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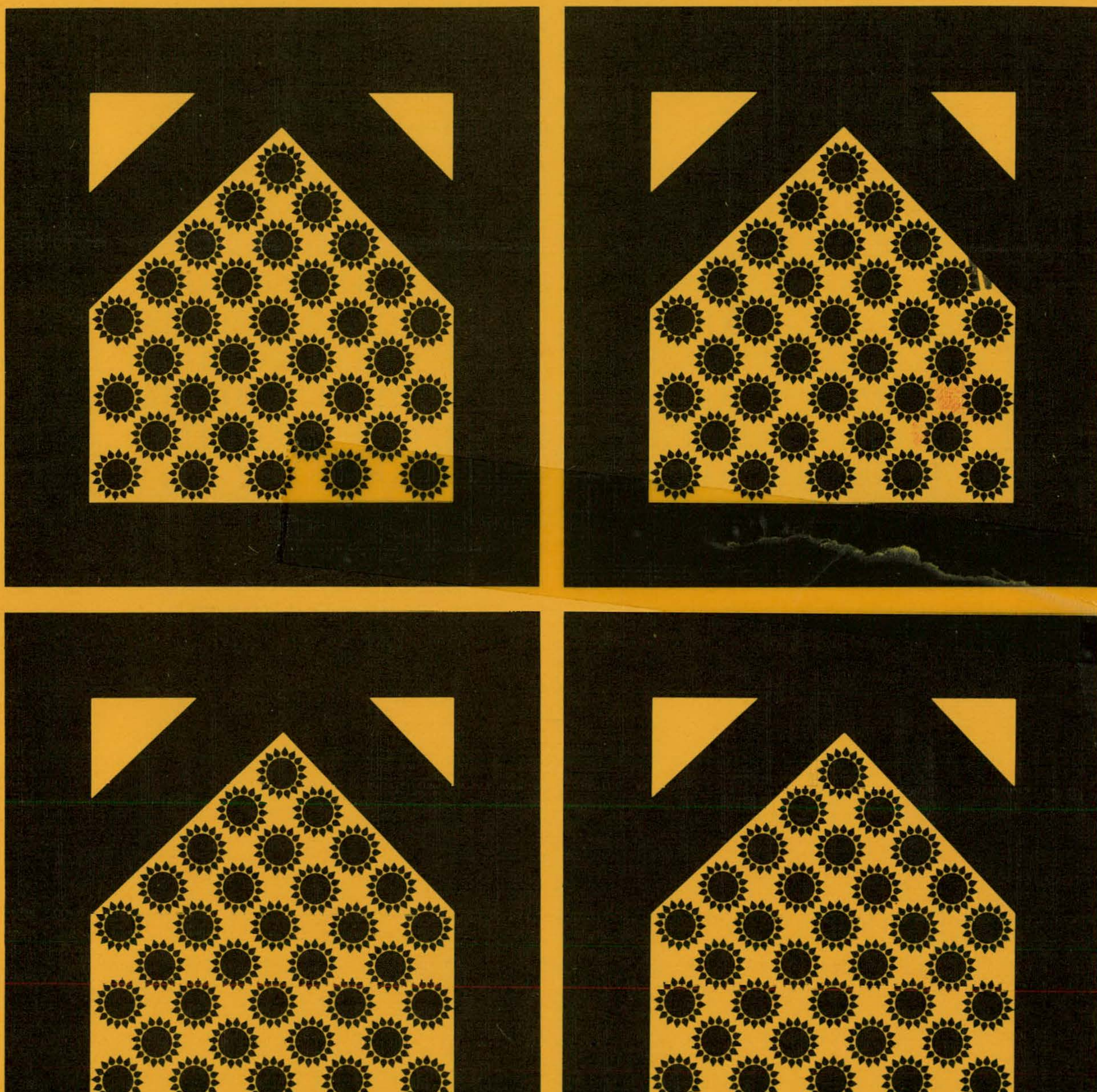
SUBMITTED PAPERS

"CONFERENCE ON PERFORMANCE MONITORING TECHNIQUES FOR EVALUATION OF SOLAR HEATING AND COOLING SYSTEMS"

April 3 and 4, 1978
Shoreham Americana Hotel, Washington, D.C.



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Submitted Papers

"CONFERENCE ON PERFORMANCE
MONITORING TECHNIQUES FOR
EVALUATION OF SOLAR HEATING
AND COOLING SYSTEMS"

April 3 and 4, 1978
Washington, D.C.

Sponsored by

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through contract
EG-77-S-04-4094

Organizer
R. F. Boehm
University of Utah

MASTER

In Cooperation With
The Electric Power Research Institute
American Section of the International Solar Energy Society
Solar Division of the American Society of Mechanical Engineers

Purpose of Conference

To determine the status of techniques, instrumentation and data analysis for reporting of the performance of solar energy systems for building climate control.

Acknowledgements

The financial support of this conference by the U.S. Department of Energy through Contract EG-77-S-04-4094 is gratefully acknowledged.

A need for a conference of this sort has been recognized by a number of people, too numerous to mention here. However, the appreciation of many existing problems in the monitoring area by DOE Headquarters personnel Mike Maybaum, Fred Morse and Jack Hale, as well as Walt Adams of Sandia Laboratories, made this conference a reality. Invaluable assistance with many details was furnished by Elmer Streed of NBS and Bud Wildin of the University of New Mexico.

R. F. Boehm

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ANALYSIS OF DATA USER'S NEEDS FOR PERFORMANCE EVALUATION OF SOLAR HEATING AND COOLING SYSTEMS

David L. Christensen
Research Associate
Kenneth E. Johnson Environmental and Energy Center
The University of Alabama in Huntsville
P. O. Box 1247
Huntsville, Alabama 35807

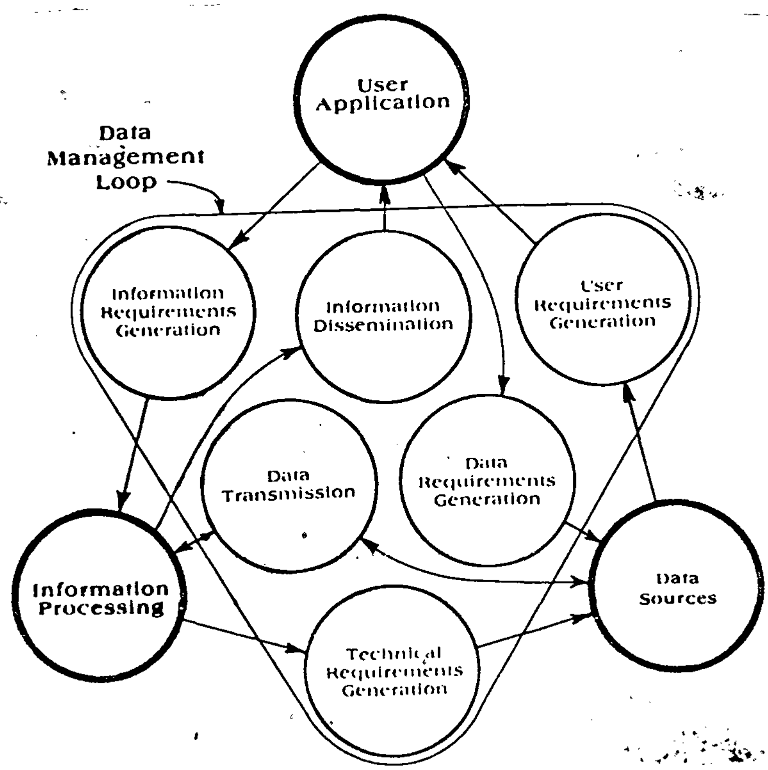
ABSTRACT

This paper provides a general review of solar energy monitoring systems; their relationship to data users and their needs; and provides a methodology for developing instrumentation systems and performance evaluation techniques based on a systematic procedure for addressing the actual needs of the data user.

INTRODUCTION

Meeting the actual needs of the data user and providing quality information is critical to a successful data acquisition program. Data is only useful if it conveys information which is helpful in reaching decisions. To serve the needs of the user, the required information needs must be evaluated, the design and cost factors of the program must be determined, and a data management loop organized and operated to gather, process, and disseminate the needed information in useable formats. These program elements should interact in a systematic manner as shown in Figure 1.

FIGURE 1 - INFORMATION SYSTEMS DIAGRAM



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This paper describes each of the above program elements in detail to aid the solar heating and cooling data manager and user to implement effective data acquisition and monitoring systems, and to allow evaluation techniques which will aid in the determination of solar energy systems performance.

PROCEDURE FOR DATA USER AND NEEDS ANALYSIS

By contacting the data user, various needs will become quite apparent during the initial design phases of the data system.

Analytical techniques to evaluate the user community should be developed and applied. These might include:

- identification of potential users
- direct user contact through the use of meetings, telephone surveys, etc.
- questionnaires and surveys to identify actual and potential needs
- categorization of the data requirements and the users (volume, cost)
- review of performance evaluation techniques to be used
- publication of available sources and currently available instrumentation for review, sensor selection, etc.

The user requirements should be defined by identifying and classifying both the needed data and the users. The users of the data must be contacted and procedures established to meet their requirements, not necessarily through the use of a new program, but also considering the use of alternate methods and existing sources of data. If a new data acquisition system is required, it should be evaluated on the basis of the following considerations:

- availability of facilities
- availability of hardware and software
- availability of trained personnel
- prospects for continuous operation
- capability for routine maintenance
- cost-benefits-analysis of the system.

Thus, a definition of the potential interest and needs, the data volume requirements, the interface requirements and a cost and benefit analysis should be performed before proceeding with the development of a new data acquisition and management system.

DATA MANAGEMENT REQUIREMENTS

Data managers need to initially identify their actual program management requirements. Then a definition of overall systems criteria is needed to assure that all program factors are carefully evaluated. Standardization of terms, formats and definitions for the data acquisition system is likewise necessary to allow effective development of the overall system. Data users usually require rapid data gathering, handling and dissemination of the results of the program. The identification of necessary funds and expertise is required by both the data managers and by the users to allow maximum benefits from the program and to meet the needs of both.

There is an obvious need for a document to describe various terms and standards for solar energy data acquisition systems, including a detailed description of instrumentation requirements, data processing requirements, quality control, dissemination techniques, and other related programs. Likewise, a management control handbook should be developed for specific research, development or demonstration projects to aid the manager and user in the acquisition, processing and dissemination of useful information.

Several methods (and the related costs) should be considered for disseminating the potential results of the data program. Brochures, handbooks, data user's guides, computerized data bases and various other data storage and retrieval techniques should be compared before proceeding with the final design and selection of hardware, and display formats.

A knowledgeable data manager will be required for any continuing program. This manager will need a broad background in data systems; an awareness of current techniques in recording, processing, storing and retrieving data; a knowledge of the monitoring and display formats needed for summarizing data; a background in cost management; and a dedication to continue the data-operating procedures on a sustained basis. Finally, a continuous review must be made of the costs and the potential results, as well as the actual results, to ensure that the system output continues to meet the user requirements at minimum justifiable costs.

