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ABSTRACT

The Lawrence Berkeley Laboratory, D.O.E., has developed the Energy Signature Monitor (ESM), an innovative data acquisition system which addresses the data acquisition and analysis requirements of test programs which involve monitoring of large samples of buildings. Information about the typical number of sensors and the accuracy requirements for such large monitoring projects was incorporated into the development of the ESM in order to meet the needs of most researchers without adding unnecessary and expensive features. The ESM hardware includes a microprocessor-controlled data acquisition program, 16 analog channels, two pulse-count channels, a RS232 computer interface, and a removable EPROM-based data storage module. In conjunction with the hardware a complete data management software package, written to operate on a personal computer, was developed to facilitate analysis of the recorded data. A total of 23 ESMs have been built to-date, all of which are being used in a field monitoring study currently being conducted by Lawrence Berkeley Laboratory. Technical support is being provided to two private-sector companies that are interested in marketing a commercial version of the ESM.

INTRODUCTION

There have been many studies in which researchers have needed to monitor a large sample of real buildings during an extended time period in order to accurately determine a particular operating characteristic, but were unable to proceed because of prohibitively high monitoring costs. A factor that is often overlooked is that the monitoring costs incurred during a field study include much more than just the data acquisition hardware cost. Major costs include the technical manpower required to install and maintain the equipment, retrieve the recorded data, and manage the recorded data at a central analysis station. A significant, and costly, time-investment by technical personnel is required to both install and maintain most commercially-available data acquisition equipment. Since very few hardware manufacturers provide any integrated software with their hardware, software must be developed to both operate the data acquisition and manage the large amount of data collected from a large monitoring project. The bottom line is that experience has repeatedly shown field monitoring projects to be very expensive to conduct.

The Energy Performance of Buildings Group at Lawrence Berkeley Laboratory (LBL) has addressed the data acquisition and analysis demands of large-scale monitoring projects with the development of the Energy Signature Monitor (ESM). The ESM was developed as an innovative data acquisition system that integrates measurement, data collection, and compilation and is designed to provide low-cost (approximately $2000 per unit), sophisticated data in a standardized format. Information about typical number of sensors and accuracy requirements for such large monitoring projects was incorporated into the development of the ESM in order to meet the needs of most researchers without adding unnecessary, and expensive, features. The ESM development philosophy was to minimize the need for technical personnel during normal operation by providing menu-driven software for both data acquisition and management, easy sensor connections by using standard modular telephone connectors, and integrated data storage and retrieval by using a built-in data module. The data module can record a month's worth of data before being easily replaced. The ESM can monitor total energy consumption (broken down by end-use), as well as related variables as diverse as temperature, lighting levels, indoor pollutant concentrations, office equipment loads, thermostat settings, and door openings.

Based on our field monitoring experience and conversations with other researchers, it is clear that large-scale monitoring projects typically require only a nominal number of sensors per test site, with less stringent sensor accuracy demands as compared to laboratory investigations. Within the commonly-used A (laboratory-grade investigations), B (general real-time field monitoring), and C (compilation of utility meter readings) monitoring classifications, the ESM is designed to operate as a class B data acquisition system.

The original ESM design has evolved to its present configuration based on considerable laboratory and field evaluation of a number of prototype units, all of which have been built at LBL. Six prototype units based on the original ESM design were assembled during 1983. Although the basic design philosophy worked well, evaluation of the original prototypes revealed the need for some major modifications to simplify maintenance and increase system versatility. There have been 23 second-generation ESMs built, all of which are being used as part of a field-monitoring study currently being conducted by Lawrence Berkeley Laboratory.

DATA ACQUISITION HARDWARE DESCRIPTION

The ESM is a microprocessor-based data acquisition system designed for long-term unattended operation. Data acquisition and communication are controlled by a 6502 central processing unit (CPU) microprocessor with 10K bytes of program memory contained in erasable programmable read-only memory (EPROM) and 2K bytes of random-access memory (RAM) for intermediate data storage.

There are two pulse-count input channels, which count the number of TTL-level voltage signals received, and sixteen analog-input channels, which will accept a sensor output range of -4.095 to +4.095 volts. A 12-bit analog-to-digital converter processes the analog input channels for an effective resolution of 1 millivolt. Each of the analog-channel inputs can be recorded either as an analog millivolt value or as a digital ("ON/OFF") value. The "ON" digital signal is defined as a sensor value that is greater than a user-defined threshold millivolt value.

