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DISTRIBUTED AGAINST CENTRALIZED DATA ACQUISITION SYSTEMS

Eduardo Figueroa K.
Monitoring Center for Energy Research
Royal Institute of Technology
S-100 44 Stockholm
SWEDEN

ABSTRACT

Microprocessor technology have been making available compact and advanced BEMS and data acquisition systems to modern building operation technologies. As a consequence, BEMS (incluiding both control, regulation, data acquisition and monitoring) becomes either centralized or distributed. The essential features of both techniques are reviewed and analyzed in terms of the needs of Demonstrated Energy Projects. The impact of microprocessors techniques in data acquisition and emerging sensor technology are discussed in terms modern needs and possibilities.

INTRODUCTION

Historically, building data acquisition and management began with the first operator who had direct access to the dwellings significant HVAC operating parameters. He could measure and log relevant values, analyze the acquired data, and manually adjust functions to optimize performances. Since both data acquisition, control and management were dependent on the operator abilities rather than on the system, the system can be thought as being non-intelligent.

As measuring technologies develops, systems became available that allows for a growing degree of automation. Development bring us today to the use of sophisticated intelligent microprocessor controllers that not only perform data acquisition but even control building operation and optimize performance.

This impressive technological advancement have been tacking place just during the last decades. Digital techniques provide with advanced integrated control, automation and data acquisition systems that allows for sophisticated global building management systems. Among other features, microprocessor based systems integrate the same sensors to provide monitoring, control and management, optimizing HVAC building performances and lowering total costs.

The structure of a computerized building automation, data acquisition and control system takes different forms depending on where and how the computer intelligence is being allocated.

Initial non-intelligent, passive measuring systems that relies on operator ability to perform, have been substituted by first centralized and more recently by distributed data acquisition systems. The complexity of systems experienced a development that have been passing through different stages, among them it can be recognized the following systems:

- Manual data registration and man-made controls
- Simple centralized data acquisition
- Centralized data acquisition and control
- Global energy management systems
- Hierarchical data management and control
- Completely distributed **non-host** systems

At present we are facing a rapidly growing development that brings to buildings control and performance optimization, an enormous capability. Therefore, the aim of the present work is to summarize the most relevant features of modern BEMS as a data acquisition and to point out some needs of coordination and system specification.

CENTRALIZED SYSTEMS

Centralized energy management and monitoring systems basically comprise a single **central station**, where all the system intelligence is concentrated. This is connected in turn, through a network of signal transmission cables, to the sensors and actuators required by the system.

These systems are normally based upon a micro- or mini-computer control station. Additional components in a typical monitoring system are a integrated DVM coupled to a scanner for analog signals, a multichannel counter system for pulse counting, a real-time clock, a watch-dog as a controlled auto-start self-safe system (e.g. power failure, etc), monitors, printers, plotters, memory units (disk, tapes, etc), etc. They are normally allocated as a complete system within the same building being monitored and controlled. The dedicated system can also be reached through modem communication from other computers. Fig. 1. gives a schematic description of a centralized system.

Centralized BEMS can be thought as being a monitoring equipment that has been implemented to give output control signals upon intelligent decisions made on the basis of measured values. That demands a significant processing capability to perform decision selections upon pre-established patterns of system regulation. Consequently, software requirements are very high for a reliable and secure energy management procedure.

Large building complex with centralized energy monitoring, control and regulation systems (BEMS) were developed around mini-computers (e.g. PDP-11, HP-1000, micro-VAX and alike). However, the lower cost of mini- and more recently micro-processors technology has extended the range of costeffective installations to smaller buildings. The improvements of microprocessor-based system capabilities has further displaced the mini-computer system.

Centralized EM and monitoring systems have, among other features, the following characteristics:

- The soft- and hardware available is known as a well developed and established technology.

- The systems available are products from large companies that can afford the expenses of system development.

- As a consequence of the systems being developed by large organizations, they are normally associated with a good back-up from suppliers.

- Operation depends on a single CPU.

- A significant amount of software is available in the market, but systems are less user-friendly.

- System documentation tend to be focused on the operation of the micro-computer rather than on the energy management and monitoring needs.

- In multi-tasking operating modes, systems can be implemented to perform additional tasks such as database management and data analysis.

- Centralized EM systems are associated with a very high initial outlay. However, once the central unit is installed, incremental extension expenses are comparatively low. (Typical initial investment range US$ 50.000 to 80.000).

- High investment cost in the wiring network for signals transmission. The network extension demands skilled installation, documentation, etc, while reliability, vulnerability to EMI, etc, grows.

Those features made Centralized EM and monitoring systems more suited for large buildings and sites such as:

- Industrial sites with large amount of occupants.

- Large public buildings such as railway stations, airport terminals, hospitals, etc.

- Office buildings, e.g. banks, governmental administration buildings, large schools, etc.

From the point of view of Energy Efficiency Demonstration Projects, there are a few questions that calls upon some attention. In the first place, it is quite clear that if Centralized BEMS systems are used in Demonstration Projects, the needs of a separated monitoring system involvement in large buildings must be obviated. However, it should be needed a careful system specification to assure that measurements for studies and evaluation are comprised in the BEMS system.
Although, in general large BEMS installations are often not just energy management systems but rather **"building automation systems"**, they can still accomplish extensive monitoring, providing proper software implementation.

Multitasking along with advanced data communication, will allow for data transference to other systems for evaluation without interference with ongoing control and automation. Also sensors specifications and measurement strategies should be required.

Since large **"Building Automation Systems"** normally include non-energy related functions such as lift controls, theft and burglary security alarms, fire security systems, etc, it would be necessary a careful evaluation of the central computer capability for even comprising data acquisition. However, in most of the cases, large building systems will normally even cope with the accomplishment of data acquisition and file management without interfering with the normal BEMS functions.

Centralized BEMS systems are currently intended to assist even the general management of large buildings, therefore, they will often have paybacks derived as much from manpower saving as from energy savings. Software implementations to account for data acquisition should be a rather easy task to accomplish, and therefore as a complementary investment should be rather low.

The needs for monitoring, as complementary task of **Centralized** BEMS systems in Demonstrated Energy Efficiency projects will thus demand the following:

- Careful formulation of data acquisition procedures.
- Careful specification of file formatting.
- Multitasking operational system specification.
- Careful specification of data transference to others than the central computer system for evaluation.
- Specification of backup and file management procedures.

- Security procedures for the generated energy database.
- Elaborated routines for regular reports of energy performance of the building.
- Thoroughly elaborated documentation of system, sensors, software, procedures, operational modes, etc.

DISTRIBUTED SYSTEMS

Distributed Intelligence Systems, in contrast to centralized systems, comprise a series of local microprocessor based substations or systems. Those substation can be implemented to different degrees of performance making them able to control parts of functions, devices, building services, etc. See Fig. 2.

Each intelligent sub-system comprise a full range of input/ output facilities (analog input, pulse counter channels, internal clock, digital event registration, conditional scanning controllers, A/D outputs, etc). Among other typical features, they are compact, operate at low energy rates, can normally be battery operated or battery powered to hold memory, etc. Currently, they are addressable and can be interfaced (normally RS232/RS485) for data communication. Data transference and collection can thus be sequentially requested.

The distributed BEMS system can be either local or remote, comprise one single building or groups of geographically distant buildings linked to a central supervisor unit. A group of distributed subsystems can be interconnected by databus standards (RS232/RS485), LAN or telephone network, into a monitoring system implemented with peripherals and software to allow for supervisory management functions.

Furthermore, a network based distributed BEMS systems will enable active intercommunication between the subsystems. LAN's greatly increases the operational flexibility where intercommunication allows sophisticated control strategies to be operated. Additionally, in LAN's, several control station levels can coexist. Thus, the operational status of the building can be monitored either at a central computer facility, with output peripherals, or at field-mounted or portable monitoring units. See Fig. 3.

Distributed intelligence EM systems include the following characteristics:

- Distributed intelligence systems are inherently more flexible than centralized systems.

- Distributed systems can be operational as a single small system at a initial stage. Subsequent completion of the system can be adequate to the actual needs and complexi-

ty of the dwellings, the building construction progress, etc, ending as an integrated final configuration.
- Distributed systems can cover a wider range of building and energy systems.