PROCEDURE FOR SYSTEMS ANALYSIS

It is desirable that a systems analysis approach be made before the final design for the data system is decided upon. This will allow the development of logical and quantitative techniques for identifying and illuminating alternative courses of action in terms of cost effectiveness and improved decision-making methods. Several discrete steps should be performed in order to perform this analysis. A statement of the need should be made as well as a clear statement of the goals and objectives for the program. Performance specifications should be described to allow the resulting data acquisition and monitoring system to meet the expected system output. This is required to provide the reaction times to meet the needs of the data users, and to insure that the system is reliable.

Related design specifications should likewise be developed to meet the proposed hardware and software requirements, the estimated cost of the system and the proposed step-by-step schedule for overall development. At this time, the general feasibility of the system can be investigated, including the technical, the economic, and the institutional factors which will relate to user acceptance.

Throughout the process, various changes and alternatives should be evaluated, and, if possible, fed back into the original statement of goals, objectives and performance specifications. In this way, the overall systems analysis can be refined and, hopefully, the final output will be closely matched to the needs of the user. Figure 2 shows the various steps involved in the performance of a systems analysis for data systems.

OVERALL PROGRAM DEVELOPMENT FOR DATA SYSTEMS

Figure 3 shows a model to be followed in developing a data system, showing the output achieved by using the best available methodology.

A generalized decision model can thus be used for arriving at any particular end result, in this case, a data system program. The requirements and objectives of the project must be defined based on the actual needs and priorities of the data user. The statement of approach must be made based on the constraints, the capabilities and the resources available at the time. The method to achieve the goal, and the evaluation of the method itself must be made by reiteration to make sure that the procedure meets the initial objectives. Finally, the program must be integrated and tested

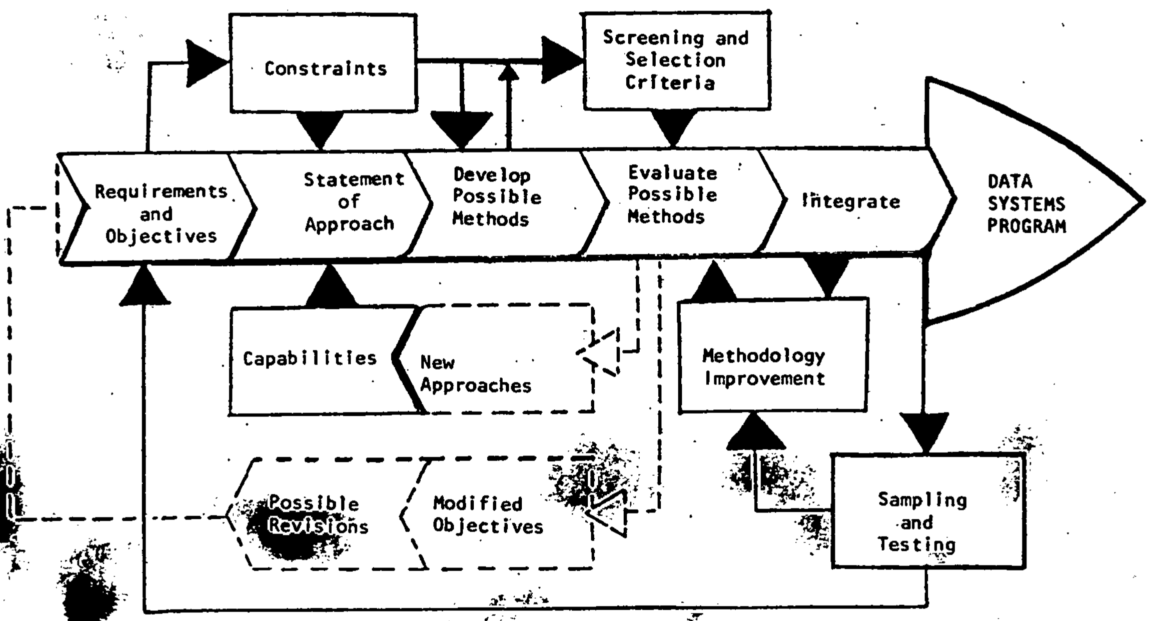
FIGURE 2 - PROCEDURE FOR ANALYSIS OF DATA SYSTEMS

1. Statement of Need
2. State Goals and Objectives
3. State What the System Will Do
4. Performance Specifications
   - Expected Output
   - Reaction Times
   - Reliability
5. Design Specifications
   - Proposed Hardware
   - Proposed Software
   - Cost of System
   - Schedules
6. General Feasibility
   - Technical
   - Economic
   - User Acceptance
   - Institutional Factors

Changes

Alternatives

FIGURE 3 - OVERALL PROGRAM DEVELOPMENT FOR DATA SYSTEMS



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to see if it works; the output produced in this case is a data system program.

In addition, the future's context should be considered as a critical element with this particular model. The long term aspects of the data system should be carefully considered, including the potential modifications which might be needed based on changes in available resources or in the user's requirements.

OTHER SYSTEM CONSIDERATIONS

If properly applied, the various analytical efforts described above can provide a framework for developing effective data acquisition, monitoring, processing and dissemination techniques for solar energy heating and cooling systems. However, the application of useful experience as acquired from similar and related programs can also provide an invaluable source of information to assist in establishment of an efficient, cost effective data program.

A detailed survey of planned and operational data systems used in various research, development and demonstration programs for the solar heating and cooling of buildings is needed at this time to aid in the design of new systems being considered for this purpose. Evaluation of sensor selection criteria, processing techniques, display formats, problem areas and "lessons learned" from these similar programs would be extremely valuable and useful for the practical application of cost effective systems.

General data system requirements and typical operational problems could be described in a design handbook which might also include discussions and recommendations such as the:

- need for simple, low cost data acquisition and monitoring systems for "on-site" performance evaluations of solar energy systems
- need for improved techniques to evaluate passive and hybrid solar heating and cooling systems
- need for "standard" methods to test and evaluate solar equipment and systems
- need for back-up channels for use during periods of data system repair (also redundant or dual measurements for critical parameters and spare parts may be necessary)
- need for consolidated index (listings) of equipment compatible with solar energy programs
- need for improved methods to record, evaluate, and apply solar radiation measurements
- need for improved subsystem-system performance correlations, simulation, and design validation techniques
- comparison of "in-place" calibration and calculated curves provided by the equipment manufacturer
- analog versus digital techniques (flexibility, time and cost factors)
- automatic versus manual data acquisition and processing systems
- need for mechanical filters in front of flowmeters
- limitations of flowmeter calibration values at higher temperatures
- comparisons of strip chart tape and other data recording techniques (accuracy, flexibility, cost)
- pitfalls to avoid through misinterpretations, human error, "noise" problems, etc.
- comparisons of initial costs, hardware versus software, maintenance and operational costs based on actual programs.

Hopefully, many of these types of considerations will be brought out at this conference to aid in the development of needed reference materials.

SUMMARY

There is an obvious need to apply a systematic approach when designing, developing and operating data acquisition, monitoring and display systems. Likewise, an awareness of the actual data and information needs of the users and the experiences of the managers of similar data systems can help to provide more effective performance evaluation techniques for solar heating and cooling systems analysis.

Additional review and summaries of instrumentation techniques common to solar energy systems and the development of hardware and software information catalogs, design guidelines for data systems, and the sharing of common experiences and problems are also needed at this time.

ACKNOWLEDGEMENTS

The contractual and other support of the Department of Energy, the National Aeronautics and Space Administration, industrial organizations and individuals that have supported the research programs leading to this presentation is appreciated.

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NATIONAL SOLAR DATA SYSTEM

L. J. Murphy
IBM Federal Systems Division
Huntsville, Alabama

A major activity of the National Solar Heating and Cooling Demonstration Program is the collection and analysis of data which is used to determine solar energy system performance. Specifically, the data which is collected and analyzed in support of this program is used to:

1. Improve the general knowledge and understanding of the performance and operating characteristics of solar energy systems.

2. Develop performance criteria for solar energy systems.

3. Provide a basis for improving solar energy systems and their components.

4. Estimate the economic importance of solar energy systems in reducing the consumption of conventional fuels.

The National Solar Data Network is being employed in this collection and analysis activity. Through this network, accurate, consistent, and orderly data is obtained from a variety of solar energy systems located at various sites throughout the country having a wide range of climatic conditions. A central facility in the network organizes and maintains the data to ensure consistent performance evaluation and system alaysis.

The National Solar Data Network was developed for the Department of Energy by the Federal Systems Division of International Business Machines Corporation. Numerous schemes of data gathering were considered, but studies showed automatic data collection at a central facility to be the most cost-effective approach. Thus, the National Solar Data Network was developed to gather, convert, transfer, and analyze demonstation site data using six basic steps: three to prepare each site for connection to the network, and three to provide for data collection and analysis.

Site Preparation

1. Analyze each site and its instrumentation requirements.

2. Select sensors and personalize standard data acquisition equipment to meet specific site requirements.

3. Install and check out site instrumentation.

Data Collection and Analysis

1. Automatically retrieve data via telephone lines connected to the central facility.

2. Process data in the central facility computers; this includes error checking, performance evaluation factor computation, and data base maintenance.

3. Analyze data and document the analysis in a standard report format for distribution.

The following describes each step in detail.

The first step in the preparation process is the careful study of the solar energy system installed at each selected demonstration site. Using information supplied by the site contractor, both the system and its environment are investigated to establish performance evaluation equations and associated instrumentation requirements. The performance evaluation techniques follow general guidelines which were established by a governmental inter-agency committee for use in evaluating solar energy systems. The results of the site study are documented in an Instrumentation Plan which describes in detail all elements of the instrumented system. In addition, a Solar Energy System Description Document is published that documents the solar energy system and its instrumentation.

Performance evaluation factors are then defined using the energy balance concept. Simply stated, the energy entering a system (or subsystem) is equal to the sum of: the energy leaving the system, the energy accumulated in the system, and the energy lost through thermal leakage and conversion inefficiency. As stated in the Instrumentation Plan, the sensors selected are those necessary to accurately and economically determine this energy balance.

The second step in site preparation is the selection of sensors and the personalization of standard data acquisition equipment to meet the requirements specified in the Instrumentation Plan. Sensors are selected from a standard set which has been established to insure compatibility with the Site Data Acquisition Subsystem (SDAS) and to optimize software development. Typical sensors are:

- Pyranometers
- Flowmeters
- Temperature Probes
- Electrical Power Meters
- Wind Speed and Direction Indicators

These sensors are connected to the SDAS. The SDAS is a microprocessor-controlled electronic unit developed by IBM which collects and stores data from the sensors several times an hour and transmits it to the central facility once a day. The collection process, data treatment procedure, and other functions of the SDAS are directed by a microprogram which is custom developed in the preparation process for each SDAS, according to the Instrumentation Plan for a specific site. The microcode is "burned into" the programmable read-only memory of the SDAS before it is shipped to the site.

The third step is installation and checkout of the SDAS and the sensors. The site contractor installs the supplied sensors in accordance with installation procedures (Reference: Instrumentation Installation Guidelines, DOE Report No. SOLAR/0001-77/15) and verifies that the wiring is correct before the SDAS is connected. Sensors are connected to the SDAS through a junction box which is wired according to the site Instrumentation Plan wire list and attached to the SDAS by a standard interface cable. The SDAS is connected to the National Solar Data Network through a data coupler installed by the local telephone company.

