hardware and software) along with field testing and analytical protocols to measure the efficiency of refrigerators in situ.

A simple true watt hour meter fits in the palm of the hand and accurately records electric energy use on a six-digit display. An enhanced system monitors and stores as time series data records: true watts (demand); true watt hours (energy); defroster run time; door opening events and duration; and refrigerator, freezer, and ambient (room) temperatures. Two other analog channels may be configured to measure other parameters such as ice-maker energy use, evaporator coil temperature, outside air temperature, temperature in the space between the back of the refrigerator and an adjacent wall, or humidity. Two digital channels may be used to record ice maker functions or other binary operations. The system stores up to 15,000 data records taken at one, five, fifteen, thirty, or sixty minute intervals (as selected by the user.) It displays information in real time through a hand-held terminal and provides data transfers through a serial port to a laptop or a remote PC via modem, thereby enabling further analysis, the graphing of collected data, and the production of various indices of performance.

The system is being used to measure the field performance of a sample of new and old refrigerators, including units produced under the Super Efficient Refrigerator Program (SERP).

Introduction

It is common knowledge that most of the roughly 115 million refrigerators presently operating in American homes are substantially less efficient than they could be. Refrigerators use eight percent of the electric energy consumed in this country and account for seven percent of demand (Meier and Megowan 1993). However, it is possible to produce refrigerators that are three to five times more energy efficient than the average, which is on the order of 1200 kWh per year. For over a decade, a small California manufacturer (Sun Frost) has produced refrigerators whose performance far exceeds the 1993 standards established by the National Appliance Energy Conservation Act. Whirlpool, the winner of the "Golden Carrot" award sponsored by a consortium of utilities under the Super Efficient Refrigerator Program (SERP), is now manufacturing refrigerators whose energy performance is at least 30 percent better than the 1993 standards. (Competitors for the SERP award were also required to employ only insulation material and refrigerants that are "ozone friendly.")

In 1990, only seven of 2,113 models of refrigerators on the market met the 1993 standard (Turiel et al). Now all refrigerators on the market must meet the 1993 standard. To take an example, this standard stipulates that units with top mounted freezers and automatic defrost, the most popular model of refrigerators on the market, must use less than 355 plus 16.0 times (adjusted volume in ft^3) kWh per year, where the adjusted volume = actual volume of the fresh food compartment plus 1.63 times the actual volume of the freezer compartment. In consequence, consumers in the market for new refrigerators can make choices virtually all of which are better—from the energy standpoint-than were possible only a few years ago.

The measuring of a refrigerator's energy performance for purposes of the standard is determined according to a laboratory procedure ANSI/AHAM HRF-1 1988, better known as "the DOE test." Energy use by an empty refrigerator whose doors are kept closed over a period from a specific point in a defrost period to the same point in the subsequent period is measured while ambient air is maintained at 90 F in an environmental chamber. The test is run with the anti-sweat switch on, then off, and the results are averaged. Annual consumption is estimated from these measurements by multiplying the results times the number of days in the year.

The DOE test has a number of advantages, primarily simplicity and ease of application. Nonetheless, it could be argued that modification to the DOE standard should be undertaken or that other standards for the laboratory testing of refrigerators should be adopted; standardized procedures that employ door openings, testing at a range of temperatures and humidities, and assessment of the effects of ice makers and water coolers readily come to mind. However, such is not our present intent. No matter how complex laboratory standards might become, there will always be questions important to answer that cannot be adequately addressed without testing in the field. Further, it's likely that there will continue to be a need for both field and laboratory testing that yield results of interest to design engineers, DSM program designers, evaluators, and educators—but which are not suitable for standards .

In all events, there is a need for tools for testing and related procedures. This paper addresses questions of interest to various parties and a project of developing electronic tools to answer them cost effectively.

Project Origins

The project was initiated when several research organizations realized that current methods of measuring parameters necessary to determine the performance of refrigerators in the field were inadequate on the one hand or complicated and expensive on the other. A necessary condition for optimizing programs for accelerating the adoption of energy-efficient refrigerators is to be able to know how much is saved versus how much is invested. How much is saved requires being able to determine the answer to a key question: how much is consumed by existing units under local environmental conditions versus how much is consumed by replacement units under the same (or improved) environmental conditions. The specific case of older refrigerators in multifamily dwellings is of special interest when landlords buy units yet tenants are responsible for paying for electricity consumed. The answers to these—and a group of related questions—were used to design hardware and software, and to develop a number of testing protocols.

A project advisory committee was formed to obtain insights from potential users with different applications for field test data. This group consisting of representatives of research organizations, manufacturing companies, and utilities interested in the design and performance of high-efficiency refrigerators. A meeting of the project advisory committee is scheduled to coincide with the ACEEE 1994 Summer Study and will be open to all interested parties.