- The operational function of each unit in the distributed system is not dependent on the central station. A failure of one distributed units or the central monitoring, will not affect the function of the other units.

- Consequently, reliability of Distributed BEMS and monitoring is higher that in Centralized systems.

- Very low initial and total outlay per unit. (Investment demands per unit in a distributed system is about US$ 1.000 - 5.000).

- Since distributed system can be placed closer to the sensors and actuators, wiring expenses are low and interference problems are reduced.

- Groups of geographically dispersed buildings can be linked to a central station through public telephone networks.

- The system operation do not depend on the central monitoring station. Upon failure of the central monitoring or in non connected state, the sub-stations will continue to operate normally.

- Advanced used-friendly software is available in the market. The operation of system is becoming less dependent on trained manpower.

Distributed systems can be applied either to single houses or to complex buildings, even to groups of geographically dispersed buildings. Additionally, the technique provide a wide opportunity for advanced and effective technical solutions of monitoring and BEMS, despite of being rather new.

COMMON FEATURES OF DISTRIBUTED AND CENTRALIZED SYSTEMS

It is necessary to stress the fact that both centralized and distributed BEMS have been mainly developed for the needs of control and regulation. The data acquisition they may include, it is frequently intended for simple energy consumption statistic and for billing procedures.

For Demonstrated Energy Projects and for research purposes, this information is by far insufficient. However, the computer capacity normally installed in BEMS system can be used for those goals, providing thoroughly coordination at early stages of the project.

The possibilities of centralized system for the accomplishment of extensive data acquisition are generally very good. In distributed systems however, the extension of the programed functions to even comprise data acquisition may be more complicated. Nevertheless, in both cases it is clearly affordable to complete the systems with extensive data acquisition. Careful system specification is therefore highly necessary for the proper accomplishment of the tasks.

Development is going ahead at incredible speed, new products are such that microprocessors can now be found at the sensors or actuators it self.

In the case of actuators, however, a microprocesor will reduce the compexity of the software requiremets at the central or distributed intelligence, allowing each actuator to operate on a standalone basis and increasing the speed of the system reaction.

Occasionally, the unrestricted use of microprocessors in sensors can be quite a problem. We can consider modern devices that integrate liquid flowmeters, temperature of incoming and outgoing liquid, their difference, max- and min-values over the last hour, volumetric flow rate, the calculated effect and energy and the run-time of the flow meter. Parameter can be displayed or accessed through serial interface.

In those systems it is not given the information about the algorithm used for the calculation of density and specific heat products of water. Additionally, they could be end up in systems where the liquids are other than water (e.g. ethylene glycol + water).

It should be noticed that the needs of careful documentation and system specifications are mandatory for reliable and successful data acquisition projects. Particularly, calculated values generated while performing data acquisition, demands very rigorous planing.

Other point to be noticed is the fact that simple distributed systems do not have the intelligence for the performance of calculated variables wile measuring; not either the capability of performing data acquisition conditioned to the status of nominated input channels.

CONCLUSIONS

Data acquisition and monitoring as request in Demonstrated Energy Projects is being affected by the growing availability introduction of microprocessor based systems. In general, data acquisition should be possible of integration in planed

BEMS installations, however a careful system specification will be a mandatory request in order to attain proper performance.
The absence of standards or patterns of procedures in these matters call upon the need of a working group, at least at national level, with the task of studying and elaborating a basic document that can help the planing and specification of both BEMS and combined BEMS and data acquisition systems.

Furthermore, as development enrich the functionality of available products with microprocessors based controls and functions, a need for careful specification of those devices is becoming urgent.

While the issue of whether centralized or distributed system is the most convenient solution will remain as an economical issue, the technical aspect related to system configuration and specification urgently need to be reviewed.

These mater have been a subject of working comities and studying groups in several countries. Some documents are already available at national levels. The Monitoring Center for Energy Research at the Royal Institute of Technology have been considering these mater since a wile and it is our opinion that a document that regulate the specification of monitoring and data acquisition systems, particularly as related to BEMS systems is becoming a sensitive need.

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FIGURES

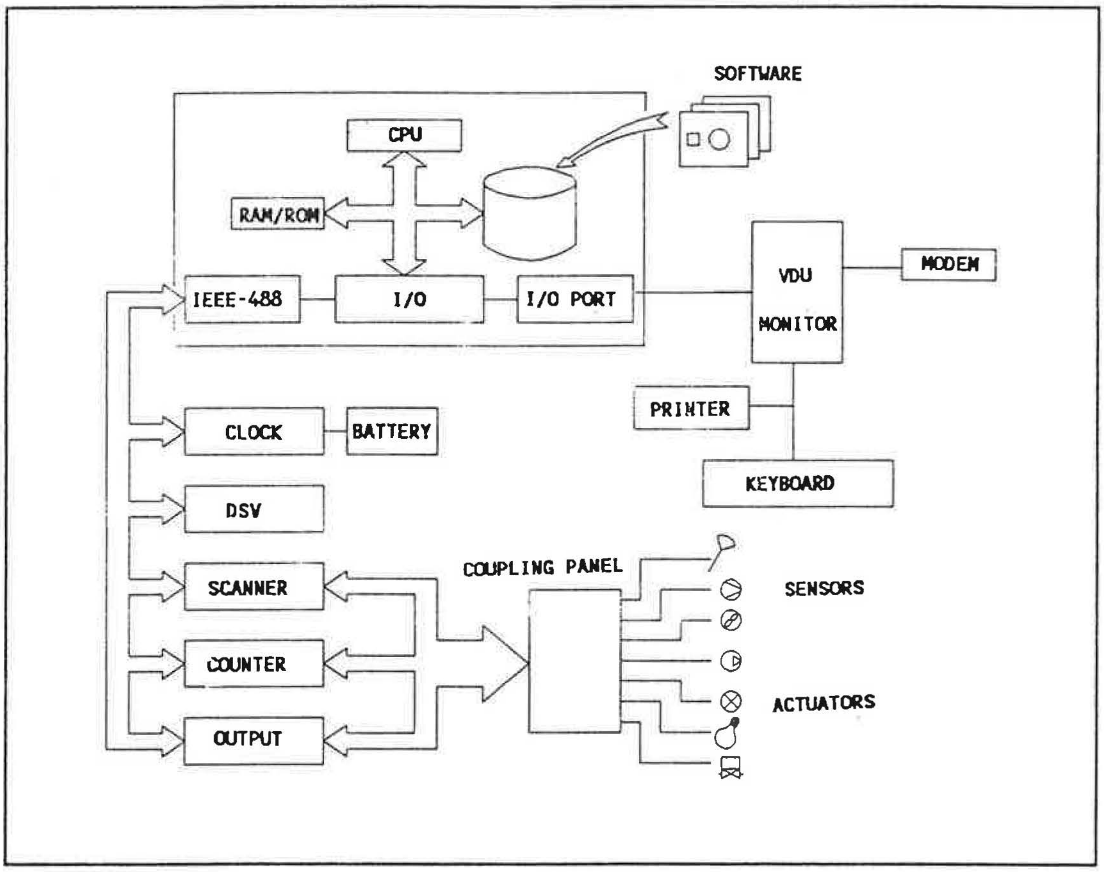

Fig. 1.: Typical basic configuration of a Centralized Monitoring and Data Acquisition system.