After the SDAS has been installed, checkout procedures are initiated to verify correct local operation of the sensors and data acquisition equipment, and correct transmission of data to the central facility. An on-site monitoring unit is provided to allow a direct readout of the system measurements and thereby verify that the solar energy system and the SDAS are performing correctly.

After the data acquisition equipment has been installed and checked out, data collection and analysis begins. The first step in this ongoing daily activity is the transferral of data from the on-site SDAS to the Central Data Processing System (CDPS) located at the IBM facility in Huntsville, Alabama using the standard commercial telephone network. (This data was collected during the previous day by the SDAS which scans sensor inputs several times an hour and stores raw data on a cassette tape. The Communications Processor (an IBM System/7) at the CDPS calls each SDAS daily, the SDAS identifies itself, and then rewinds the cassette tape and plays back the data.) The Communications Processor receives the data, performs error checking and formatting operations, and passes the data to the CDPS Host Computer (an IBM System/370 Model 145) for further processing.

The Host Computer prepares the data for analysis by checking for errors, preparing error reports, and updating data files. This data is then used to compute performance evaluation factors which are made available to the site analysts who review system performance on a weekly basis.

The performance evaluation factors will be used to:

1. Determine the savings in fossil fuel and electrical energy resulting from the use of solar energy for space heating, space cooling, and/or hot water.

2. Determine the total heating, cooling, and/or hot water thermal energy loads, and the fraction of each load supplied by solar energy.

3. Measure the efficiency of the solar energy system in converting solar radiation into useful thermal energy.

4. Measure the thermal performance of major subsystems or components and the thermal interactions among collector array, storage, and energy conversion components.

5. Measure the occupant's use of the system by means of parameters such as the temperature level maintained and the demand for hot water.

6. Determine the major system operational characteristics and degradation over the life of the demonstration.

7. Obtain records of the incident solar radiation and other pertinent site environmental parameters that could affect the performance of the system over the life of the demonstation.

The systematic analysis and evaluation of the data from the National Solar Data Network is reflected in the documentation produced. The Solar Energy System Description Document results from careful study of the solar energy system and its site. This document describes the system, the site, and the required instrumentation, and also predicts system performance. A Monthly Performance Report contains system status and a monthly performance tabulation generated by the CDPS Host Computer. A Solar Energy System Performance Evaualtion Report containing a more comprehensive analysis of system performance is published periodically for each site. Comparisons of data from the various sites along with multiple site evaluations are presented in the System Wide Analysis Report. Reports are also issued which pertain to special studies defined for the Demonstration Program. In addition, Solar Bulletins containing timely items of general interest to the solar energy community are widely distributed. The reports are distributed primarily through DOE's Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee, 37830.

In summary, a systematic approach has been taken for the development of data requirements, instrumentation techniques, collection procedures, and analysis methods. The program to establish a large body of data on the performance of diverse solar energy systems has been implemented using a systems approach in which all steps from site study to report generation have been formalized and centrally controlled. As installations are completed and an ever-expanding accumulation of data becomes available, the National Solar Data Network will be an indispensable resource for establishing the direction to be taken by the nation in the energy field.

PROCESSING OF INSTRUMENTED DATA FOR THE NATIONAL SOLAR HEATING AND COOLING DEMONSTRATION PROGRAM

J. T. Smok, V. S. Sohoni, and J. M. Nash

International Business Machines Corporation
Federal Systems Division
150 Sparkman Drive
Huntsville, Alabama 35805

ABSTRACT

A major goal of the National Solar Heating and Cooling Demonstration Program is the collection and analysis of data used to determine solar energy system performance. To meet this goal, the International Business Machines Corporation has developed a solar energy Central Data Processing System for the United States Department of Energy. This system is a critical component of the National Solar Data Network and provides the mechanism to: automatically retrieve data from the solar energy demonstration sites, convert sensor output data to engineering units, compute solar energy system performance, and generate selective data printouts, plots, and reports. This paper discusses the structure of the computer software and the computation techniques used in the implementation of the data collection, performance evaluation and report generation processes.

INTRODUCTION

The solar energy Central Data Processing System (CDPS) is an integral part of the National Solar Data Network (Figure 1). Although the CDPS resides at the terminal end of the system, its activity is most visible since it must accumulate, process and report on the solar energy parameters collected at the sites throughout the National Solar Data Network.

The CDPS was developed to address a major goal of the demonstration program. This goal is the collection and analysis of solar data to determine solar energy system performance. The CDPS organizes and maintains the data to ensure consistent performance evaluation and system analysis.

To achieve this objective, a set of software algorithms have been developed. These algorithms direct: retrieval of sensor data from the solar demonstration sites, required data transformation, and subsequent control of calculations to determine solar energy system performance. The CDPS is the vehicle which ties these functions into a coherent system.

DATA RETRIEVAL

The Communication Processor is the retrieval link between the Demonstration Sites and the CDPS. The Communication Processor interfaces with site data collection hardware to automatically retrieve data using a standard commercial telephone network. The onsite hardware consists of sensor instrumentation, instrumentation Junction Box (J-Box), Site Data Acquisition Subsystem (SDAS), and telephone network coupler. The SDAS, working with sensors through the Junction Box, gathers, checks for validity, and records the site measurement parameters. These data are stored on a cassette tape and, upon command from the CDPS, are transmitted by telephone to the CDPS facility.

The Communication Processor interfaces with each site's SDAS using a predetermined command and reply sequence as shown in Figure 2. The data

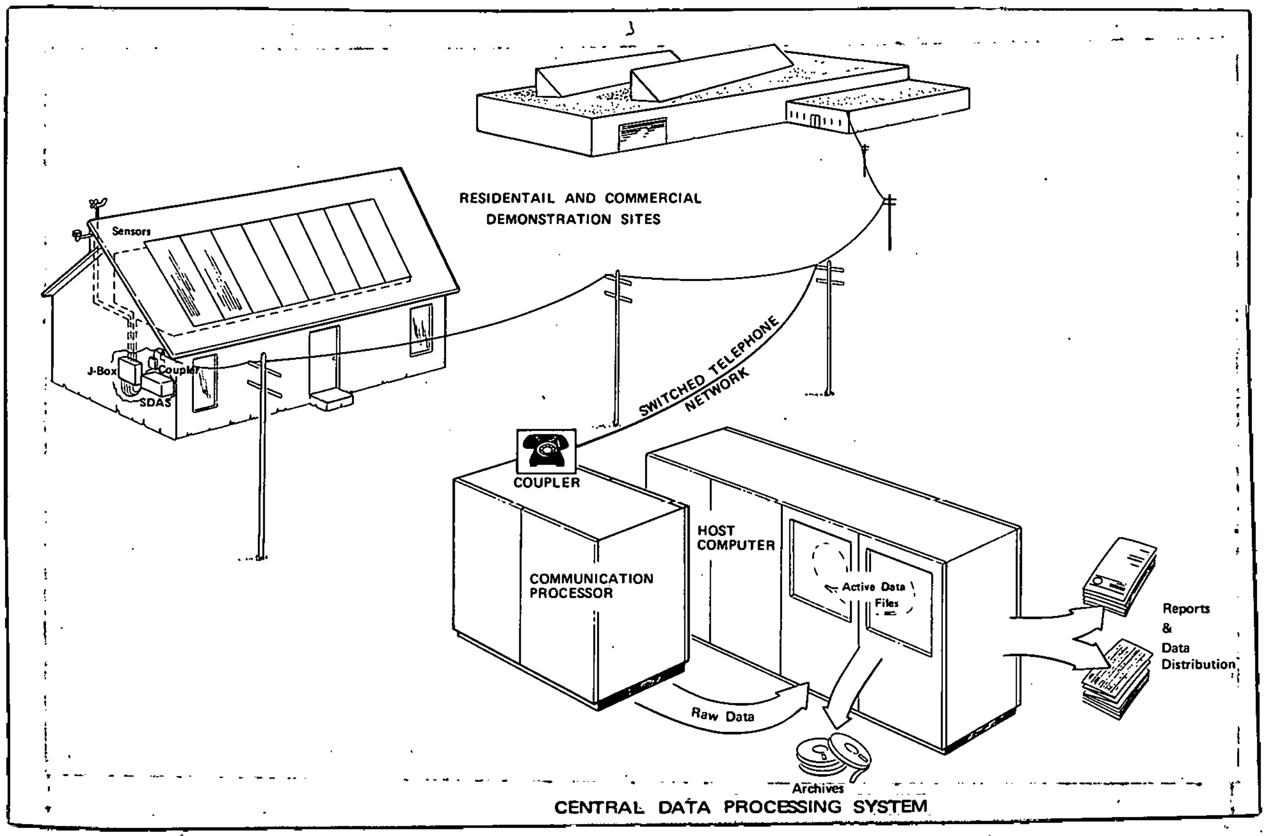

Figure 1. National Solar Data Network

collection begins with the recording of measurement data from the sensors placed on the solar energy system. The retrieval process interrupts this collection by providing an end-of-file command to the site. After an end-of-file has been written, the tape at the site is rewound. The data are then collected from the site and the tape is again rewound to restart the collection process. The tape cassette at the site is capable of holding several days worth of data. This capacity varies and is related to site instrumentation complexity, the number of SDAS units,---etc., (i.e., the more data sensors collecting data the shorter the time period the tape will hold). After the site data has been collected the Communication Processor automatically continues to the next site in the network until all sites have been contacted and their data obtained.

Upon completing site data retrieval, the Communication Processor prepares the data for transfer to the CDPS Host Computer. This data preparation is a two-step operation. The first involves calculation of a cyclic redundancy code. This code is first calculated at the site by the SDAS and is transmitted with the data to the CDPS. The Communication Processor recalculates this code based on each eight bytes of transmitted data. This second value is checked against the transmitted code for similarity. If the two values are identical, the data group has not been perturbed by the information collection, transmission, and retrieval process. If they are not identical, the data group is considered in error and flagged as invalid. Following the code calculations and comparisons, the data are formatted for acceptance by the Host Computer and transmitted over a computer-to-computer communications link. This data flow is shown in Figure 3.