Hardware Design

The decision was made to design two separate systems: a low-cost watt hour meter that is as small and simple as possible; and an enhanced system tailored to refrigerator monitoring.

Simple kWh Meter

The simple system is housed in a small enclosure (3" x 4" x 2.5") and has a female plug for the load on one end and a male plug for the line on the other. It has a six digit register which measures 999.999 kWh when full (then it "turns over" like an odometer). This capacity represents well over a year's worth of energy consumption data for a SERP refrigerator, for example, yet the resolution is adequate for performing accurate, short-term appliance audits.

The system employs a large storage capacitor to maintain memory for at least 20 minutes during short-term power outages. This avoids the need for a battery and charging circuitry and enables using a small enclosure. The single control is a reset switch on the circuit board which is actuated through a small hole using a paper clip-like wire. This keeps the watt hour meter from being reset by those who shouldn't—and yet be readily resettable by those who should.

The Enhanced Refrigerator Monitoring System

Figure 1 shows a functional block diagram of the enhanced refrigerator monitoring system designed for this project. The system as ultimately configured has a main enclosure which groups the microprocessor, associated electronics, and sensor interfaces along with the power electronics. The result is a "clean" (though smart) box with no controls or displays whose dimensions are 12 inches by 12 inches by 5 inches. During routine operations, this box stands alone, without the need for other hardware. Electronic communication with the main box is via a single standard J-38 telephone plug. Access to it is