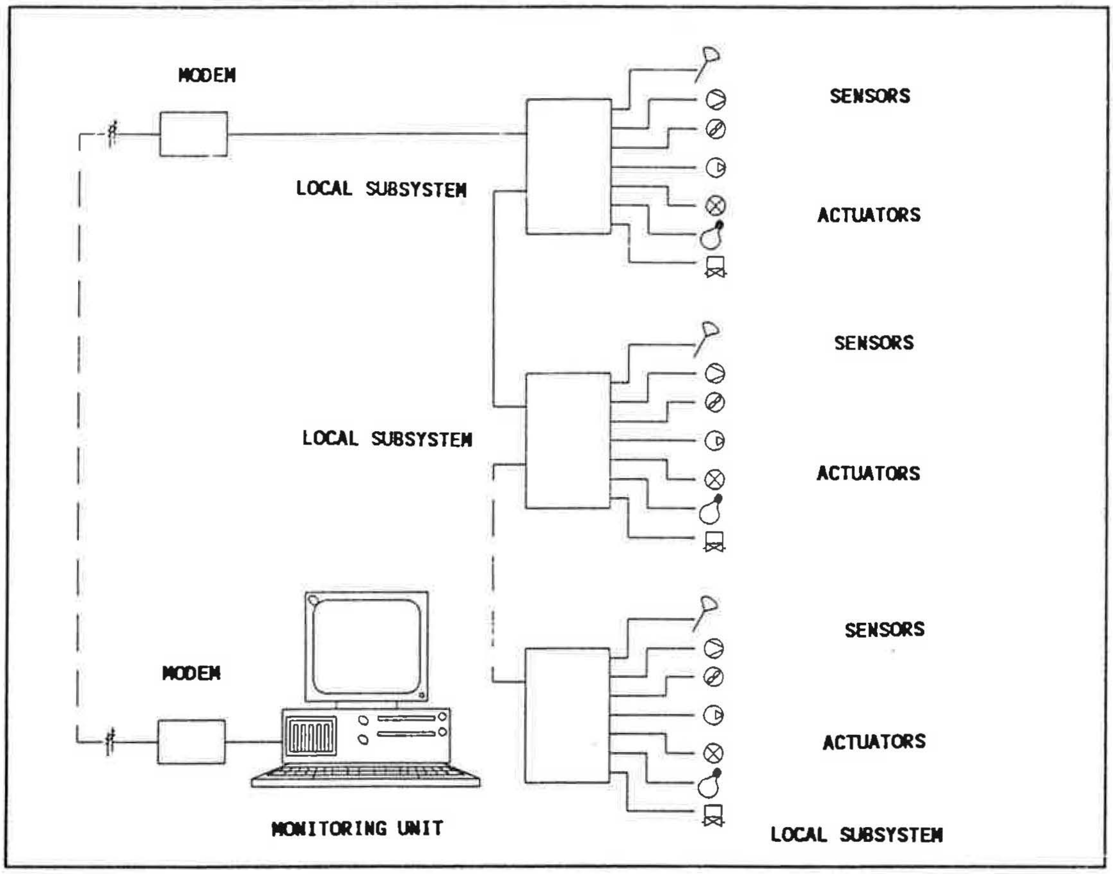

Fig.2.: Schematic diagram showing a typical Distributed Monitoring and Data Acquisition system. Notice that the monitoring unit, namely the computer does not need to be continuously coupled to the various addressable subsystems.

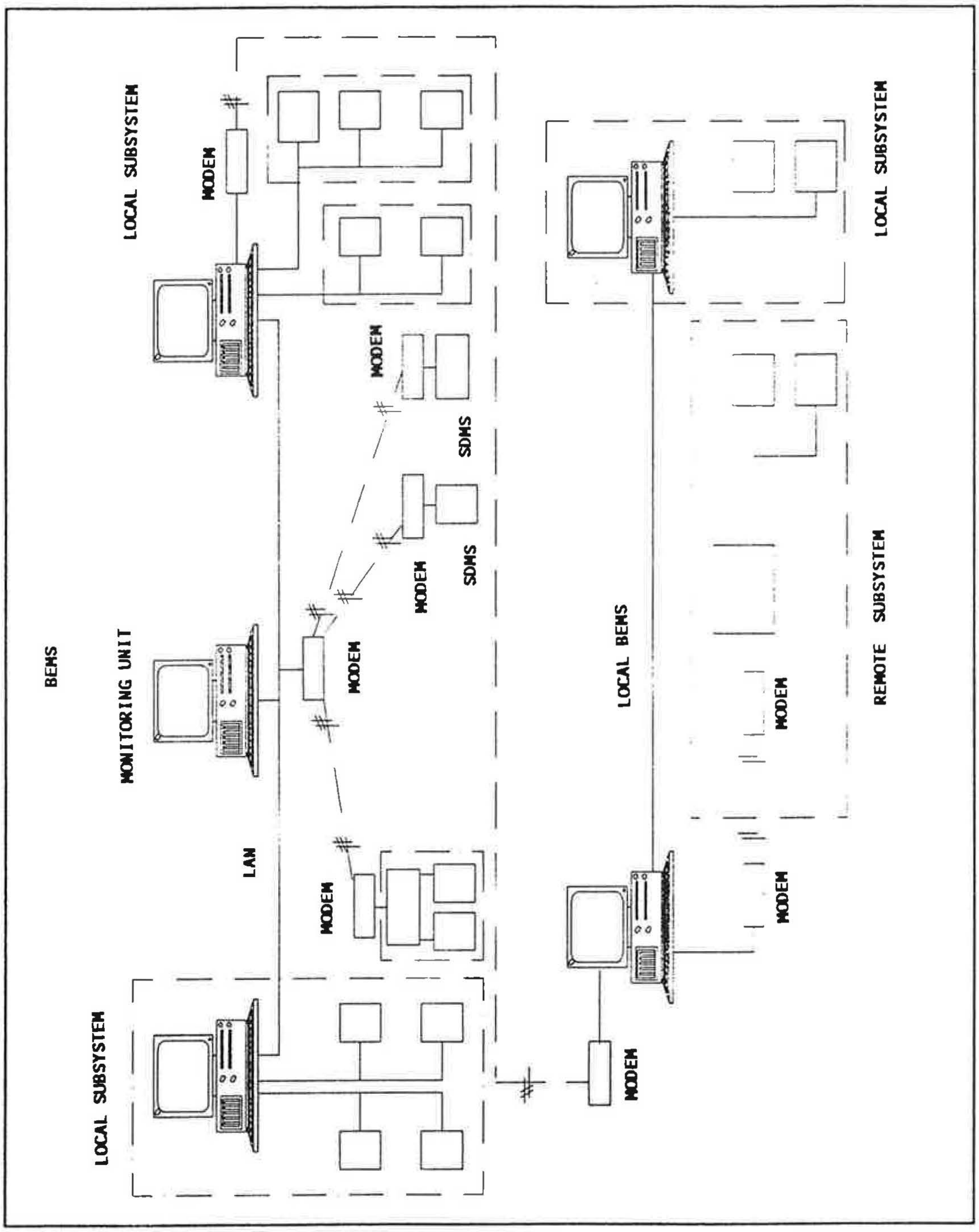

Fig.3.: A schematic representation of an extended Hierarchical Distributed system. The system combine both LAN system at local areas and remote stations, as well as dedicated and distributed intelligence.

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COMPUTER MONITORING AND CONTROL OF THE ADVANCED HOUSE

Nathan B. Sheaff, P.Eng., Chief Engineer
John Gusdorf, M.A.Sc., Manager Of Applications
Sciemetric Instruments Inc.
27 Northside Road
Nepean, Ontario, Canada
K2H 8S1
(613) 596 3995

ABSTRACT

The Advanced House represents the latest state-of-the-art demonstration of residential energy efficiency technology in Canada with energy saving estimates at 73% of that required for a "normal" conventional house. Among the many energy efficient technologies implemented in the dwelling is an advanced personal computer based control system that shifts peak electrical loading, manages energy consumption, and controls security lighting. A sixty-five channel computerized monitoring system is also installed to collect data which will allow an in-depth performance evaluation of all building sub-systems over an initial 2-year period.

KEYWORDS

Personal computers, measurement, monitoring, control systems, data acquisition, peak loading, energy systems, R-2000 housing.

INTRODUCTION

The Advanced House represents the current state of the art in residential energy efficiency. It has been designed to use only 27% of the energy costs of a similar conventional style house. The building itself is extremely well insulated and air tight, and uses advanced windows. This latest revolution in housing technology is even predicted to significantly out-perform R-2000 generation houses.

Space heat, air conditioning, hot water, and ventilation are all supplied by a novel Integrated Mechanical System (IMS) which uses a heat pump and ice storage tank to recover and use heat from the exhaust air and the grey water discharged from the house. The south side of the house incorporates a two story sunspace which is designed to capture and store solar energy, and supply it to the IMS. The house is fully equipped with the latest in energy efficient lighting and appliances.

The Advanced House is a joint effort of Energy Mines & Resources Canada, the Ontario Ministry of Energy, Ontario Hydro, Fram Building Group, and other agencies and organizations. It is located in the Nortonville Subdivision of Brampton, Ontario (near Toronto), and will be open to the public for the next year. For more information, or for tours, contact Fram at (416) 675-9179.