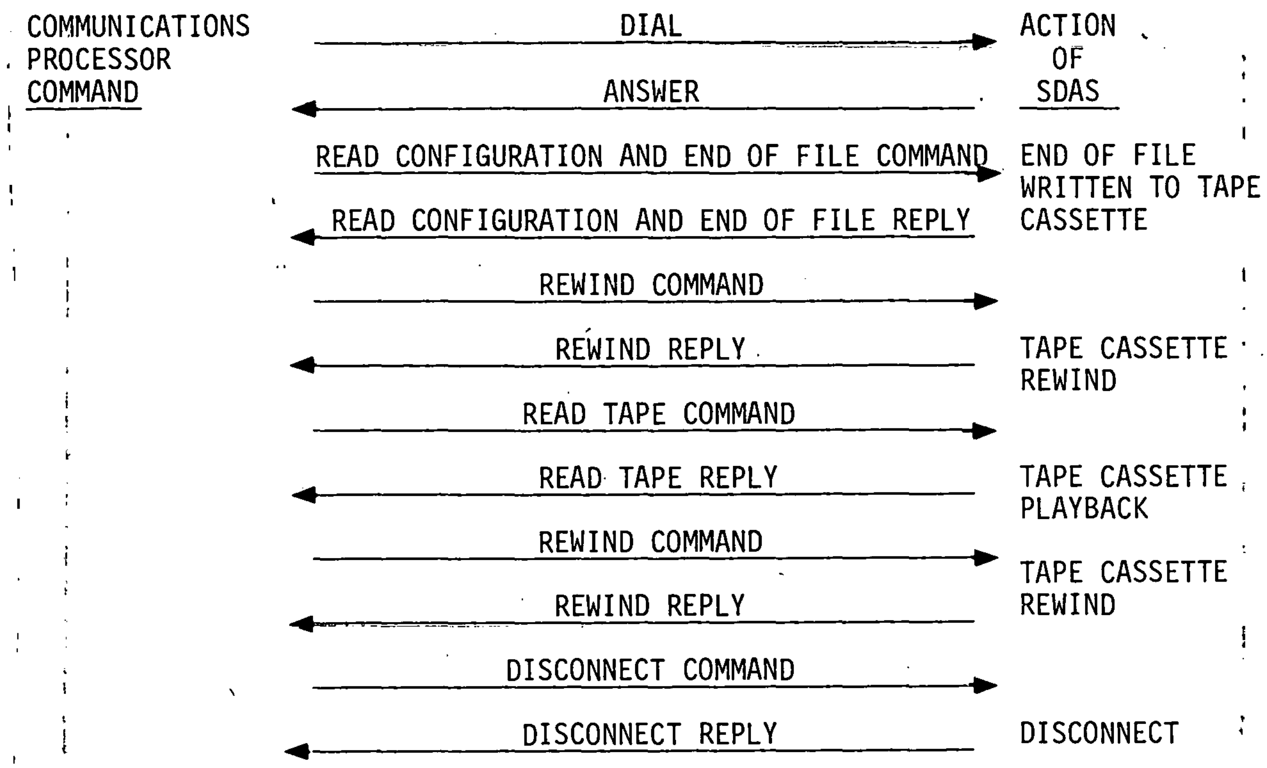

Figure 2. Communications Processor/SDAS Command/Reply Sequence

DATA CONVERSION AND TESTING

Site data transferred from the Communication Processor are operated on in three phases in preparation for use in solar energy system performance evaluation. The first phase accumulates the data on a per-site basis and converts site base time to local time. Site data are accumulated with previous data from the same site on a continuity file to provide history and traceability. Since the site SDAS uses a "relative" base time, this base time is converted to local site time for analysis and processing. These accumulated data and converted times are then provided to the second phase.

The second phase separates the accumulated site data into site data and error flag files. The site data file is further separated into sensor scan files for conversion into engineering units. This conversion is dictated by predetermined algorithms using coefficients associated with individual sensors for each site. (See Figure 4) The conversion algorithms presently provided can be either linear, quadratic, third order or discrete. Site and sensor data conversion requirements are predefined on a per-site basis and stored on a data file to be utilized during the conversion process. These converted data are passed to the final phase prior to system performance evaluation.

Converted data passed to the final step are first checked to determine if an error flag has been set. If the flag has been set, the information for that sensor for that particular scan is considered invalid. Data not noted as invalid are then tested for reasonableness. These limits are predefined for each sensor for each site. Sensor data passing all tests are accumulated in a detail record file which is merged into an active detail measurement site file for performance factor calculations. Information which has failed any of the tests is migrated to a rejected variable file for error reporting purposes.

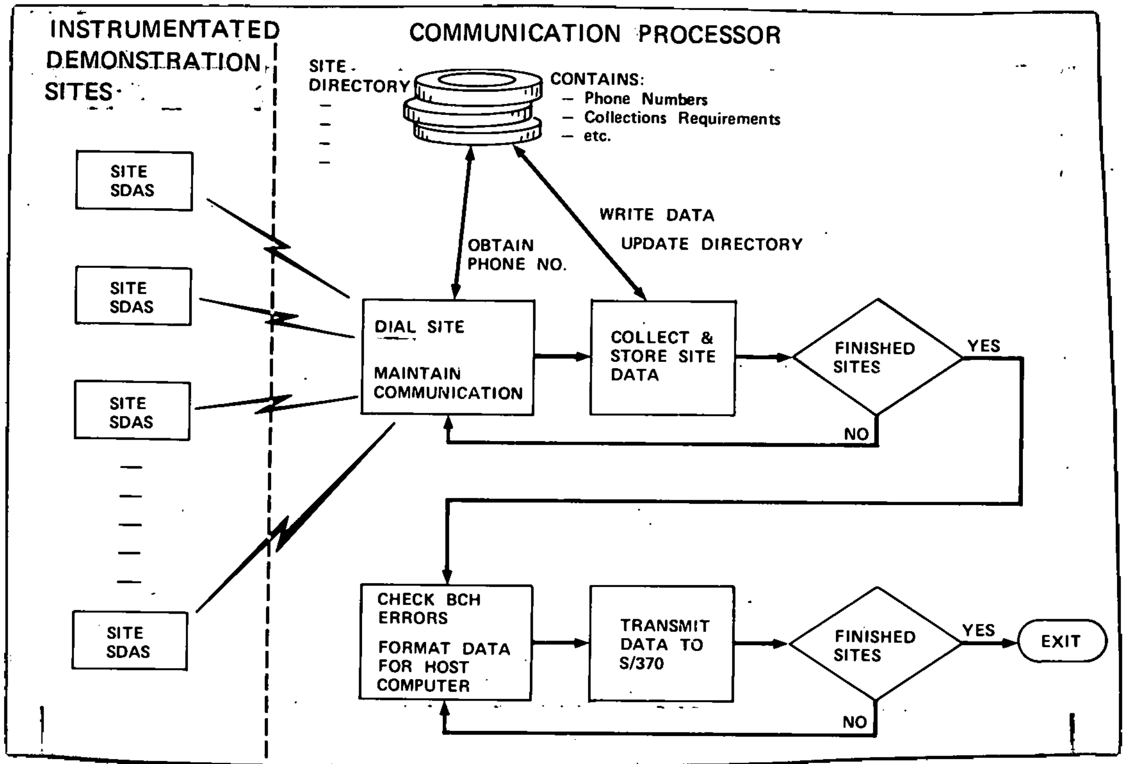

Figure 3. Communications Processor Data Flow

SYSTEM PERFORMANCE FACTOR CALCULATIONS

The solar energy system performance evaluation methodology has been set down in the intergovernmental agency developed document "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program". However, since all sites are not identical, the standard site data processing software is personalized for most sites to properly evaluate the site's system performance.

Converted and tested data passed to the system performance factor calculation phase are first operated upon in an hourly evaluation process. This hourly process obtains all detail measurements for a particular hour, and performs the computations necessary to determine the hourly performance parameters. These hourly calculations create the basis for subsequent daily and monthly system performance evaluation. In accomplishing these computations, guidelines are followed to assure performance validity throughout the parameter evaluation process. These guidelines provide the requirements for the number of valid samples used in the hourly, daily and monthly performance calculations.

For the scan periods where samples of data are determined to be in error, a "data weighting" technique is applied to the data used to represent the sample period in error. This technique varies for each level of calculations (i.e., hourly, daily and monthly).

REPORT GENERATION

Because of the large number of monitored site parameters and the many subsequent performance calculations, the amount of data processed by the CDPS is voluminous. To aid analysts in assimilating this varied information, the CDPS provides a set of output reports which can be used in monitoring the daily performance of each solar energy system. These reports include detail measurement records of converted data, reports on data errors and rejected variables, and time of day plots of monitored site data. Figures 5 through 8 illustrate typical examples of these output formats.

SDAS DATA INFORMATION FILE UTILITY PROGRAM
UTILITY RUN FOR PURPOSE OF ** ADDING A SDAS **
SDAS ID 020

DATE : 02/28/78
TIME : 0240

CODED MEASUREMENTS REPORT

MEASUREMENT		SCAN POS	LEN	NIPS POS	CONV TYPE	CONV #1	CONV #2	CONV #3	CONV #4	MINIMUM VALUE	MAXIMUM VALUE	MAXIMUM CHANGE	MUST. CHNG?
CH01	CALIB	1	2	1	L	0.000000	1.000000	0.0000000	0.00000E+00	0.00000	1024.00000	1023.000000	YES
CH03	EP100	5	2	3	L	0.000000	0.002930	0.0000000	0.00000E+00	0.00000	1.94990	1.949000	YES
CH11	EP300	21	2	11	L	0.000000	0.000976	0.0000000	0.00000E+00	0.00000	0.65000	0.650000	YES
CH21	EP400	41	2	21	L	0.000000	0.001953	0.0000000	0.00000E+00	0.00000	1.30000	1.299999	YES
CH09	F300	17	2	9	L	0.000000	0.000977	0.0000000	0.00000E+00	0.00000	1.30000	1.299999	YES
CH05	F400	9	2	5	L	0.000000	0.000977	0.0000000	0.00000E+00	0.00000	1.30000	1.299999	YES
CH07	I001	13	2	7	L	0.000000	3.039469	0.0000000	0.00000E+00	0.00000	485.40991	485.409912	YES
CH13	SP001	25	2	13	L	0.000000	1.000000	0.0000000	0.00000E+00	0.00000	1024.00000	1023.000000	YES
CH20	T001	39	2	20	T	-19.027496	0.139584	0.0000025	6.69300E-11	-19.02750	163.07999	182.109985	YES
CH22	T100	43	2	22	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES
CH24	T101	47	2	24	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES
CH02	T150	3	2	2	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES
CH10	T151	19	2	10	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES
CH26	T200	51	2	26	T	31.999786	0.128170	0.0000022	5.44200E-11	31.99899	215.17000	183.159998	YES
CH28	T201	55	2	28	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES
CH30	T202	59	2	30	T	31.999786	0.128170	0.0000022	5.44200E-11	31.99899	215.17000	183.169998	YES
CH32	T203	63	2	32	T	31.999786	0.128170	0.0000022	5.44200E-11	31.99899	215.17000	183.169998	YES
CH12	T250	23	2	12	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES
CH23	T300	45	2	23	T	-19.027496	0.139584	0.0000025	6.69300E-11	-19.02750	163.07999	182.109985	YES
CH25	T302	49	2	25	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES
CH14	T350	27	2	14	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES
CH16	T351	31	2	16	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES
CH18	T352	35	2	18	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES
CH27	T400	53	2	27	T	31.999847	0.202482	0.0000047	1.82400E-10	31.99899	317.57983	285.579834	YES

Figure 4. Data Conversion and Testing Information

As each site produces its information throughout the month, other reports are generated to present total system performance. This presentation provides a common representation of performance by using standardized system evaluation procedures. A Monthly Report Site Summary shows the information generated to describe overall system performance. (Figure 9) This information is accumulated through hourly and daily performance computations and summarized for the monthly report. Monthly system summary reports are usually accompanied by a set of subsystem summaries which provide a daily record of performance.