The data acquisition program, which is written in assembly language, monitors the pulse-count channels as interrupts and scans all the analog and digital channels either every fifteen seconds, or once per record interval, depending on a user selected recording option. The total number of pulses for the pulse count channel, the total number of "ON" scans for each digital channel, and the average millivolt value for each analog channel are recorded in the data module at the end of each record interval. No software signal conditioning is built into the ESM data acquisition program. The user may select a record interval from 1 minute to 5.5 days. Also, he may select either to scan the sensors every 15 seconds and average the data for the record interval, or take only one reading of the sensors per record interval.

Data is stored in 24K bytes of EPROM memory, which is contained on a removable 3.5x5-inch data module for convenient physical transfer to a central data analysis station. The data module can store up to 29 days of hourly averages from a typical set of eighteen sensors, which consists of two pulse-count sensors, eight analog, and eight digital channels. The use of less channels for a monitoring project would mean a proportionally longer data-recording time per data module.

The data module contains not only the time-sequential data for each of the input channels used, but also critical information about the experiment which will be required to manage and analyze the data. When the ESM is first set up for a monitoring project the user must input information about the test name, location of the monitored site, type of sensors used, codes for what is actually being monitored, etc. All of this information is automatically recorded in the first part of each data module before any data is recorded. The field technicians do not have to write any of this information in a log book, and since the information is always available with the data there is little chance of misinterpreting the data. If a new data module is inserted in an ESM, the data acquisition program will check to make sure that it is either fully erased, or that any existing information in the data module is compatible with the test configuration in the ESM RAM memory.

During normal operation the ESM is line-powered, but battery backup power is supplied for RAM memory, clock, and short-term data acquisition operation. The ESM will continue normal data acquisition operation during a line-power failure until the end of the next record interval, at which time the ESM will go into a "sleep" mode. The "sleep" mode, which conserves battery power, can be continued for more than six days. The clock remains operational during the power failure, and the ESM will automatically continue normal operation when line power is restored.

A menu-driven program is used by the ESM to communicate with a terminal through a standard RS-232 interface. The communication program is written so the operator does not need extensive knowledge of the program options and input requirements. Although a computer terminal is used to communicate with the ESM during setup at a test site, it is not required during operation of the experiment. An external telephone modem, connected via the RS-232 interface, can be used to check on the test site during the study.

An ESM identical to the field units is used to transfer the data recorded in the data modules to a microcomputer at a central data analysis station. Spare ESMs would be required for a large monitoring project, one of which could be used to transfer data recorded on the data modules to a microcomputer. A microcomputer-based data management and analysis program is used to process the data into a useful form.

The original ESM design, which was developed in 1982, has evolved to its present configuration based on two years of laboratory and field evaluation of a number of prototype units, all of which have been built at Lawrence Berkeley Laboratory. The current ESM design, along with a standard computer terminal, is shown in Figure 1. The computer terminal, which could be replaced by a much smaller portable terminal (such as the Texas Instruments Silent 700 or Radio Shack TRS-80 Model 100) is used to communicate with the ESM during setup at a test site and is not required during operation of the test, thus reducing site equipment requirements. Since the ESM was designed for long-term unattended operation, there is no need for a built-in display (except for the front panel's four status-indicator lights), a printer, or a keyboard. A removable data module and three ESM operation control switches are located behind the front panel access door. The rear panel has connectors for the sensors, power supplies, and a standard RS-232 connector for communication with a terminal or another computer.

DATA MANAGEMENT SOFTWARE

The ESM data management software, designed to be used on a personal computer at the central data processing station, in conjunction with the data acquisition hardware forms an integrated system that will allow a user to monitor a large number of sites, perform automatic data management on the recorded values, and process the aggregate data into a usable form with a minimum of time and expense. The data management software was written to operate with both CP/M and MS-DOS computer operating systems, which covers most of the commonly-used personal computers. The data recorded on the ESM data module includes information as to the test site identity and the sensors used so that time-consuming cross-referencing with logbooks and installation reports can be avoided. Transformation of the raw data recorded by the ESM to physical units and management of the data from multiple sites is handled automatically by the data management software. Both the data acquisition and data management software are menu-driven to facilitate their ease-of-use with non-technical personnel. The recorded data can be displayed as individual readings or averages, transferred to other computer programs, or plotted to analyze trends.