Sciemetric Instruments of Nepean, Ontario, Canada supplied and installed two independent computerized systems for control and monitoring within the dwelling. The control system is a permanent part of the house, while the monitoring system will gather detailed information on the performance of the house and IMS over the initial 2-year period to permit engineering analysis and allow comparison with computer programs used to simulate the house.

THE CONTROL SYSTEM

The control system has three major functions:

- to limit peak electrical demand below 10 kW
- to save energy and provide improved air conditioning
- to provide security lighting

The system is designed to be fail safe, to be flexible and user friendly, to provide on-screen information to the occupants and visitors, and to save a permanent record of its data and operations on disk.

The specific functions of the control system are as follows:

Peak Electrical Demand Limiting

The control system limits the electrical demand of the house during the peak period. The peak period is defined by Ontario Hydro as between 7:00 AM and 11:00 PM Monday through Friday. During this period, the total house electrical power draw is to be less than 10 kilowatts (kW) over any 15-minute interval. This means that the house should not use more than 2.5 kilowatt-hours (kWh) in any 15 minute interval during the peak period.

The control system limits demand by load shedding two backup heating elements. The first is a 3 kW in-duct heating element which is controlled by the lower of two heating setpoints in the house thermostat. The second is a 6 kW element in the domestic hot water (DHW) tank of the Integrated Mechanical System (IMS).

Load shedding is accomplished by turning off relays within the control system. Turning a relay off prevents a backup heating element from being turned on, regardless of the thermostat or IMS internal control setting for the heating element.

The impact of load shedding on the occupants of the house should be negligible. They would not normally be aware of whether a backup heating element is on or off, and the chances that shedding either element could result in low temperatures in the house are insignificant.

The data collected and recorded by the control system will allow for a thorough evaluation of the DHW backup element use. These data include energy use, time on and time shed for the element, and consumption and temperature of DHW. Analysis of the data should allow the amount of energy which the element supplies to DHW to be separated from the amount it supplies to space heat, and should also allow the impact of load shedding on both DHW and space heat to be evaluated.

Each time that load shedding conditions occur the control system writes a set of messages to disk describing the conditions before and after the load shedding operation. These messages include the house and IMS backup heating element demand before and after the load shedding occurs. Similar messages are written when the control system restores a backup heating element. Special messages are written if the control system is unable to keep the house electrical demand below 10 kW.

Energy Saving

At the same time that the control system is scanning for conditions which require load shedding, it also looks for opportunities to save energy. In load shedding, a given use of electrical energy is merely postponed in order to limit the peak demand; if the backup heater is shed, then it will be turned on, or the compressor will have to stay on longer, at a later time to make up the difference. In energy saving, the total amount of electricity used in a day or a week is reduced.

Energy is saved by seasonal control of the IMS, improved IMS air conditioning, and by control of the motorized skylight in the sunspace.

IMS Seasonal Control:

The IMS has two seasonal modes of operation: summer and winter. In winter mode, the IMS recovers heat from both the exhaust air stream and the house's grey water. This recovered heat is used for space heat and hot water. In summer mode, this heat is not recovered since it could not be used; the heat extracted from space cooling should be more than adequate for hot water. The IMS is normally switched from one seasonal mode to the other by a manual switch which the occupant must change twice a year. In the advanced house, the control system switches the IMS from one seasonal mode to the other, based on the date and on the outside temperature over the last two weeks.

Improved Air Conditioning:

The IMS cools the house (acts as an "air conditioner") by having its heat pump take heat from the fresh air stream entering the house and put it into the DHW tank. As the DHW tank becomes hotter, this space cooling function becomes less efficient. To maintain efficiency, hot water is dumped from the tank when:

a) the IMS is in summer mode, and;

b) the temperature of the brine line returning from the IMS Ice Tank is greater than 8 C.

The hot water dump continues until the brine line temperature is less than 4 C. Two temperature sensors are used on the return brine line, and hot water is not be dumped unless these sensors agree to within 0.25 C. This redundancy prevents the loss of all hot water should one sensor give an erroneously reading. The times and amounts of hot water dumps are recorded by the control system.

Motorized Skylight Control:

The skylight/vent located in the sunspace ceiling includes a motor which allows it to be opened or closed by throwing a switch. This skylight/vent is opened and closed by the control system, depending on the temperature in the sunspace and the season. During the summer, the skylight is opened whenever the sunspace temperature exceeds a programmable setpoint, e.g., 20 C; this helps to prevent the sunspace from overheating, and thus make space cooling of the house more efficient.

During the winter, the skylight may be set to open at a much higher temperature, e.g., 35 or 40 C, or it may be programmed not to open at all; excess heat in the sunspace will then be transferred directly to the house, or stored by the IMS for use as space heat or hot water.

The control switch for the motorized skylight has three positions: CLOSED, OPEN, and AUTOMATIC. In the AUTOMATIC position, the skylight will be opened and closed by the control system as described above. In the OPEN or CLOSED positions, the skylight will simply be open or closed as indicated, regardless of the actions of the control system. This will allow the occupants to keep the skylight closed for security purposes, or when a storm threatens, or to open it in winter if they are in the sunspace and find it too hot.

Security Lighting

The control system turns two inside light circuits on and off for security purposes. Each circuit can be separately programmed. The program for each circuit can include times of day for turning the circuit on and off, and exterior light levels below which the circuit is turned on.

Each of the lighting circuits is equipped with a switch labeled ON, OFF, and SECURITY. In the ON or OFF positions, the light circuit will simply be on or off as indicated, regardless of the control system. In the SECURITY position, the light circuit will be turned on or off by the control system.

All of the control system's functions have override switches which allow the occupants to counteract or deactivate the control system's control of each function. In addition to the override switches for each load, there is a master system override switch which will deactivate the control functions, allowing all loads to revert to normal control, i.e., to behave as if there were no control system in the house.

Control System Hardware

The control system hardware consists of an IBM-compatible personal computer with a Sciemetric-manufactured SYSTEM 200 Modular Measurement And Control System. The SYSTEM 200 is supplied in a wall mounted chassis and allows the computer to measure all sensors and control the relays used for load shedding.

Three SYSTEM 200 input/output (I/O) modules are used in the system. A Model 231 Integrating A/D Converter Module used with a Model 251 16-Channel Multiplexer Module provide 16 differential analog inputs to sense temperature, electrical demand, and exterior light levels. The I/O modules allow the computer to measure the various sensors using a precision low-noise Analog to Digital converter. Two 16-bit counter inputs are also provided which are used to count pulses from the electrical kWh meters for the hot water tank and the total house draw. A Model 220 8-Channel Relay Module supplies 8 electro-mechanical relays which are to switch electrical loads on and off, according to the control strategy.

The control system also includes a Watchdog Timer which prevents the PC from "hanging" due to a brief power failure or period of low voltage (i.e., brown out). It also has a modem which allows data to be transferred by telephone, and files to be erased from remote locations. These abilities decrease the need for routine site visits to verify operation and change the data disk.

The use of a personal computer in this initial demonstration offers many advantages over a dedicated "internal" CPU. First, it provides a user-friendly easy-to-use pop-up menu-system with which to operate the system. Second, it provides a real-time video display of all sensed parameters and control actions. Third, it allows the control algorithm running the house to be modified quickly and easily as performance data is acquired. Fourth, it stores all relevant performance data on PC-floppy disk simplifying the data analysis phase.

Should this type of control system become widely used in future houses, then a Sciemetric CPU Module would replace the PC used to drive the system, thus making the system entirely self contained within a wall or shelf chassis. Additional features such as a complete security system could also easily be integrated into the system improving the cost effectiveness.

THE MONITORING SYSTEM

A monitoring system is also installed in the Advanced House to collect performance data over the initial two-year period of operation. The system uses several Sciemetric data collection modules which interface with a second personal computer and operate independent of the control system.

The monitoring system scans sixty-five inputs every thirty seconds. The data is averaged, summed or integrated, and saved to disk every fifteen minutes. The data will be compared with the results of sophisticated computer simulation programs of the energy systems in the house to allow validation and/or adjustment of the mathematical models describing the systems.