SUMMARY

A systematic approach has been taken in the development of the CDPS to provide the generation of a standard set of performance evaluation parameters. These standard parameters are attained through the use of site equations personalized for the various solar energy system configurations in the Demonstration Program. As more solar installations are completed and an accumulation of analysis results becomes available, the National Solar Data Network and the CDPS will serve in aiding the goals of the National Solar Heating and Cooling Demonstration Program.

ACKNOWLEDGEMENT

The processing system described in this paper was developed by Virginia Alexander, Vince Aquila, Clarence Guyette, Cecil Logan, and Louellen McNight of IBM, Federal Systems Division, Huntsville, Alabama.

DETAIL RECORD PRINT FOR SDAS 020 SITE 064 SUBTYPE 1 — RUN TIME 78/02/28 02.41 — PAGE 3

YR/MO/DA.HR.MN.SC	CH01 CH11 CH21 CH31 CH41	CH02 CH12 CH22 CH32 CH42	CH03 CH13 CH23 CH33 CH43	CH04 CH14 CH24 CH34 CH44	CH05 CH15 CH25 CH35 CH45	CH06 CH16 CH26 CH36 CH46	CH07 CH17 CH27 CH37 CH47	CH08 CH18 CH28 CH38 CH48	CH09 CH19 CH29 CH39	CH10 CH20 CH30 CH40
78/01/27 00.53.21	0.000 0.000 0.004 64.618 N.A.	44.775 54.738 60.033 60.306 N.A.	0.003 0.000 68.445 N.A. N.A.	106.959 37.065 66.151 N.A. N.A.	0.000 -462.300 81.281 N.A. N.A.	14.778 32.405 61.599 N.A. N.A.	0.000 0.709 67.376 N.A. N.A.	52.244 32.000 74.119 N.A. N.A.	0.000 0.992 63.768 N.A.	37.673 42.301 66.123 N.A.
78/01/27 00.58.41	0.000 0.000 0.004 64.335 N.A.	44.978 53.923 60.441 60.435 N.A.	0.003 0.000 68.303 N.A. N.A.	77.186 36.862 66.151 N.A. N.A.	0.000 -462.300 81.281 N.A. N.A.	11.569 32.405 61.081 N.A. N.A.	0.000 1.002 66.560 N.A. N.A.	-5.897 32.000 73.709 N.A. N.A.	0.000 1.403 63.343 N.A.	37.673 42.442 65.735 N.A.
78/01/27 01.04.01	0.000 0.002 0.002 64.335 N.A.	43.963 53.516 60.237 60.177 N.A.	0.006 0.000 68.445 N.A. N.A.	61.052 36.862 65.947 N.A. N.A.	0.000 -462.300 80.666 N.A. N.A.	13.167 32.405 60.823 N.A. N.A.	0.000 0.709 66.356 N.A. N.A.	-17.461 32.000 74.118 N.A. N.A.	0.000 0.992 63.202 N.A.	37.673 42.442 65.864 N.A.
78/01/27 01.09.21	0.000 0.000 0.406 64.335 N.A.	47.213 51.482 59.218 60.177 N.A.	0.205 0.000 67.877 N.A. N.A.	105.722 36.659 65.947 N.A. N.A.	0.982 -462.300 80.666 N.A. N.A.	14.778 32.405 60.823 N.A. N.A.	0.000 0.000 65.335 N.A. N.A.	1066.739 32.000 74.323 N.A. N.A.	0.000 0.992 63.060 N.A.	37.470 42.301 65.994 N.A.
78/01/27 01.14.41	0.000 0.004 0.199 65.043 N.A.	46.400 52.092 59.218 60.823 N.A.	0.085 0.000 68.445 N.A. N.A.	153.360 36.862 66.151 N.A. N.A.	0.000 -462.300 80.666 N.A. N.A.	11.569 32.607 61.598 N.A. N.A.	0.000 1.002 66.968 N.A. N.A.	99.867 32.000 74.119 N.A. N.A.	0.000 0.000 63.768 N.A.	36.659 42.161 65.605 N.A.
78/01/27 01.20.01	0.004 0.000 0.004 64.618 N.A.	45.384 54.738 60.033 60.564 N.A.	0.000 0.000 68.728 N.A. N.A.	112.112 36.862 66.151 N.A. N.A.	0.000 -462.300 81.281 N.A. N.A.	14.778 32.607 60.952 N.A. N.A.	0.000 1.417 66.764 N.A. N.A.	40.533 32.000 74.118 N.A. N.A.	0.000 0.992 63.626 N.A.	36.659 42.442 65.605 N.A.
78/01/27 01.25.21	0.000 0.000 0.004 64.901 N.A.	44.775 53.720 59.829 60.564 N.A.	0.006 0.000 68.445 N.A. N.A.	80.666 36.862 65.947 N.A. N.A.	0.000 -462.300 80.871 N.A. N.A.	11.569 32.607 60.952 N.A. N.A.	0.000 0.709 66.968 N.A. N.A.	17.259 32.000 74.323 N.A. N.A.	0.000 1.403 63.485 N.A.	37.065 42.161 65.476 N.A.

Figure 5. Detail Measurement Report

```
INPUT PROCESSING SYSTEM. CONVERSION OF RAW INPUT TO DETAIL RECORDS BEGUN FOR SDAS 020        RUN TIME 78/02/28 02.41
SITE:064-WASHINGTON NATURAL GAS          SUBTYPE:1    ANALYST:UNKNOWN          ENGINEER:UNKNOWN
SDAS DATA INFO REV TIME     78/02/28 02.40
SDAS CLOCK BASE TIME        77/01/06 18.55.29
PREV SDAS CLOCK BASE TIME   77/11/17 23.09.21
  #RAW_DATA_RECORDS     4         #RAW_DATA_BYTES     752        #BCH_ERRORS      0
STREAM PROCESSING COMPLETED WITH ERROR CODE  0
SCANSEP
SCANSEP:SCAN WITH TIME 78/01/28 13.21.31 HAS BEEN DROPPED BECAUSE OF A TIME JUMP. SDAS=020
  DATA BLOCKS      TOT:    1     OUTPUT:     1      REJECTED:    0
  SCANS            TOT:   11     OUTPUT:    10      REJECTED:    1
  #RAW_DATA_BYTES       EXPECTED:    752        ACTUAL:     752
SCANSEP PROCESSING COMPLETED WITH ERROR CODE  8
CNVTEST
  TIME OF PREV LAST SCAN 78/01/28 08.48.01
  TIME OF FIRST SCAN       78/01/28 13.21.37
VARIABLE CH13    HAS CONSTANT VALUE          0.000
  TIME OF LAST SCAN        78/01/28 14.15.29
  #_OF_SCANS_OUTPUT       10
  ANALYSIS BY VARIABLES
```

VARNAME	#OUT_OF_LIMITS	#BCH_ERRORS	#CHNG_TOO_FAST	#REJECTED	MIN_VALUE	MIN_VALUE_TIME	MAX_VALUE	MAX_VALUE_TIME
CH01	0	0	0	0	0.000	78/01/28 13.21.37	0.094	78/01/28 13.26.57
CH03	0	0	0	0	0.003	78/01/28 13.21.37	0.223	78/01/28 13.54.09
CH11	0	0	0	0	0.000	78/01/28 13.26.57	0.001	78/01/28 13.21.37
CH21	0	0	0	0	0.002	78/01/28 13.26.57	0.461	78/01/28 13.54.09
CH09	0	0	0	0	0.010	78/01/28 13.37.37	0.012	78/01/28 13.21.37
CH05	0	0	0	0	0.000	78/01/28 13.21.37	0.455	78/01/28 13.54.09
CH07	0	0	0	0	3.039	78/01/28 13.37.37	6.079	78/01/28 13.21.37
CH13	0	0	0	0	0.000	78/01/28 13.21.37	0.000	78/01/28 13.21.37
CH20	0	0	0	0	43.992	78/01/28 13.54.09	44.978	78/01/28 13.21.37
CH22	0	0	0	0	58.810	78/01/28 13.54.09	60.645	78/01/28 13.32.17
CH24	0	0	0	0	63.499	78/01/28 13.21.37	64.519	78/01/28 14.10.09
CH02	0	0	0	0	61.052	78/01/28 13.59.29	62.887	78/01/28 14.15.29
CH10	0	0	0	0	63.703	78/01/28 13.37.37	64.315	78/01/28 13.26.57
CH26	0	0	0	0	59.015	78/01/28 13.54.09	60.823	78/01/28 13.32.17
CH28	0	0	0	0	65.131	78/01/28 13.54.09	66.151	78/01/28 13.32.17
CH30	0	0	0	0	60.435	78/01/28 13.54.09	61.081	78/01/28 13.21.37
CH32	0	0	0	0	56.562	78/01/28 13.32.17	57.207	78/01/28 14.04.49
CH12	0	0	0	0	62.479	78/01/28 13.49.47	63.499	78/01/28 13.59.29
CH23	0	0	0	0	62.635	78/01/28 13.32.17	63.060	78/01/28 13.26.57
CH25	0	0	0	0	64.723	78/01/28 13.37.37	65.947	78/01/28 13.48.47
CH14	0	0	0	0	66.151	78/01/28 13.59.29	67.172	78/01/28 13.21.37
CH16	0	0	0	0	66.968	78/01/28 14.04.49	68.193	78/01/28 13.32.17
CH18	0	0	0	0	72.493	78/01/28 13.37.37	73.505	78/01/28 13.21.37
CH27	0	0	0	0	58.607	78/01/28 13.49.47	59.625	78/01/28 14.10.09
CH29	0	0	0	0	58.531	78/01/28 14.10.09	59.946	78/01/28 13.48.47
CH04	0	0	0	0	60.849	78/01/28 13.49.47	119.512	78/01/28 13.54.09
CH31	0	0	0	0	57.259	78/01/28 14.10.09	57.683	78/01/28 13.37.37
CH06	0	0	0	0	13.167	78/01/28 13.54.09	16.401	78/01/28 13.48.47
CH15	0	0	0	0	-7.746	78/01/28 13.54.09	-2.896	78/01/28 13.21.37
CH17	0	0	0	0	0.000	78/01/28 13.26.57	1.417	78/01/28 13.37.37
CH19	0	0	0	0	0.702	78/01/28 13.21.37	1.559	78/01/28 14.15.29
CH08	0	0	0	0	-29.032	78/01/28 13.32.17	99.867	78/01/28 13.54.09

```
CNVTEST PROCESSING COMPLETED WITH ERROR CODE  0
DATA FOR SDAS 020 PROCESSED WITH HIGHEST ERROR CODE  8
```