It is important to realize that the availability of data management software compatible with the data acquisition hardware is a major cost savings for the monitoring project. The ESM was designed to be marketed with the data management software as an integral part of the data acquisition system.

SENSORS

To accommodate the two most common sensor types used by building energy researchers, air temperature and electrical power, specific sensors were incorporated into the ESM design. The Analog Devices AD590 temperature transducer was used because of its good accuracy and linearity, insensitivity to supply voltage (4 to 30 volts), high output sensitivity (2.732 volt at 0 deg C, with 10 mV/deg C sensitivity), and low cost ($5-15). The ESM supplies +15 volts at the sensor's modular telephone connector to power the temperature transducer. Any other sensor can use this supply voltage as well. Field comparisons of ESM-recorded average air temperatures have shown the ESM to be within 0.5 deg C of air temperatures recorded at the same locations by a class A data acquisition system. The disadvantages of the AD590 temperature transducers are that temperature values are limited to 150 deg C, and the sensors must be protected from direct contact with moisture.

Commercial electrical power sensors that fully account for power factor effects cost $200-600, which was deemed excessive for the ESM. A simple, inexpensive ($50) clamp-on wattmeter was developed as part of the ESM, with electrical signal conditioning for eight sensors built into the ESM in order to reduce the cost of multiple electrical power sensors at one site. Unfortunately, field experience has shown that the accuracy is not adequate for most applications. An improved version of the clamp-on wattmeter has been designed but not been adequately tested at this time.

A photocell has been successfully used with the ESM to monitor gas fired water heater and furnace operation. The photocell simply measures the light intensity in the burner compartment to detect if the burner is on or off. For this application the user selects a digital recording option for an analog input channel. The ESM interprets the sensor value to be either above a user set threshold value, "ON", or below the threshold value, "OFF", and records the total number of "ON" scans during a recording interval.

It is not practical to develop specific ESM interfaces for all of the many sensors that are used by researchers. But the ESM will accept any sensor that outputs a signal between -4.095 and +4.095 volts, which means that most sensors need minimal signal conditioning in order to be compatible with the ESM. The pulse-count channels accept standard TTL-level voltages.

In order to simplify the field hardware of the ESM, a design compromise was to include all software sensor signal conditioning in the microcomputer-based data management program instead of the ESM. All sensor outputs are recorded by the ESM as voltage levels; there is no built-in linearization for non-linear sensor outputs. This means that non-linear sensor outputs must be linearized before being read by the ESM if average values are to be recorded.

FIELD EQUIPMENT INSTALLATION EXPERIENCE

One of the major non-hardware costs incurred in a monitoring project listed earlier was that of installation and maintenance. By providing simple menu-driven software and very easy-to-use and foolproof standard telephone connectors for all sensor connections the ESM design attempts to minimize the actual time required to install the hardware. But, depending on the monitoring project complexity, installation may still be a major expense. It is also evident that even though the installation personnel may be non-technical with regard to the ESM, they must be fully qualified with regard to sensor installation or the results of the monitoring project may be compromised. Three case studies of field equipment installation experiences with the ESM are discussed below, but they are typical of most data acquisition systems. The first case study was a very simple monitoring project close to LBL that was conducted by LBL personnel very familiar with the ESM. The second and third case studies were conducted 700 miles from LBL by field personnel who were under contract to LBL, and who had received a one-week training session at LBL before beginning the field study.

The first case study was part of a LBL-conducted ESM field evaluation in an unoccupied housing unit that was part of a public housing research project. The housing unit was concurrently monitored with a second, class A, microprocessor-based data acquisition system to provide a baseline for comparison. The ESM installation had a total of sixteen sensors, which included inside, outside, and attic dry-bulb and dew-point temperatures, weather conditions, and electric power use. Hardware installation and setup required approximately five manhours, although had the housing unit been occupied the installation time would have been a couple hours longer because of the need to assure that all sensor wiring was neatly secured where it would not be accidentally disturbed by the occupants.

Installation of ESMs in three additional occupied housing units in the same housing project required only 3.0 manhours each due to fewer and simpler sensor wiring configurations (five sensors per site, all inside). In all cases the ESMs were simply located on a closet shelf, which hid the wiring from the occupants while allowing convenient access for the LBL researchers. Removal of the ESMs from the four housing units required only one manhour each. There was a minimum of interference with the occupants during the field evaluation since LBL researchers were in the units only three times during the study; once during installation, once for data module retrieval, and once for removal of the equipment. There were no occupant complaints about the equipment or sensor wiring.