The collected data includes:

- 3 air flows, into and out of the IMS.
- 26 temperatures, including five temperatures in the house, the outdoor temperature, temperatures of air flows into and out of the IMS, hot and cold water temperatures, and the temperatures of several points within the IMS.
- 7 relative humidities, in the house, the outdoors, and in the fresh and exhaust air streams.
- 18 values of electrical consumption, including the entire house, and several of the energy efficient appliances, e.g., the refrigerator, dishwasher, clothes washer and dryer. The electricity used by the entire IMS, its compressor, and its backup heater are also monitored.
- 6 liquid flows, including hot and cold water, the hot water dump for improved air conditioning (see above), and three flows within the IMS.
- Solar energy, both horizontal and vertical.
- The status of three control relays within the IMS.

Monitoring Software

A sophisticated software package called CoPilot is used to control the monitoring process. CoPilot is an integrated data acquisition, management and analysis software package produced by Howell-Mayhew Engineering of Edmonton, Alberta (Canada) and marketed by Sciemetric. The package was initially designed for research level monitoring of all R-2000 houses, and is well suited to long term (months or years) monitoring projects.

CoPilot provides more flexibility than virtually any other energy monitoring package. The software allows the User to define a monitoring job, and to collect, display and analyze the data. The entire package is menu driven and requires a minimum of training and experience to use. Up to 400 monitoring functions can be defined in any combination to describe any number of data points, scan rates, and save rates. Equations for many types of thermistors, and all standard thermocouples are included. In addition, the user can define mathematical equations to convert raw sensor data into performance factors to allow sub-system performance factors to be displayed in real-time.

CoPilot also supports several types of mechanical multiplexing equipment. This feature is used, for example, to allow a single pressure transducer or carbon dioxide (CO_2) sensor to acquire data from many points within the building. CoPilot controls the movement of a mechanical valve assembly to switch one-of-several plastic tubes into the single transducer, waits for a prescribed time, and then measures the transducer output through a normal A/D channel. This scheme not only makes multi-point pressure or gas measurements affordable (cost per transducer estimated at $1k-$5k), but also eliminates the inherent zero-drift problem of these transducers by allocating one channel as a known reference (e.g., a mechanical short circuit in the case of a pressure sensor).

Micrologger™

Distributed Data Loggers

The **MICROLOGGER** by Architectural Energy Corporation is a low cost, battery powered solution to your real world data acquisition problems.

Up to 15 **MICROLOGGER**'s can be used in separate, remote locations in a true, distributed data acquisition system. Their small size makes them convenient to use almost anywhere you would want to collect data.

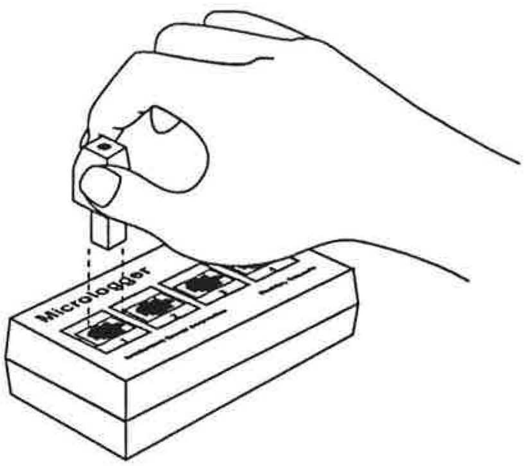
The **MICROLOGGER** can be set up through the serial port of a DOS based computer using the convenient, menu driven **MICROLOGGER** software. Drivers are also provided which enable you to develop custom data acquisition solutions.

Following data collection, the **MICROLOGGER** is downloaded to the computer. The data is stored in files, which can then be used in graphs, or input into popular spreadsheet or data analysis programs.

Up to 4 different sensors can be used on each **MICROLOGGER**, with those for temperature, humidity, air flow rate, static pressure, electric power and switch status presently available. Analog current (4 to 20 ma) and voltage (0 to 2.5 V) inputs can also be measured, allowing a wide variety of other sensors to be used.

The **MICROLOGGER**'s 32 K memory stores enormous amounts of data. For example, with 4 sensors installed, a **MICROLOGGER** stores over 8 months of hourly averaged data. Data averaging intervals from one second to one day can be programmed into the **MICROLOGGER** memory.

Contact Donald Frey or Michael Holtz at **Architectural Energy Corporation** for more information on how **MICROLOGGER**'s can provide you with convenient and cost effective solutions for your data acquisition needs.



Architectural Energy Corporation 2540 Frontier Avenue, Suite 201 Boulder, CO 80301 USA
Telephone: (303) 444-4149 Fax: (303) 444-3404

(August 2). A computer controlled solenoid valve was installed to dump the tank contents before sunrise each morning.

The protocol of Section III was repeated every day, with data extending from approximately summer to winter solstice. Test results from June 29 to December 10 are reported here. Although we will examine the parameter values, the repeatability of the annual prediction from F-Chart indicates the validity of the method.

V. MEASUREMENT TECHNIQUES

We have used a spectrally sensitive photovoltaic pyranometer for measurement of insolation. We have concluded that this sensor is adequate for this test, although data taken under highly diffuse radiation conditions should be eliminated using filter #6 (dicussed above).

Several techniques are available for measuring the temperature of water in the storage tank. It is desireable that this measurement require minimal disruption of the plumbing at the storage tank. Sensors applied externally to the surface of the pressure tank would be the easiest to use but they must be shown to provide accurate results. If measurements are made at a limited number of discrete points, then a decision must be made as to how many points are needed to obtain a valid spacial average. This is an especially important concern in highly stratified tanks. Sensors that measure a continuous spacial average temperature along their length may be desireable in this application. For the experiments discussed in this paper, tank temperatures are measured using type T thermocouples at three internal points (sensors immersed in the tank) and three external points (sensors fixed to the pressure vessel, under the insulation). Test results using internal and external measurements are compared.

Lastly, the tank capacitance must be determined. Since there is considerable uncertainty in the accuracy of the manufacturer quote (they are allowed a 10% margin of error), at present we recommend that the tank volume be calculated by measuring the dimensions of the outside of the pressure vessel. The volume of the liner/pressure vessel should be included in the storage volume estimate to approximately include this capacitance in the total tank capacitance number. (Although denser than water, the specific heat of steel is proportionately smaller, yielding reasonably equal volumetric heat capacity for steel and water.)

VI. RESULTS

Figures 2 through 5 all show data from a typical test, test # 68. Storage tank temperature rise during the test is shown in Figure 2. Figure 2 shows that the tank was purged before sunrise, with subsequent tank temperature rise of about 40 °C. Figure 3 shows that the day was mostly clear in the morning, followed by intermittent clouds in the afternoon. Figure 4 shows the data and best-fit line on the efficiency plot before the data filters were applied.

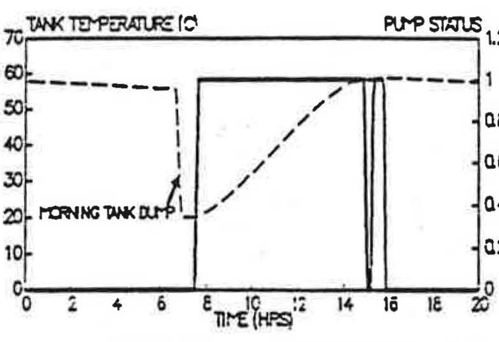


FIGURE 2 STORAGE TANK TEMPERATURE TEST DAY 68

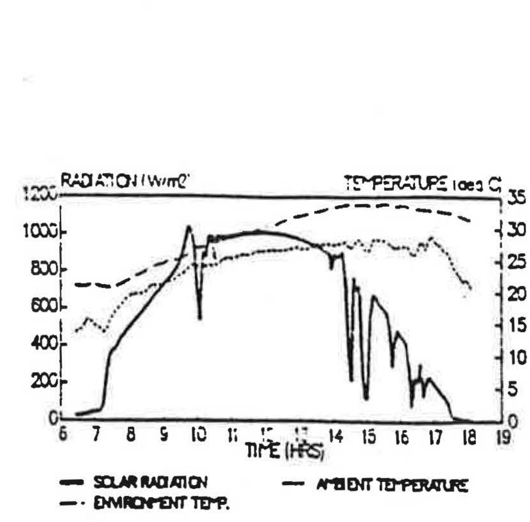


FIGURE 3 DRIVING FUNCTIONS TEST DAY 68

The filter settings for this analysis are given in Table II. Figure 5 shows the regression results when all data filters were applied. It is clear that the transients (filtered out in Figure 5) had caused large scatter in the data shown in Figure 4, as could be expected from previous collector testing work.