Figure 6. Error Report

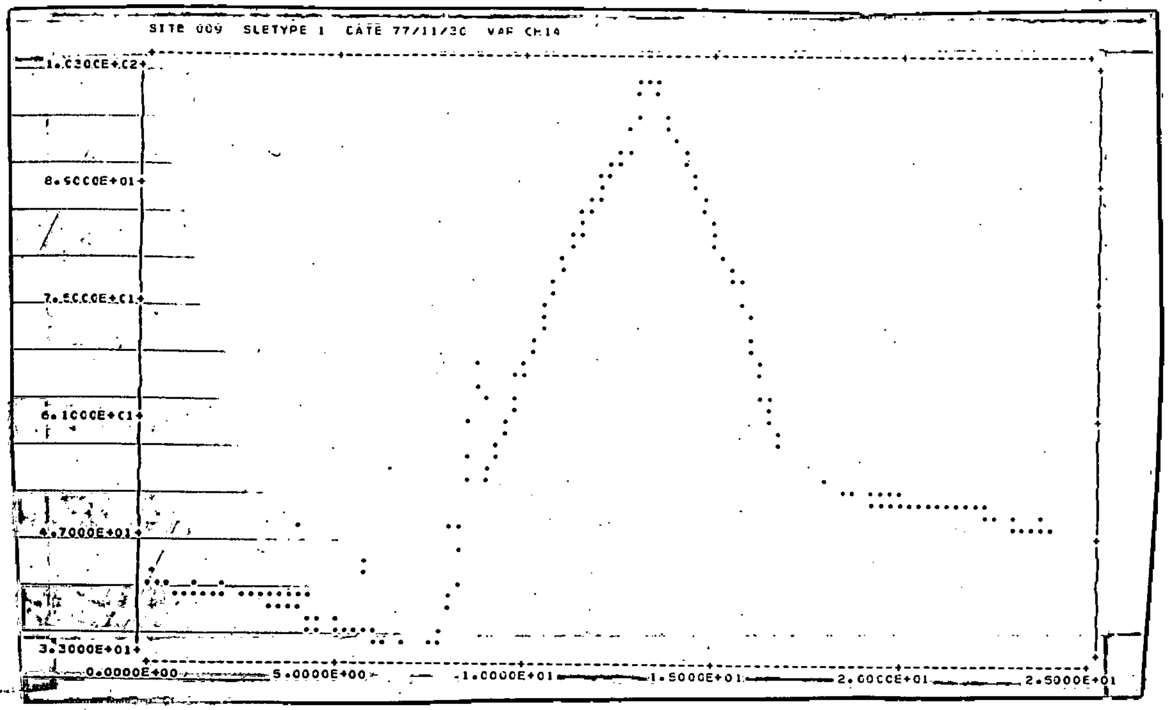

Figure 7. Single Page Plot

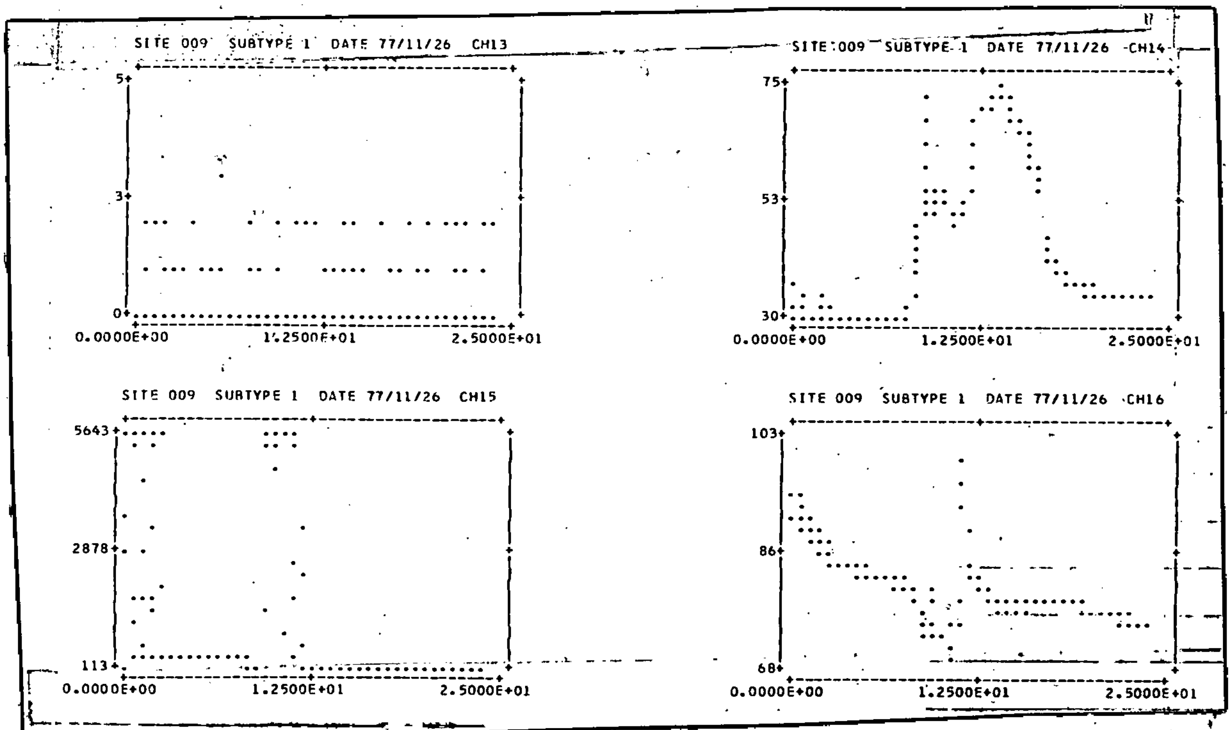

Figure 8., Multiple Plots/Single Page

SOLAR HEATING AND COOLING DEMONSTRATION PROGRAM

MONTHLY SITE REPORT

SUMMARY

SITE: RADIAN, INC.
REPORT PERIOD: SEPTEMBER, 1977

SOLAR/2002-77/09
REPORT DATE: 22 OCTOBER 1977

SITE/SYSTEM DESCRIPTION: THE RADIAN INSTALLATION IS A HEATING/COOLING SYSTEM DESIGNED TO SERVICE APPROXIMATELY 800 SQUARE FEET OF A SMALL OFFICE BUILDING. THE SOLAR PORTION IS DESIGNED TO SATISFY 100% OF THE LOAD AND FUNCTION IN PARALLEL WITH A CONVENTIONAL GAS-FireD HEATING ELECTRIC VAPOR PARALLEL COMPRESSION COOLING SYSTEM. THE SOLAR SYSTEM WILL EMPLOY THE NORTHROP CONCENTRATING, TRACKING COLLECTOR, AN ARKLA 501-WE LITHIUM BROMIDE COOLING UNIT WITH A 7-1/2 TON MARELY COOLING TOWER AND 1500 GALLONS OF WATER STORAGE.

GENERAL SITE DATA:

INCIDENT SOLAR ENERGY	20.454 GIGA JOULES
	629068 KJ/SQ. M.
COLLECTED SOLAR ENERGY	1.294 GIGA JOULES
	39823 KJ/SQ. M.
TOTAL ENERGY CONSUMED	9.011 GIGA JOULES
AMBIENT TEMPERATURE AVERAGE	28 DEGREES C
BUILDING TEMPERATURE AVERAGE	23 DEGREES C
ECSS SOLAR CONVERSION EFFICIENCY	0.00

LOAD SUBSYSTEM SUMMARY:

	HOT WATER	HEATING	COOLING	TOTAL	
LOAD	NA	0.000	15.636	15.628	GIGA JOULES
SOLAR FRACTION	*	100	0	0	PERCENT
SOLAR ENERGY USED	NA	0.000	0.000	0.000	GIGA JOULES
OPERATING ENERGY	NA	0.000	0.000	0.214	GIGA JOULES
AUX. THERMAL ENG.	NA	0.000	NA	0.000	GIGA JOULES
AUX. ELECTRIC FUEL	NA	NA	7.505	7.505	GIGA JOULES
AUX. FOSSIL FUEL	NA	0.000	NA	0.000	GIGA JOULES
ELECTRICAL SAVINGS	NA	*	0.000	*	GIGA JOULES
FOSSIL SAVINGS	NA	0.000	NA	0.000	GIGA JOULES

SYSTEM PERFORMANCE FACTOR: 0.61

* - DENOTES UNAVAILABLE DATA
NA - DENOTES NOT APPLICABLE DATA

REFERENCE DOCUMENTS:

Figure 9. Monthly Report Site Summary

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THERMAL DATA REQUIREMENTS AND PERFORMANCE EVALUATION PROCEDURES FOR PASSIVE BUILDINGS*

BY

William Ducas
Elmer Streed
Thermal Solar Program

John Holton
Solar Criteria and
Standards Program

Center for Building Technology
National Engineering Laboratory

and

William Angel
Thermophysics Division
Center for Thermodynamics and Chemical Kinetics
National Measurements Laboratory
National Bureau of Standards
Washington, D. C. 20234

ABSTRACT

A systematic classification of passive solar buildings and performance factors are proposed to standardize the evaluation procedures. Two measurement levels are described with appropriate sensors and data acquisition systems to obtain detailed data for complete component and system evaluation or to obtain "critical" data for evaluating the energy saved at many sites.

INTRODUCTION

An assessment of solar heating and cooling technology has indicated that although passive systems are in general use, quantitative performance data for the thermal processes are lacking and the design of a particular passive heated and/or cooled building for quantitative comparison with another passive or actively heated and/or cooled buildings is difficult (1). At the request of the Department of Energy (DoE), the National Bureau of Standards (NBS) has undertaken a project to prepare a reference document that will provide for the systematic and standard classification, instrumentation, evaluation and reporting of the thermal performance of passive components, systems and buildings.

The objectives of the measurement and data analysis program are as follows:

1. Determine energy savings of fossil fuel and electrical power
2. Determine the fraction of the building hot water, heating and/or cooling load contributed by the passive method
3. Evaluate the passive component characteristics and verify analytical models
4. Determine the building comfort level and establish a method of comparing with conventional buildings
5. Determine the extent of occupant interaction required for functional performance or other operational requirements

* This paper was presented at the Second National Passive Conference, Philadelphia, Pa., March 15-17, 1978.

6. Determine the system degradation for the measurement period
7. Obtain insolation and other ambient environmental data for design and evaluation purposes
8. Establish practical, cost effective passive building thermal performance measurement methods

The data requirements necessary to achieve these objectives are determined using an approach as shown below:

1. Establishment of pertinent performance factors
2. Determination of the type, accuracy, range and frequency of required measurements
3. Identification of appropriate instrumentation
4. Recommendation of data analysis and reporting techniques

Performance factors defined with appropriate equations are presented for the three categories of passive/solar energy systems including: direct gain, indirect gain, and isolated gain. These performance factors are similar to the active solar system factors previously established (2). The factors are obtained by measurement and/or calculation of essential temperatures, heat flow rates and energy balances of building components and systems and human comfort.

At least two levels of evaluation are required to meet the needs of the consumer, building contractor, architect engineer, regulatory official and economist or planner, two types of instrumentation packages are described. The simple system is capable of providing data on auxiliary energy usage and the interior comfort level. For systems under evaluation for both component and system thermal performance, a relatively full complement of sensors and a data acquisition and recording system will be described. A special system capable of performing special measurements for such things as air movement and gradients, temperature profile infiltration and localized heat leaks may be required for short time periods to completely characterize the system/building performance.

CLASSIFICATION

In assessing the thermal performance of buildings that utilize solar energy or natural energy sinks for heating or cooling, it is recognized that certain types of designs function very effectively with relatively little mechanically powered assistance. These buildings and/or systems which are designed for thermal energy flow between a collector, a storage mass occupied space by natural means: radiation, convection and conduction are known as PASSIVE SYSTEMS. If these changes all involve forced flow, the system is considered ACTIVE. If some of the exchanges are by natural means and some by forced flow, the system is considered HYBRID. Energy used for control of these flows is not considered in the classification but low energy consumption is clearly most desirable (3).