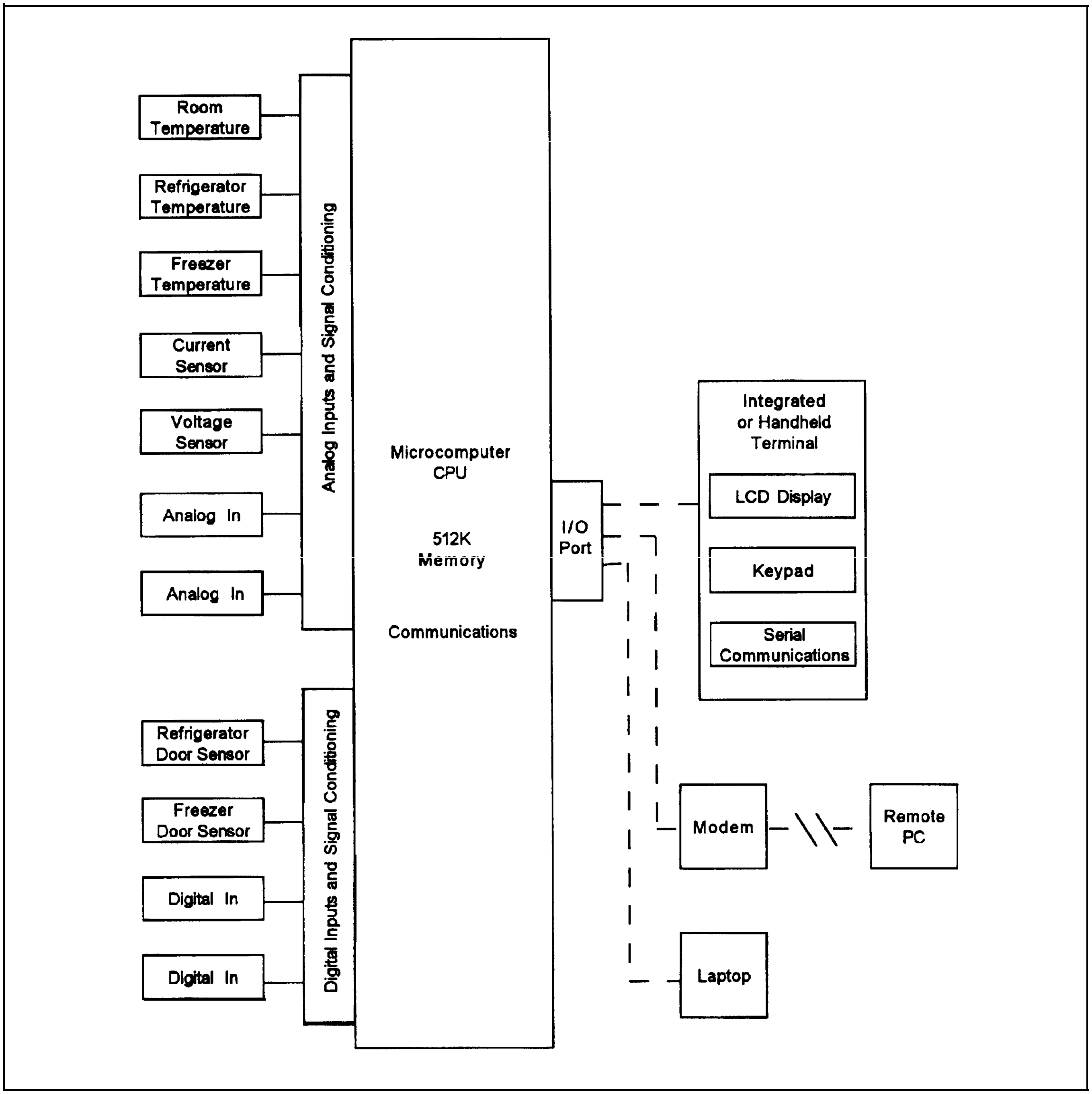

Figure 1. Block Diagram of Enhanced System. The door opening sensors (which sense light) are co-extensive with the temperature sensors.

through a hand held terminal-a small enclosure with a simple board, display, and custom key pad—the serial port of a laptop computer, or a modem. A single hand-held terminal may be used by a field auditor to handle any number of "smart" boxes. A second model includes the display and key pad on the main box.

As originally conceived, the enhanced system was designed specifically for short-term monitoring of refrigerators in the field. Accordingly, data gathering intervals were set at 15 minutes and memory was initially specified to provide 250 time series data records (TSDRs). However, members of the advisory committee pointed out that some users will need substantially longer monitoring periods—and that hourly data would be adequate. On the other hand, other users may be interested in finely tracking ice maker performance, for example, or estimating the effective R-value of the unit via short-term drift tests (see below, "Procedures for Measuring the Effective R-Value of Refrigerators".) Thus, taking data at intervals as short as one minute might be useful for these purposes. Accordingly, the data collection interval was set up to be user selectable to intervals of one, five, fifteen, thirty, and sixty minutes. In addition, the memory was enhanced to 512K so that over 15,000 time series data records (TSDRs) from all channels can be stored. This represents more than 20 months at 60 minute data collection intervals or over ten days at one minute data collection intervals.

Software. Three kinds of software are associated with the enhanced refrigerator data logger. Machine code contained in the data logger's central processor calibrates, controls, handles the basic functions of the data logger, and permits communication between the data logger and the hand-held terminal or a PC. Machine code processes the recorded data into a comma-delimited ASCII format.

The second kind of software handles host routines for the hand-held terminal and for PC applications. The PC host software allows an operator to communicate with the refrigerator monitoring system. It provides specialized routines for programming the data loggers, retrieving data, and processing data files. It also facilitates downloading files to the third level of software which consists of a macro-based routine written in a well-known spread sheet package. The third level of software enables data translations and the efficient production of graphs and a variety of quantitative analyses useful for a range of needs from simple auditing to research.

Table 1 outlines a sample of analyses possible using the data gathered with the refrigerator monitoring system.

Applications

The questions that could be addressed by this refrigerator monitoring system are almost limitless. Currently, application studies are being conducted on the following topics:

How does consumption vary with changing conditions of use, season, and related variables such as indoor air temperature and humidity?

How do field results vary with US DOE tests on the same model refrigerator?

What are the consequences of control settings, like the thermostat and anti-sweat switch?

What are the energy consequences of cleaning the coils?

What are the consequences of having a refrigerator in a confined area where heat from the compressor cycle builds up? What are the energy consequences of mechanical, passive ventilation, or active ventilation retrofits/changes? What are the costs and benefits of each?

Table 1. Representative Analyses for Monitored Data

Monitored Quantity	Analytical Uses
kWh energy consumption and kW demand (e.g., at 15 minute averages)	Average, standard deviation, and other measures of central tendency Load shapes (daily and seasonal) Maximum and minimum demand times of day or season Illustration of effects due to occupants, from food loading habits to control of kitchen temperature and humidity Regression and correlation analyses with other measured quantities
Internal and kitchen temperatures	Consumption as a function of T Comparisons with DOE ratings on the basis of **in situ** T
Door openings	Consumption as a function of door opening frequency and duration
Volume	Simple indices of performance: kWh consumption/adjusted cubic feet
Presence of convenience features	Comparative studies across different models

How does uncovered food affect refrigerator humidity? Defrost cycles? How do refrigerators affect the moisture content (as determined by weight before and after refrigeration) of uncovered food?

What is the incremental energy cost of ice making? What is the effect of incoming water temperature? What is the effect of various rates of harvesting ice? Are there interactive effects with other refrigerator functions which have energy consumption consequences? Can a useful coefficient of performance of the ice-making system be developed?

What is the incremental energy cost of cold water making? What is the effect of incoming water temperature? What is the effect of various rates of harvesting cold water? Are there interactive effects with other refrigerator functions which have energy consumption consequences? Can a useful coefficient of performance of the cold-water system be developed?