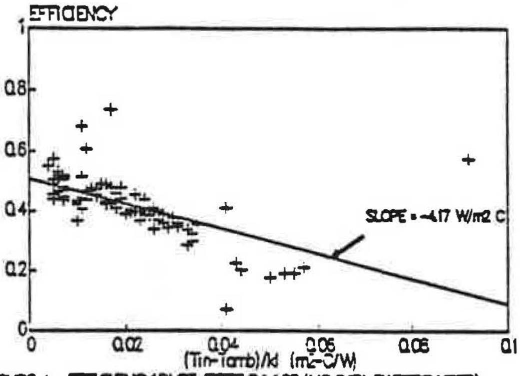


FIGURE 4 EFFICIENCY PLOT, TEST DAY 68 (NO DATA FILTERS USED)

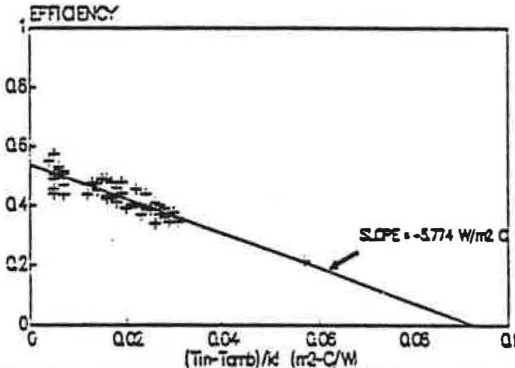


FIGURE 5 EFFICIENCY PLOT, TEST DAY 68 (WITH DATA FILTERS)

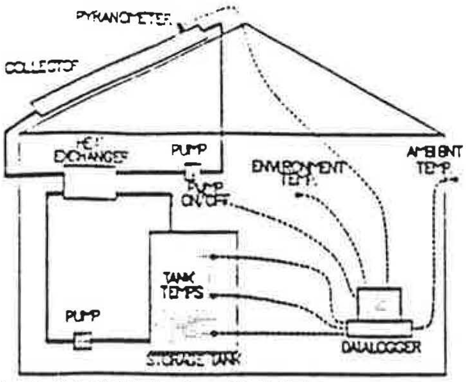


FIGURE 1 SCHEMATIC OF TESTED GLYCOL SYSTEM

The test protocol specifies the instrumentation and system operation. Test data channels are given in Table I. We recorded data on a five minute time step, although other choices are reasonable. The system should be operated as follows:

1) In the morning, replace the water in the solar tank with mains water. This can be done by running the hot water for a sufficient amount of time. This is done to force a sufficient spread in the efficiency plot for adequate slope determination.

2) Allow the solar system to run normally all day while keeping the load at zero (no hot water draw).

Table I. Data Channels for STM

(1)	Time-averaged solar radiation on collector	Ic
(2)	Time-averaged ambient temperature	T_{amb}
(3)	Time-averaged tank temperature	T_{tnk}
(4)	Instantaneous tank temperature	$T_{tnk,t}$
(5)	Time-averaged temperature of fluid to collector loop from tank	T_{in}
(6)	Pump duty cycle	

The analysis is quite simple, consisting of a linear regression on the system efficiency plot. Tank UA may be determined from a simple fit to some nighttime data. However, we have chosen to estimate tank UA from tank description, since we would like to complete the test in one day and since a fairly large error can be tolerated in the estimate of the tank UA (this was noted by (Christensen 1988) and has since been verified through simulation studies).

Several gates or filters are implemented in the analysis for rejecting data not representative of a steady-state test. Each filter is listed and explained briefly below.

(1) Maximum beam incidence angle:
Any data taken when the beam incidence angle on the collector is greater than about sixty degrees must be eliminated because the incidence angle modifier (eq. 3) is only accurate for angles less than sixty degrees.

(2) Previous pump-on time interval:
Because collector loop capacitance is ignored in the analysis, it is important to specify a time interval between when the pump turns on and when test data may be considered to represent approximately steady-state conditions. All data taken during the time interval is not

(3) Maximum radiation change:
A value of change in radiation level over a five-minute period which represents an approximately steady-state condition must be specified, since capacitance effects are ignored in the analysis.

(4) Interval after radiation change:
As in filter (2) above, data which was taken after a change in radiation larger than the "maximum radiation change" (filter #3) must be ignored for an interval of time.

(5) Minimum radiation level:
Since the STM method depends on the measurement of changes in tank temperature, it is important that the change in temperature over a time interval be large enough to detect accurately. By specifying a minimum radiation level, we effectively specify a minimum temperature change of the tank.

(6) Minimum clearness index:
Since the photovoltaic pyranometer that we used can give up to 10% errors in measured radiation under highly diffuse skies, all data taken during a period of low K_t is ignored.

(7) Minimum spread in x-axis of efficiency plot:
Since some measurement error is expected, a large enough spread in the x-direction of the efficiency plot (after all other filters have been applied to the data) must exist to obtain a reasonably low level of uncertainty in the parameter estimates (obtained through linear regression).

All of the above filter settings are user inputs to the software system, and specific values are recommended in Table II below. The use of these filters allows one to have a successful test on a partly cloudy day, since any undesirable data points are eliminated while retaining the useful data. Of course some days' tests will result in so few useful data points that the system parameters cannot be estimated with good confidence and the test is deemed a failure for that day.

The analysis can integrate the raw data intervals into longer analysis intervals. The integration period is determined primarily by the accuracy of the sensors used to make the measurements and by the particular characteristics of the system being tested. Typically, an integration period is chosen so that the change in tank temperature over one period is large compared to the resolution of the temperature measurement technique. We have found that a five minute analysis period gives good results for the types of systems and measurement techniques used thus far. Larger intervals were found to give comparable performance estimates but resulted in a significant increase in rejected days.

Key steps in the analysis are:

1. Eliminate unwanted data by applying the filters discussed above. (Quantitative levels will be given below).

2. Perform a linear regression on the day's set of efficiency versus $(T_{in}-T_{amb})/(K_{eff}Ic)$ values to obtain the two collector parameters $F_R U_L'$ and $F_R'(\tau\alpha)'_n$.

3. Obtain a prediction of the annual solar contribution to the load using the STM-estimated values of $F_R U_L'$ and $F_R'(\tau\alpha)'_n$ and an annual performance prediction tool such as F-Chart (Klein 1976). Note that the F-Chart prediction assumes a load profile which may be radically different from that appropriate for the actual system, and is thus not necessarily a prediction of displaced auxiliary.

IV. DESCRIPTION OF TESTED SYSTEM

Tests have been conducted on a closed-loop glycol SDHW system installed at Red Rocks Community College in Lakewood, Colorado. The system and the instrumentation employed are shown schematically in Figure 1. The collector is mounted on the roof of a small shed, with very little external pipe run. The pipes were uninsulated when testing began, and were insulated on test day #30

(SRCC) intends to incorporate a field test component in the forthcoming revision of the SDHW certification process, SRCC-OG-300. The field test component corroborates the system rating (annual performance in a standard climate, derived from collector test data and modeling of system effects) and checks the adequacy of installation directions and installer skills.

Field monitoring is not intended as a substitute for consensus standard laboratory tests, such as (ASHRAE 95-83). Such standards strive for the highest practical accuracy under well-defined conditions, using certified, highly-instrumented facilities run by testing specialists. On the other hand, field monitoring has broader purposes and will inevitably achieve lower accuracy because conditions and instrumentation cannot be as well controlled.