All buildings to some extent are affected by the solar radiation source and the sky heat sink to which they are exposed, and develop a dynamic energy balance with this outside environment. In considering a building or system for evaluation purposes as a passive system, it is appropriate to limit consideration to those designs which "consciously manage" these effects for the beneficial use of the building occupancy. This may be done by static building design means or by more complex management methods which employ changeable elements to manipulate dynamic energy conditions.

Generally, the same functional elements exist for passive systems as for active systems such as the collector, storage and control mechanisms. However, while physical distinction between passive system elements and building elements are not always possible, a passive system, whether it be an entire building or a group of components, consists of a number of elements which have specific performance characteristics and interrelationships.

Experience to date suggests that three categories of passive systems classify the primary thermal exchange interrelationships between the occupied space, the system elements, and the natural heat source (solar) or sink (outside environment). These categories described in Table 1 and illustrated in Figure 1 are: 1) direct gain, 2) indirect gain, 3) isolated gain. The sensitivity with which solar gain or heat loss may be modulated for the benefit of the occupant is the key parameter in determining these categories and it is this classification that forms the basis for the passive thermal performance evaluation procedures in this document.

In a direct gain system, there is a direct thermal exchange link between the occupied space and the natural heat source/sink. Consequently, the occupied space environment will be most sensitive to natural heat source/sink variations. For the indirect gain systems, the occupied space is linked to the collector or storage element for thermal exchange but is not directly linked to the natural heat source/sink. Therefore, variation in occupied space conditions due to changes in the natural heat source/sink are moderated by the characteristics of the intervening collector or storage elements. The isolated gain system is characterized by distinct thermal separation of the occupied space from collector storage elements such that thermal exchange between the occupied space and these elements occurs only through a transfer medium flow (air, liquid) which may be controlled as desired.

Performance Evaluation Approach

The items listed below outline the key elements for the approach to obtain, evaluate and compare thermal performance data.

° Measurements for passive/hybrid buildings will be taken on two levels.

(i) one level will be detailed, where on site sensors will provide data to determine: solar energy contribution on a component and system basis, auxiliary energy requirements, building heating and/or cooling load, comfort level and climatic conditions. This detailed level is recommended for a limited sample of selected generic designs.

(ii) the second level consists of limited sensors to monitor: the building auxiliary energy requirements, interior space temperature and outdoor air temeprature. This reduced level of instrumentation is applicable to a large sample of passive/hybrid buildings.

° Measurements for conventional buildings representative of local regions would be at the reduced level, provided this data were not already available.

° Selected passive/hybrid and conventional buildings will be analytically modeled to predict building and system thermal response as a function of use and measured climatic conditions.

- ° A typical general building nodal model for analytical predictions is illustrated in Figure 2, which may be generated to simulate a passive/hybrid or conventional building. The predictions for each model will be compared with measured data to validate the analysis. Validated analytical models may then be used to predict performance on similar buildings having reduced level or no instrumentation at all.

- ° The results of the above efforts are either measured/calculated building thermal performance or analytical generated (and validated) thermal performance or both for a specific building.

Therefore, the comparison between buildings may be made with any combination of analytical or measured results to determine energy saved. The specific conventional buildings chosen for comparison should be representative of typical local construction with at least the established minimum building standards.

- ° Additional field test data may be necessary to characterize performance as a function of time or resolve differences between predicted and measured performance.

The complete paper will be available and distributed at the Conference.

REFERENCES

1. Proceedings Passive Solar Heating and Cooling Conference, Los Alamos Scientific Laboratory, LA-6637-C, Albuquerque, N.M., May 18-19, 1976.

2. Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program, National Bureau of Standards, NBSIR 76-1137, Washington, D.C. August 1976.