The second case study involved the monitoring of eight occupied homes in the Portland, Oregon area. This project required the installation of approximately fourteen ESM-monitored sensors per site, which included air temperature, dew-point temperature, clamp-on wattmeters, photocells for monitoring furnace operation, a real-time radon monitor, and a weather tower. In addition there were stand-alone particulate samplers and a number of passive air quality samplers. Since the study was to be conducted over a five-month period the hardware had to be secured from accidental occupant disturbances. Installation and maintenance was conducted by a LBL-trained field contractor. Installation required approximately 25 manhours per site. Because of some equipment problems some of the sites required over 40 manhours.

In addition, there were weekly visits to each site to recover the passive air samplers and ESM data modules and perform regular maintenance. The weekly visits required two to three hours per site. By the end of the study some of the occupants resented the investigators weekly intrusions. An average of five manhours was required for equipment removal.

The third case study involves the ongoing short-term (two weeks) monitoring of 50 occupied homes at two sites in Washington. This project required installation of sensors very similar to case two described above. A log has been maintained by one of the field contractors to give an accurate appraisal of installation time requirements. For the first 15 sites, which includes both simple and complex installations, the installation times varied from a low of 14 manhours to a high of 48 manhours, with an average of 29 manhours. Most of the low installation time sites were due to unusually easy access and no weather tower installation. Removal times have averaged five manhours.

The reason for discussing these three case studies is to emphasize the fact that field monitoring scheduling and cost estimates must include appropriate field installation and maintenance estimates. Historically researchers have greatly underestimated the final cost of field monitoring projects.

ESM TECHNOLOGY TRANSFER

There have been 23 ESMs built at LBL as part of a design evaluation and for use in two research projects, but there are no plans for LBL to provide ESMs to outside researchers. The process of technology transfer of the ESM design to a private sector company willing to market a commercial version of the ESM was initiated during 1984. Based on an information package mailing there are two private sector companies which are currently working toward development of a commercial version of the ESM. The companies have been willing to learn from the field experience of the LBL prototypes and design advanced features into the production units before they go to market. However, both companies underestimated the development effort required to transform the LBL prototype design into a viable commercial product. There is a very large step between a laboratory prototype that works under the guidance of familiar technical personnel and a commercial product that must survive the real world. A commercial version of the ESM will not be available before mid-1985. The estimated retail cost of the commercial version of the ESM is approximately $2000.

LBL is continuing to provide limited technical design support to the private sector companies in order to influence the introduction of the design modifications, which were developed as a result of the LBL field evaluations, in the commercial ESM version.

SUMMARY

The Energy Signature Monitor has been developed by LBL as an attempt to simplify and reduce the cost of large-scale, class B, field monitoring projects. An integrate data management software package, designed to operate on a personal computer, was developed along with the hardware to provide a complete system for going from field-recorded data to final data analysis. Both the data acquisition and data management software are menu-driven to minimize operator training requirements. Although standard temperature and clamp-on wattmeters were developed for the ESM, most other sensors could be used with the ESM with a minimum of external signal conditioning.

Comparisons of ESM recorded data with a class A data acquisition system showed that the ESM, although not as versatile as the more sophisticated class A system, is just as accurate when recording hourly averages of environmental parameters such as temperatures or voltage outputs from other sensors. More accurate electric power sensing from the built-in clamp-on wattmeter signal conditioning circuit must await development of an improved clamp-on wattmeter design.