For the intended applications, the field monitoring must be relatively simple and quick (i.e., of order one day). Perhaps the simplest "test" is to verify temperature rise of the circulating fluid. Adequate for some purposes, the test does not provide system efficiency. A very simple test for estimating useful solar over some time period can be performed by directly metering the hot water auxiliary, calculating the total load from assumed mains water temperature and average hot water draw, and taking the difference of these two quantities (Rich 1989). Although useful, accuracy is an issue (especially for certification applications) because of uncertainty in the draw assumption. Although flow-temperature approaches will yield "instantaneous" efficiency, they were not considered because flow meters are intrusive and subject to calibration problems. Several authors (Buckles, 1983; Gordon, 1986; Christensen, 1988) have studied short-term methods based upon determining useful energy delivered to storage from measurement of tank temperature change, with analysis based upon the Hottel-Whillier steady-state equation. The method studied here and described in (Barker, 1989) is a refinement of these "tank-DT" methods.

Much related useful work has been done in studies of standards for determination of individual collector performance parameters. Standard tests for collectors (e.g., ASHRAE 93-86, SRCC-100) specify approximate steady-state conditions for the test. The handling of transient conditions (always present in outdoor testing) has been considered by a number of authors. Calculated corrections for the transients are considered in (Edwards, 1981; Emery, 1984; Oreszczyn, 1987; Prapas, 1988; Wang, 1987). All of these methods would need additional development to consider effects from the system's pipes and heat exchangers. The basic approach used here for handling transients is similar to that of the standards: accept only data near steady-state, determined by appropriate statistical criteria.
For the short-term monitoring (STM) method to be reliable, it is necessary to identify any effects that can invalidate the test. One useful approach is to perform simulation studies with a reasonably well-validated simulation, as in (Christensen, 1988; Barker, 1989). These studies indicated that system annual performance prediction using the regressed system parameters can be quite accurate and repeatable; however, estimates of the system parameters have a greater variance than annual performance predictions due to tradeoff between gains and losses ($F_R'(\tau\alpha)'$, $F_R U_L'$ are positively correlated, with little effect on the annual prediction). It is thus reasonable to use the annual performance calculation for the actual site as the test output, treating the parameters as intermediate quantities.

The simulation studies have also indicated that this simple tank-DT method can predict performance to better than 10% accuracy (mean bias of 0.2%, RMS 4%). Effects of wind variation and random measurement error were shown to be relatively unimportant within these error limits. However, simulation studies must be complemented with field tests, as a number of effects (such as high-frequency transients in radiation data, actual pump/tank behaviour, etc.) cannot be adequately simulated. This paper thus serves as a complement to results of (Barker 1989).

The STM method can be used to estimate the system parameters for either a stratified or non-stratified tank system, differing only in the spatial density of tank temperature measurement needed to derive a true average temperature. The field testing discussed in this paper was done on a system whose tank is fully mixed during pump-on operation, and F-Chart (Klein 1976) was used to extrapolate annual performance predictions from the system parameter estimates. It should be noted that another annual performance prediction tool could have been used instead of F-Chart, and indeed F-Chart may not be the most appropriate tool for some systems. For the purposes of this study, the goal was to demonstrate repeatability of the testing method, and thus the absolute accuracy of F-Chart for a particular system was not essential.

II. STM THEORY

The behavior of an SDHW system can be described by writing an energy balance around the storage tank when the load and auxiliary heat flows are zero. If the collector loop is modeled by the steady-state Hottel-Whillier equation (4) then the energy balance can be written:

$$dQ/dt + (UA)_{mk}(T_{mk} - T_{env}) =$$
$$A_c[Ic F_R'(\tau\alpha)' - F_R U_L'(Tin - Tamb)] \qquad (1)$$

If equation (1) is integrated over a short time step Δt and the factor K_{eff} is introduced, after manipulation equation (1) becomes:

$$[\Delta Q + (UA)_{mk}(T_{mk} - T_{env})\Delta t]/(A_c K_{eff} Ic \Delta t) =$$
$$F_R'(\tau\alpha)'_n - F_R UL'(T_{in} - T_{amb})/K_{eff} Ic \qquad (2)$$

Collector loop efficiency is expressed by the right-hand side of equation 2. Here efficiency is assumed to be a linear function of $(T_{in} - T_{amb})/(K_{eff} Ic)$ with slope $-F_R U_L'$ and intercept $F_R'(\tau\alpha)_n$. Note that these parameters implicitly include the performance degradation due to pipes, heat exchangers, and a flow rate other than the design flow rate since the only heat flow measurement is made at the storage tank. No further corrections are made for the effects of pipes losses, heat exchanger effectiveness, or flow rate.

The incidence angle modifier K_{eff} is a function of the split of radiation among beam, ground diffuse, and sky diffuse. The method of (Erbs 1984) was used to derive these beam/diffuse splits. A ground reflectivity was assumed and incidence angles were calculated using well-known algorithms (Duffie and Beckman). The incidence angle modifier for each radiation component was calculated using equation 3 (Duffie and Beckman):

$$K = (\tau\alpha)/(\tau\alpha)_n = 1 + b_0(1/\cos\theta - 1) \qquad (3)$$

The effective incidence angle modifier is then calculated as:

$$K_{eff} = (K_{beam} I_{beam} + K_{sky} I_{sky} + K_{grd} I_{grd})/I_c \qquad (4)$$

III. THE STM METHOD

The test method specifies the testing protocol and the analysis of the data. The philosophy in test design was to keep the instrumentation and analysis as simple as possible.

FIELD TESTS OF A SHORT-TERM MONITORING METHOD FOR SOLAR DOMESTIC HOT WATER SYSTEMS

Greg Barker
Jay Burch
Ed Hancock

Solar Energy Research Institute
Golden, CO 80401

ABSTRACT

A method of monitoring the performance of an installed solar domestic hot water system was investigated through repeated tests on a glycol system. The method is based upon time-integration of the storage tank energy balance, with useful delivered energy modeled by the well-known Hottel-Whillier steady-state equation. The method specifies non-intrusive measurements, requires approximately six hours to perform, and yields estimates of the system optical and thermal parameters which are used to predict the solar system's contribution to the annual load. Because the method is based upon a steady-state model, a key part of the method is the definition of filters to screen out unrepresentative data. Annual performance predictions from multiple tests are shown to be repeatable to within a standard deviation of about 4%. The effect of pipe insulation installed during the testing was detected, and the anomalous effects of pipes losing heat to temperatures other than the outside ambient temperature are noted.

NOMENCLATURE

A_c	=	collector aperture area (m^2)
b_0	=	incidence angle modifier coefficient = -0.1 for single glazing (Duffie and Beckman, 1980)
dQ/dt	=	rate of change in storage tank internal energy (W)
F_R'	=	collector heat removal factor, modified for presence of heat exchanger and for flow rate other than test flow rate
I_{beam}	=	total beam radiation in plane of the collector (W/m^2)
I_{grd}	=	total ground-reflected radiation in plane of the collector (W/m^2)
I_{sky}	=	total sky diffuse radiation in plane of the collector (W/m^2)
Ic	=	total solar radiation in plane of the collector (W/m^2)
K_{eff}	=	effective incidence angle modifier
$K_{\tau\alpha}$	=	incidence angle modifier
(MC_p)	=	heat capacity of tank (W/°C)
T_{amb}	=	ambient air temperature outside collector (°C)
T_{env}	=	temperature of environment outside tank (°C)
T_{in}	=	temperature of fluid entering collector loop from the bottom of the storage tank (°C)
T_{tnk}	=	storage tank temperature averaged over a time interval Δt (°C)
$T_{tnk,t}$	=	storage tank temperature at time t (°C)
$(UA)_{tnk}$	=	storage tank heat loss coefficient (W/°C)
U_L'	=	collector heat loss coefficient, modified for losses from pipes (W/m^2 °C)
ΔQ	=	$(MC_p)(T_{tnk,t+\Delta t}-T_{tnk,t})$, change in internal energy of storage tank over time interval Δt (J)
Δt	=	time interval (sec)
$(\tau\alpha)'$	=	collector transmittance -absorptance product, modified for losses from pipes
$(\tau\alpha)_n$	=	collector transmittance -absorptance product at normal incidence
θ	=	beam incidence angle (deg)

I. INTRODUCTION

Monitoring of installed solar domestic hot water (SDHW) systems is important for a number of purposes, including: 1) acceptance testing of systems; and 2) corroboration of certification. Acceptance testing provides assurance at start-up that the system is operating properly. In (ASHRAE 1988), several alternative acceptance tests are suggested for inclusion in the system contract. Tests are based upon either flow-temperature measurements or storage tank temperature change. The latter approach is very similar to the method studied in this paper. System certification is important for assuring quality and building consumer confidence. The Solar Rating and Certification Corporation

Table II. Filter Settings for STM

Integration time:	5 min.
Maximum beam incidence angle:	55 degrees
Previous pump-on time interval:	15 min.
Minimum radiation level:	315 W/m^2
Minimum K. value:	0.3
Maximum radiation change:	31.5 W/m^2
Interval after radiation change:	15 min.
Min. spread in efficiency plot:	.014 C-m^2/W

Figure 6 shows a comparison of the average tank temperature change measured with external and internal temperature sensors. It can be seen that the external measurements lag the internal measurements, probably due to the pressure tank capacitance.