How does a sample SERP refrigerator perform compared to a small sample of ordinary refrigerators (pre 1991 standards) and 1993 standard refrigerators with similar features?

Procedures for Measuring the Effective R-Value of Refrigerators

A number of researchers have reported on the strong dependence of refrigerator performance on outside air temperature [Proctor (1994), Meier (1993)], which is presumed (in the absence of monitoring kitchen temperature) to be highly correlated with the temperature in the immediate environment of the refrigerator. This coheres with results reported by Parker (1992) where detailed, long-term multipoint monitoring (including kitchen temperature) of both an energy inefficient and an energy efficient refrigerator showed substantial increases in consumption with kitchen temperature.

These findings illuminate a key difficulty in monitoring refrigerators. It is desirable to monitor a refrigerator for a short period—on the order of 24 to 48 hours—and be able to draw good inferences about annual consumption. However, if the period of the monitoring is not representative of the average local temperature seen by the refrigerator over the year, very substantial errors can occur. To be sure, knowing that this is the case and building up a set of long-term records of various models of refrigerators may enable the creation of a data base of correction factors. However, another approach may be useful for this purpose as well as other objectives such as enhancing refrigerator designs in the first place.

The following experimental procedure reports on work in process for the case of refrigerators. It was inspired by measuring the time constant, the product of effective overall R value and thermal capacitance, RC of a dwelling both before and after a weatherization process (Kinney, 1987). As discussed in the chapter on refrigeration load in the *ASHRAE Handbook on Refrigeration Systems and Applications* (1990), the analysis of refrigerators can be usefully handled by the familiar equations of heat loss associated with space conditioning buildings.

The efficiency of a refrigerator is a function of how much energy is needed to maintain a steady-state difference between internal and surrounding temperatures. The physical properties of the refrigerator determine the quantity of energy required for a given temperature difference. The ratio of that quantity of energy to the energy expenditure of an active cooling system to maintain the given temperature difference is the efficiency of the refrigerator.

The steady-state energy required to cool the interior material of a refrigerator is transferred at the evaporator. A first-approximation model of this energy (Q_{evap}) is given as:

$$Q_{ss} = \frac{A \, \Delta T}{R}$$

where A is the area exposed to ambient air temperature, T is the temperature difference and R is the net R-value of the refrigerator. Heat is released cyclically from the condenser into the surroundings by an amount equal to that supplied to run the compressor in addition to Q_{evaP}. The coefficient of performance (COP) is defined as the ratio of the energy expended for cooling the load (Q_{evaP}) to the energy delivered to run the compressor ($Q_{compressor}$):

$$COP = \frac{Q_{evap}}{Q_{compressor}}$$

The measurement of A and T are straightforward, and $Q_{compressor}$ can be measured with the proper instrumentation (such as the system created by this project). The net R-value is not readily measured. One method for estimating the R-value is by way of a *drift test*, whereby a refrigerator is allowed to cool to a steady-state internal temperature, after which power is disconnected. The internal temperature of the refrigerator then 'drifts', or rises, to ambient room temperature.

Under ideal conditions, one would expect the temperature inside a refrigerator to rise exponentially as soon as external power is disconnected. This is the well-known passive, or natural, behavior of a thermal system. The exponential rise of refrigerator temperature towards ambient room temperature can be characterized quantitatively by the system time constant, which is the product of the net R-value and the equivalent thermal capacity. The thermal capacity of a system is analogous to electrical capacitance (mass can store and release thermal energy, and an electrical capacitor can store and release electrical energy). If C is the term for thermal capacity, then the time constant of a system of mass inside an insulating envelope is RC, which is expressed in units of time (seconds, minutes or hours).

All that can be determined from a drift test of an empty refrigerator is the value of its time constant. At least one additional test is required for deriving the R-value. Further information can be gathered by placing a mass with known thermal properties (e.g., a few gallons of water) inside the refrigerator and repeating the drift test procedure. A second time constant can then be estimated, based on a model of how the added mass interacts thermally with the refrigerator.

The challenge is to implement a set of circumstances such that the time constant can be derived from data obtained from drift tests. The assumptions given above for the estimation of R-value have to be checked for a given implementation. Models of thermal interaction have to be validated as well.

Conclusions

Refrigerators are interesting appliances in several senses. Their widespread use means that achieving high levels of efficiency can have substantial effects on residential electric bills and on the amount of power necessary to supply the grid. Second, there remain a number of elements of their performance in the field which are poorly understood. These range from the effects of local environmental conditions and user habits to the achievement (and measurement) of superior insulation and high system coefficients of performance. Careful analyses, made possible by customized electronic tools, hold promise for enabling consumers, conservation program planner/evaluators, and refrigerator designers to better understand refrigerator energy consumption and to make better decisions related to high-efficiency designs.

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