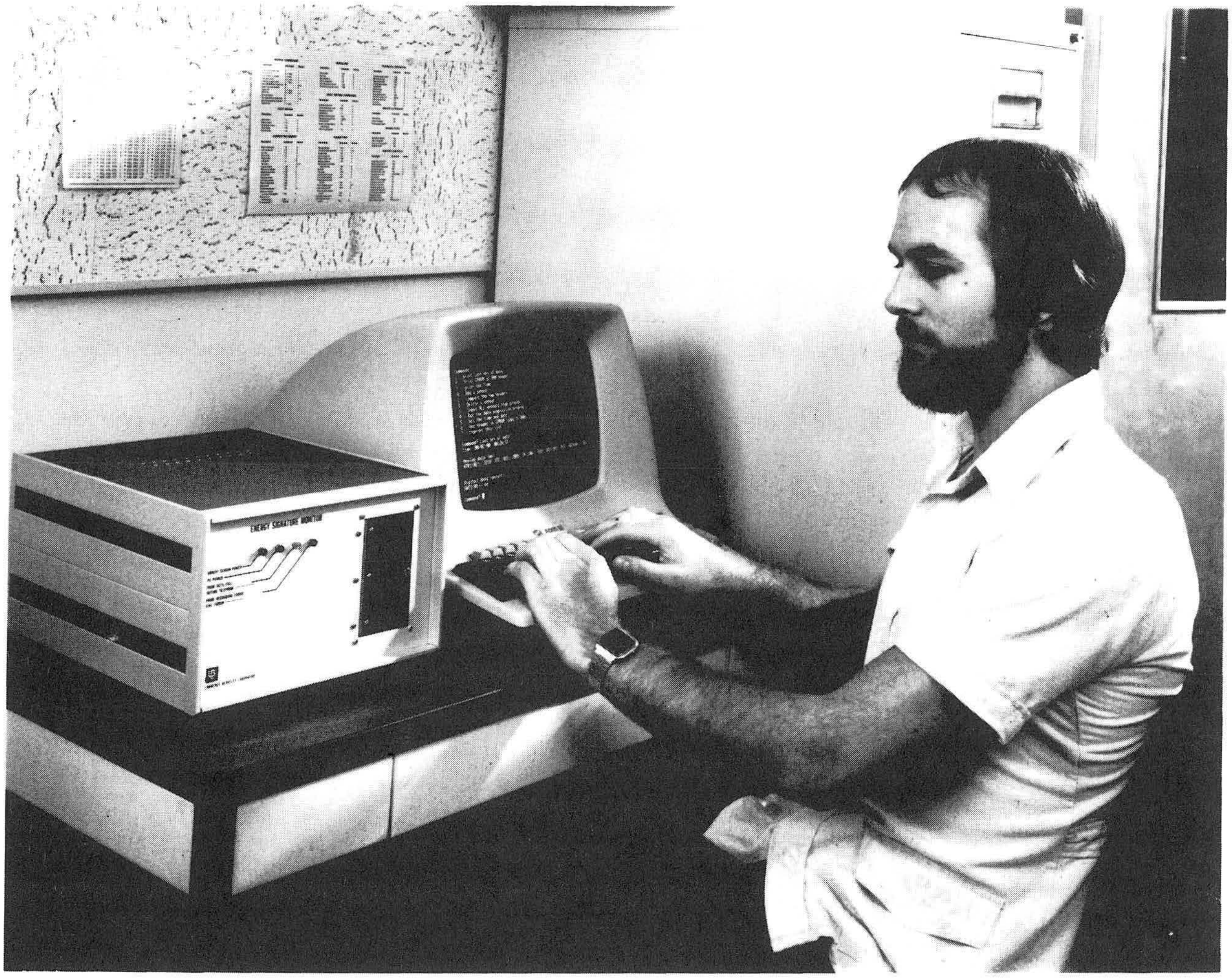
Although there have been 23 ESMs built at LBL as part of the design evaluation and for use in two research projects, there are no plans for LBL to provide ESMs to outside researchers. LBL is continuing to provide limited technical design support to the private sector companies in order to influence the introduction of design modifications in the commercial ESM versions.