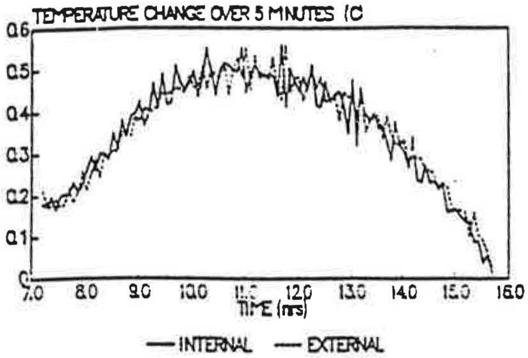


FIGURE 6 TANK TEMPERATURE MEASUREMENT COMPARISON

Figure 7 shows the results of all field tests, with external tank temperature measurement. Results for both internal and external measurement are tabulated in Table III. Days for which fewer than four points remained after application of the data filters have no results. It should be noted that the results for the internal and the external tank temperature measurement are quite consistent, with the external measurements giving results about three per cent higher on average.

As indicated in Figure 7, pipe insulation was installed after test number 30. After that date, note the consistent increase of about 1.6 GJ in the F-Chart predictions. This difference, however, could not be reliably detected from any two days of data, since it is only slightly larger than the combined RMS variation.

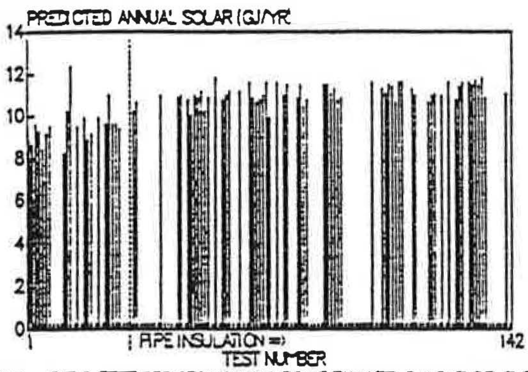


FIG7 FIELD TEST RESULTS USING SURFACE TANK TEMP. MEASUREMENTS

Also note that there are several anomalously high predictions before the pipe insulation was installed, on test days 13 and 24. The explanation for this is rather subtle. The analysis assumes that all thermal loss is to ambient temperature, whereas in reality the pipes are mostly inside, losing to the tank room temperature. When a large difference exists between ambient outdoor and the tank room temperature, it is clear that problems will occur. During the STM test performed on each of these two days, the air temperature to which the pipes were losing heat was about 7 °C higher than the outside air temperature. This lead to an anomalously low thermal loss for the system which was interpreted as a high efficiency, and an overprediction from F-Chart of the useful solar energy. This effect is the major contributor to the variation in the results when the pipes were uninsulated. Note from Table III that the RMS deviation decreased from about 10% to about 5% after the pipes were insulated. This is because once the pipes were insulated, the fraction of total collector loop heat loss attributable to pipe losses was greatly reduced, thus reducing the test's sensitivity to differences between ambient and environmental temperatures. Even the well insulated pipes were not totally immune to this effect, however, as one can see by noticing the slight upward trend from left to right in Figure 7. As the outside (ambient) temperatures decreased from summer to winter, the difference between ambient temperature and pipe environment temperature increased, thus increasing the efficiency of the system and resulting in higher F-Chart predictions.

This effect can also be demonstrated from simulation. TRNSYS (Klein 1983) was used to model a typical SDHW system, with all of the pipes running through a space kept at a constant temperature of 21 °C. The STM test was repeated every day for a year in Denver, CO, using F-Chart to generate the annual performance results shown in Figure 8. Each point on the graph represents the average of all STM predictions made during each month. A clear seasonal trend is seen for pipe insulation of 5.7 W/m^2 K, much less so for a more reasonable insulation of 1.4 W/m^2 K. When the pipes are exposed soley to ambient temperature, one sees no seasonal variation. The method thus must be applied with caution when the pipes are poorly insulated.

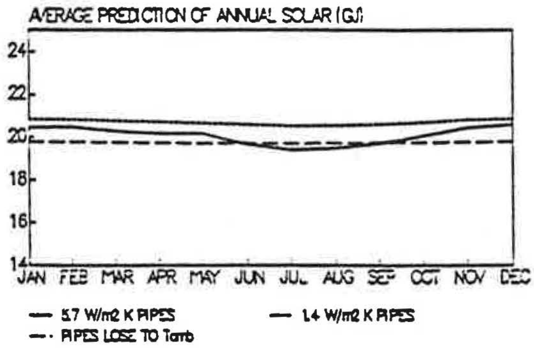
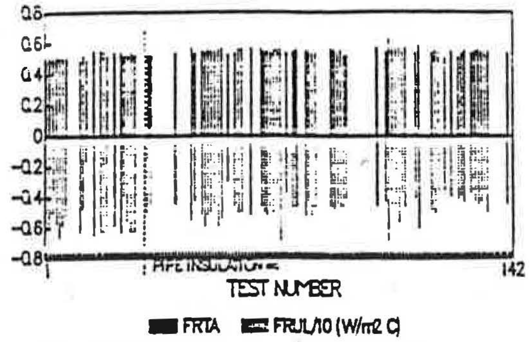


FIGURE 8 SIMULATED STM RESULTS FOR DENVER, CO

The estimated values of the optical parameter $F_R'(\tau\alpha)'_n$ and loss parameter $F_R'U_L'$ are plotted in Figure 9 and listed in Table III. Note that the standard deviation of the optical parameter is much less than that of the loss parameter. The variation in the loss parameter after the pipe insulation was installed is much less than before (21% versus 15%).



IGURE 9 STM PREDICTIONS OF SYSTEM PARAMETERS

III. Statistics of STM field test predictions before and after adding pipe insulation

	FR(τα)n avg	std	FRUL (W/m2 C) avg	std	Annual Solar (GJ/yr) avg	std
al						
	0.53	5.3%	-6.92	20.5%	9.1	10.5%
	0.58	4.8%	-5.79	16.3%	10.9	5.1%
e						
	0.52	4.3%	-5.73	21.2%	9.5	9.3%
	0.55	3.4%	-4.76	15.0%	11.1	3.9%

CONCLUSIONS

rt-term monitoring method for installed SDHW systems has ested through repeated application of a day-long protocol. F-predictions of annual performance of the system was shown to GJ +/- 9% with uninsulated pipes, and 11.1 GJ +/- 4% with ed pipes. This level of error is quite adequate for the intended the test.

shown that use of temperature sensors attached externally to rage pressure vessel give similar results compared to sensors d inside the tank. The effect of pipe losses to temperatures t from ambient can present problems when the difference s large. The effect is minimal for well-insulated pipes, and can tantial for poorly insulated pipes. The method is repeatable to % RMS with insulated pipes, and appears quite practical in f instrumentation and analysis time.

IRTHER WORK

hod must be tested under more extreme variations of climate additional systems. Preliminary results for a drainback system that different settings are necessary in some of the filters. The is applicable in principle to systems of any size; it should be n a large system to uncover any practical problems in on.

theoretical point of view, there are a number of possible ns to the data that can be added to increase useful data ut and accuracy. These corrections include: 1) collector and piping capacitance; 2) pipe loss to temperatures unequal to ambient; 3) wind variation; and 4) sky infrared losses. We would like to evolve a hierarchy of methods, with increasing instrumentation requirements for more accurate results and more specific diagnostics.

IX. ACKNOWLEDGEMENTS

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