ACKNOWLEDGMENT

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

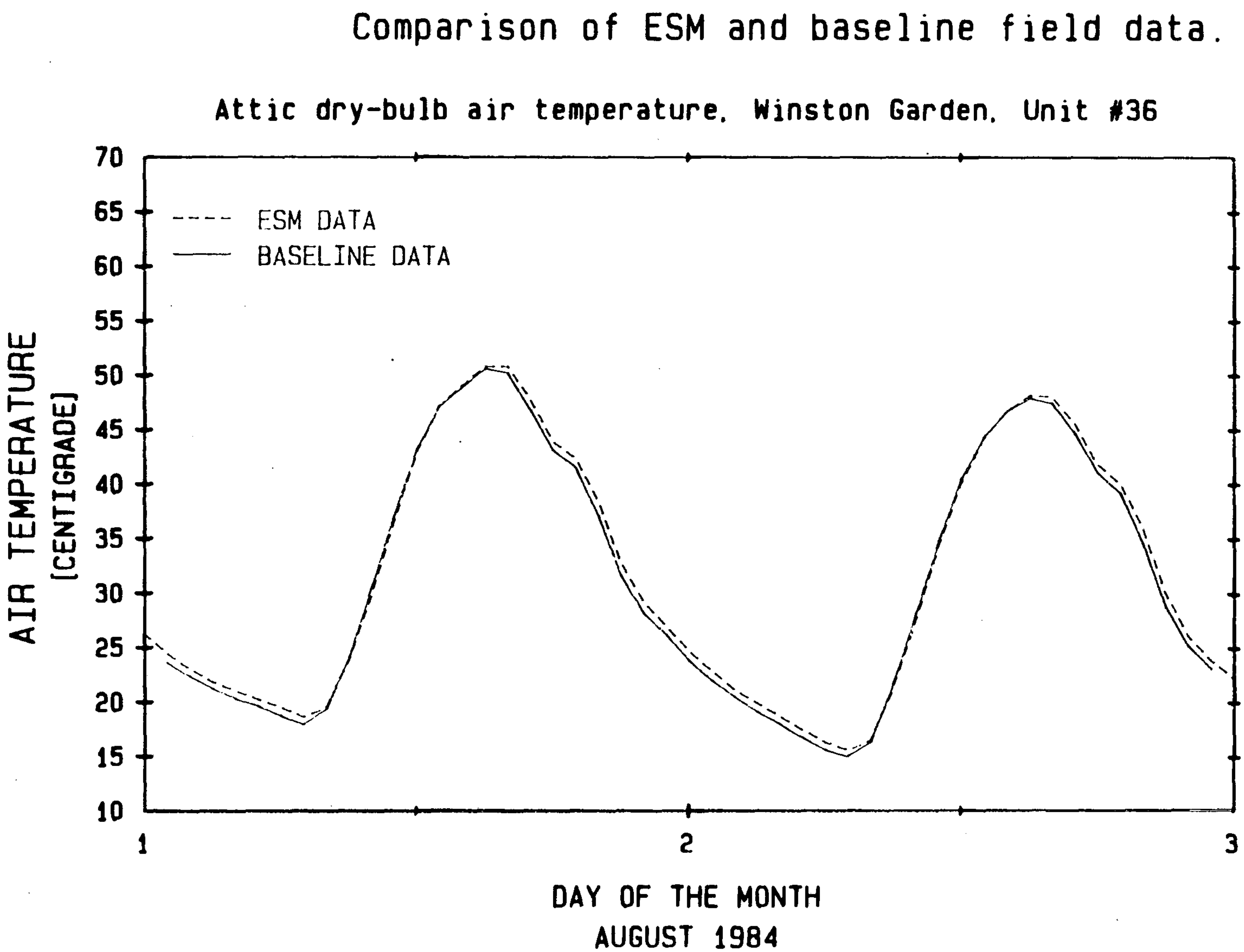
Table 1. List of ESM specifications.

Processor	Rockwell or Synertek 6502, 8-bit.
Program Memory	10K bytes of EPROM, 2K bytes of RAM, data acquisition program written in assembly language.
Communications	Built in RS232 interface, switch selectable to 300, 1200, or 9600 baud.
Analog to Digital Converter	Intersil 7109, 12-bit, dual-slope integrating, -4.095 to +4.095-volt input, 1-millivolt resolution.
Sensors Channels	16-analog channels, all of which can be recorded as millivolt values or digital "ON"/"OFF" values based on a user-set threshold.
	Two pulse-count channels, optically isolated, TTL (0-5 volts) pulses, record a maximum of 65,535 counts.
Data Storage	24K bytes of EPROM on a removable data module (3.5 x 5-inch PC card), capable of recording one month's worth of data from a typical full compliment of channels recorded hourly (13,800 points), can be both recorded and read by a standard ESM.
Battery Backup	One 12-volt gel-cell (lead acid) battery which provides one hour of full operation and one week operation of clock and internal RAM memory.
Power Source	One 24-volt plug-in wall transformer and one internal transformer providing +12 and -12 volts.
Data Management Program	Written in Pascal to operate on CP/M and MS-DOS micro-computer operating systems, requires a minimum of 64K bytes RAM, data management limited by available disk memory.



CBB 830-8721

Figure 1. The Energy Signature Monitor shown connected to a video terminal.



XBL 851-1052

Figure 2. A comparison of ESM and baseline field data.

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