3. Yellott, J.I., "Passive Solar Heating and Cooling Systems", ASHRAE Transactions, Volume 83, Part 2, 1977.

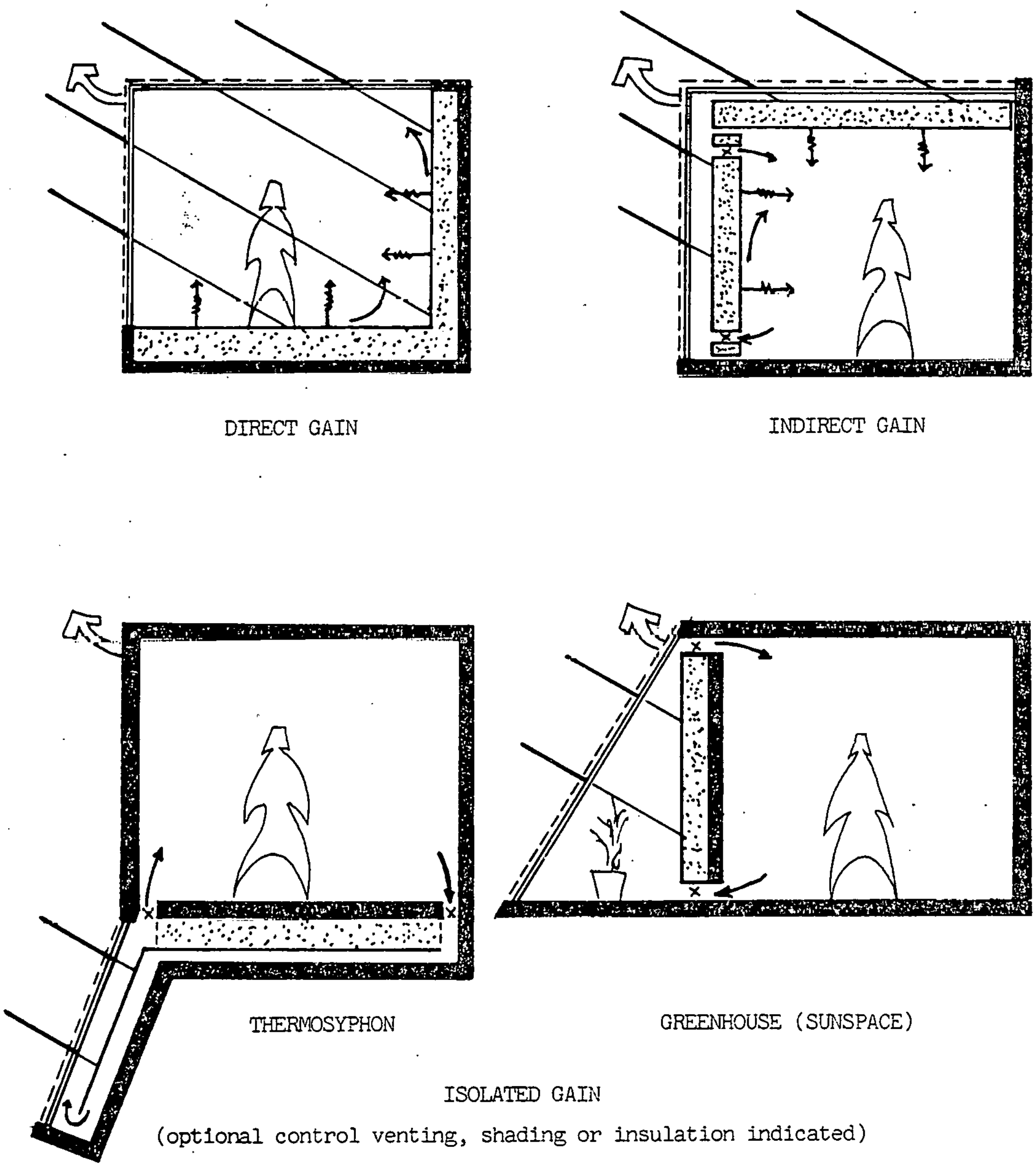


FIGURE 1 BASIC PASSIVE HEATING SYSTEMS

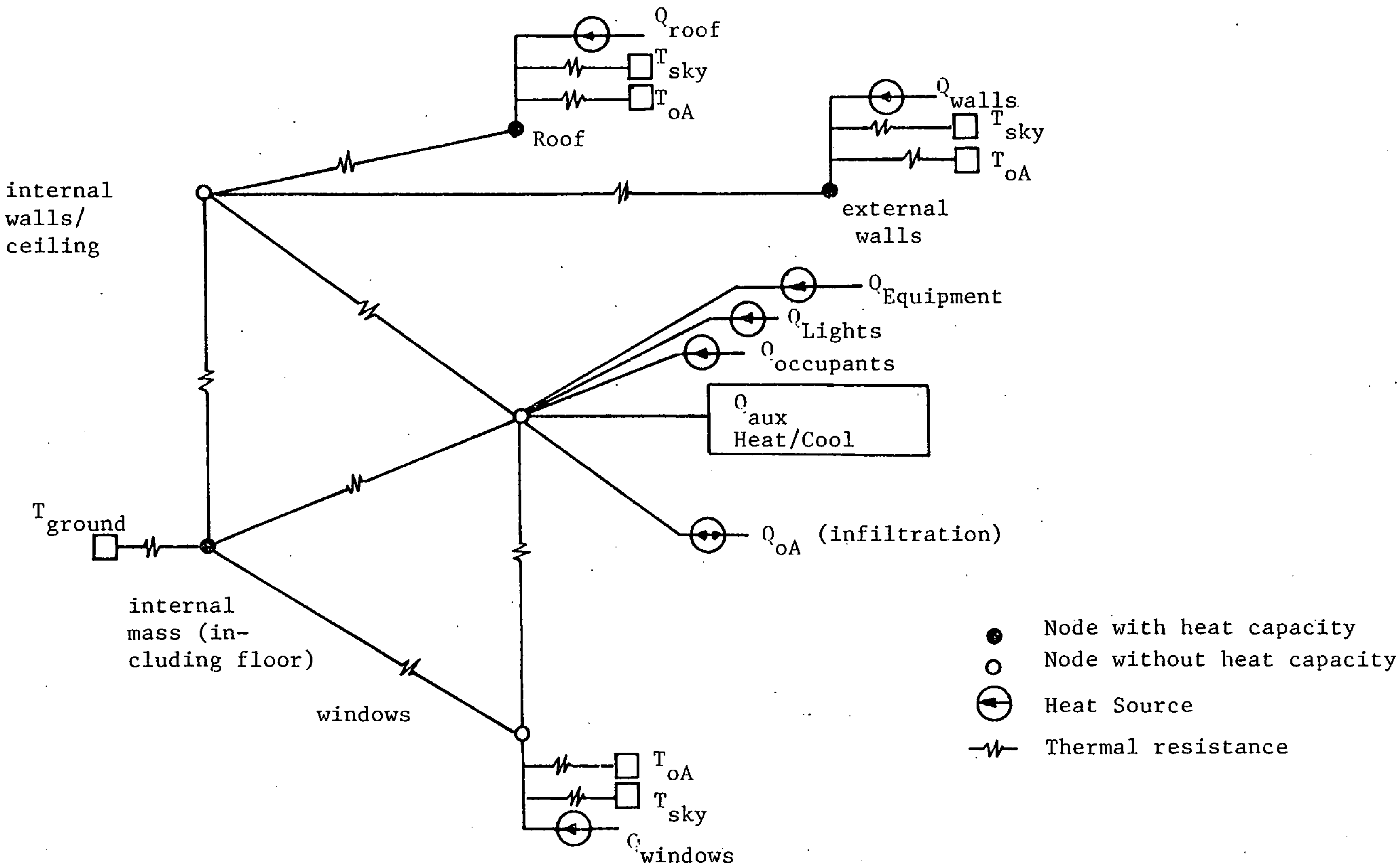


Figure 2. Nodal Diagram of Overall Building and Environment

TABLE 1

PASSIVE SYSTEM ELEMENTS & CLASSIFICATION FOR SPACE HEATING OR COOLING

Elements	Classification		
	Direct Gain	Indirect Gain	Isolated Gain
OCCUPIED SPACE	Heat gain (loss) primarily through aperture; direct link to natural source/sink.	Heat gain (loss) directly to (from) collector and/or storage; indirect link to natural source/sink.	Heat gain (loss) from transport medium linked to isolated collector (or storage).
APERTURE (Opening to natural environment source/sink)	Forms a surface of the occupied space.	Separated from occupied space by collector and/or storage.	Separated from occupied space by collector and transfer.
COLLECTOR	Surfaces of occupied space.	Linked directly to storage and/or occupied space or to storage through transfer medium.	Linked to transfer medium and/or storage; isolated from occupied space.
STORAGE	In elements forming or within occupied space.	Linked between collector and occupied space.	Linked to transfer medium and/or collector; isolated from occupied space.
CONTROL	Regulation of heat gain/loss via: movable insulation or shade over aperture, modulating vents in occupied space, movable aperture.	Regulation of heat gain/loss via: movable insulation or shade over aperture, modulating vents in occupied space, transfer medium flow control.	Regulation of heat gain/loss via: movable insulation or shade over aperture, modulating vents in occupied space, transfer medium flow control.
EXAMPLES	Direct gain space. Greenhouse-extention of space.	Storage wall (solid-w/air circulation) (solid-w/o air circulation) (liquid) (phase-change) Storage roof (solid) (liquid-skytherm) Greenhouse-storage directly linked to space. Thermosyphon-storage directly linked to space (liquid or air transfer medium).	Thermosyphon-collector and storage isolated from space (liquid or transfer medium). Induced draft ventilation. Greenhouse-isolated from space linked via transfer medium.

COLLECTION OF DATA FOR ESTIMATING
THE PROBABLE LIFE CYCLE COSTS
OF SOLAR ENERGY SYSTEMS

Russell B. Stauffer
Dynamics Research Corporation
Wilmington, Massachusetts 01887

ABSTRACT

Broader utilization of solar energy systems has been inhibited by a lack of understanding of the economics involved. The cost equation contains too many variables which are subject to broad uncertainties.

The paper suggests that the problem becomes more tractable if "hard" and "soft" data are treated separately so that areas of uncertainty are defined and can be compensated for.

STATEMENT OF THE PROBLEM

Despite the ecological benefits accruing from the use of the sun's rays as a source of energy and the fact that they are not, like other energy sources, subject to depletion; broad utilization of solar energy has been inhibited by the lack of adequate knowledge of the economics involved. The questions arise not only from a lack of understanding of the individual elements which make up acquisition, operational and maintenance costs ofthe solar-powered system but also from uncertainties related to the costs of alternative systems, particularly fuel costs and from uncertainties related to the general world economic situation.

In this paper, we shall suggest that, if we can separate the individual elements which combine to generate Life Cycle Costs, it becomes clear as to which elements can be measured in specific terms and with a high degree of certainty, and which may vary widely from a purely economic standpoint which has no direct relationship to the use or non-use of solar energy. We can then group the certain or "hard" factors as we evaluate the cost equations and use the uncertain or "soft" factors to evaluate the effect of their deviation from some standard value on the total cost.

ASSUMPTIONS

Although we believe that the concepts which are outlined would be applicable to any use of solar energy, we have, for the sake of brevity, limited our discussion to residential space and hot water heating. By so doing, we can assume that the system will not require special engineering design (i.e. Design Costs can be ignored). We can also eliminate consideration of the multiple financing alternatives which might be available to the industrial user.

Our final assumption is that the operational and maintenance costs are based on a "perfect" weather model. While such a model clearly does not presently exist, and its absence introduces uncertainties other then the economic ones, we have chosen to deal with one problem at a time.*

*Recommendations for the design of a novel "Weather Simulation Model" are the subject of another paper currently being prepared by the auther.

BASIC COST EQUATION

The basic equation for estimating the Life Cycle Cost of a solar energy residential space or hot water heating system combines the acquisition, operational and maintenance costs of both the solar system and the conventionally fueled backup system, which would be essential in all but a few locations. The equation takes the form:

$$LCC = \left[A_S+A_B\right] + \sum_{i=1}^{n} \left[(O_S+M_S)_i+(O_B+M_B)_i\right] \quad (1)$$

where:

A = Acquisition Cost
O = Operational Cost
M = Maintenance Cost
and n = Number of years in the study
and S&B are subscripts identifying the solar and backup systems

In the following paragraphs, we shall examine the elements which contribute to A, O & M and their "hard and "soft" subordinate factors.

ACQUISITION COSTS

From the point of view of the residential consumer, the cost of a solar energy powered space or hot water heating system would appear to be the simple sum of the prices charged him by the manufacturer for both the solar and the conventionally fueled backup system plus the local labor and materials costs for installing the two systems. In this case, the first part of the basic cost equation could be written as:

$$\left[A_S+A_B\right] \equiv \left[(P_S+I_S)+(P_B+I_B)\right] \quad (2)$$

where:

P = Manufacturer's Price
I = Installation Cost

and the subscripts "S" and "B" have the same definition as before.

To be sure, P_S itself is determined principally from the square feet of collector area and the required storage capacity of the system while P_B derives from the expected efficiency of the solar system. It must be remembered, however, that both P_S and P_B are complex functions of the quantities and prices of raw materials, the hours and skill levels of labor required for manufacturing and assembly, hourly labor rates, overhead allowances and desired profit, all of which are beyond the knowledge or control of the ultimate consumer. He simply signs a contract with a manufacturer whose system meets his requirements and whose price he believes to be acceptable.

If he is fortunate enough to be able to pay "cash on delivery" for the system, Acquisition Cost will probably represent the most certain element of Life Cycle Cost. If, like most of us however, the cost will be financed as part of a home mortgage, cost takes on a new dimension and Eq. (2) must be rewritten as:

$$\left[A_S+A_B\right] = \left[(P_S+I_S)+(P_B+I_B)\right] + FC \quad (3)$$

where:

FC = Financing Cost

and the other variables are defined as before.

FC, in turn, is a function of four variables

$$FC = f([A_S + A_B], R, VM_i, n)$$

where:

R = Interest rate
n = number of years of financing
and VM_i = the Value of Money in year "i"

Let us now examine which of the elements of $[A_S + A_B]$ represent "hard" data, i.e. can be determined with a reasonable degree of certainty.

Even if we break P and I into their constituent parts of materials quantities, material unit costs, labor hours, **hourly** labor rates, etc. we can, assuming the manufacturing process takes place within a reasonable time frame (say less than a year), obtain good estimates of these quantities. The major unknown remains FC. If we write that function in equation form, we have

$$FC = \sum_{i=1}^{n} FC_i = \sum_{i=1}^{n} [A_S + A_B]_{i\ bal} [R][VM]_i \qquad (4)$$

where

$[A_S + A_B]_{i\ bal}$ = Unpaid balance of acquisition cost in year "i"
R = Interest rate
VM_i = Value of Money in year "i"

Here again, everything with the exception of VM_i is "hard" data. VM_i which is related to the inflation rate is the only uncertain quantity. Since its only effect is on FC, we can temporarily set that term aside and consider it later as a separate entity.

OPERATIONAL COSTS

Except in the most benign of climates, any residential space or hot water heating system which utilizes solar energy as a source of power will always require some form of conventionally fueled backup system. Therefore, operational costs are the sum of the costs of operating the solar and the convetionally fueled system. Extracting the O_S and O_B terms from Equation (1) we can write:

$$O_i = (O_S)_i + (O_B)_i = (D_S)_i + (D_B)_i + (F_B)_i \qquad (5)$$

where:

O_{S_i} and O_{B_i} are as previously defined
D_{S_i} = Cost of distributing the heat supplied by solar energy in the year "i"
D_{B_i} = Cost of distributing the heat supplied by conventional fuel in the year "i"
F_{B_i} = Cost for conventional fuel in the year "i"

Assuming that, for the most part, the distribution cost is essentially the cost of electric power to drive a fluid pump of some sort, we can write:

$$(D_S+D_B)_i = (KW_S+KW_B)*(ER_i) \qquad (6)$$

where:

KW_S = Annual electric power consumption for solar system (in kilowatt hours)

KW_B = Annual electric power consumption for backup system (in kilowatt hours)

ER_i = Cost per KWH for electric power in year "i"

Note that once more (assuming perfect weather model) all of the variables in Eq. (6) except ER_i can be estimated with reasonable certainty. For ER_i, the uncertainty will, for the most part, be the result of inflation and some factor related to the cost of the fuel consumed in generating power. In simple terms, we can write:

$$ER_i = (ER_o)\left[\left(\frac{1}{VM_i}\right) + FAW_i\right] \qquad (7)$$

where:

ER_o = Cost per KWH for electric power in some base year

$\frac{1}{VM_i}$ = Inflation factor for year "i" (the reciprocal of the Value of Money used in Eq. (4))

FAW_i = Fuel Adjustment Charge in year "i" for each KWH of power used

It is FAW_i that represents the greatest degree of uncertainty in this portion of Eq. (5) and it is doubly critical since it will also appear in slightly different form as a part of the $(F_B)_i$ term, which we can expand to read:

$$(F_B)_i = (UF)(FCU_i) \qquad (8)$$

where:

UF = Units of fuel consumed annually

and FCU_i = Cost per unit of fuel in the year "i"

In the same way that we rewrote the ER_i in Eq. (7) we can rewrite FCU_i in Eq. (8) as:

$$FCU_i = (FCU_o)\left[\left(\frac{1}{VM_i}\right) + FAU_i\right] \qquad (9)$$

where

FCU_o = Cost per unit of fuel in some base year

$\frac{1}{VM_i}$ = Inflation factor for year "i"

FAU_i = Fuel adjustment charge in year "i" for each unit of fuel consumed

In Eq. (7) and (8) we have introduced three uncertainties into the cost equation. One of them, VM_i, appeared first in Eq. (4) and has been the subject of numerous economic studies. As of the date of this writing (1978) the inflation rate appears to be generally accepted as 7%; so that if "i" is set equal to ("Then" date–1978) we would set

$$VM_i = (1 - 0.07)^i = (.93)^i \qquad (10)$$

FAW_i and FAU_i, on the other hand, are mush less susceptible to logical thinking. The respond not only to the affects of inflation but are also established, in large measure, by the whims of the OPEC nations. Our recommendation, therefore, is that these terms be isolated and evaluated separately to determine their effect on the total cost.

MAINTENANCE COSTS

In all of the preceding discussions, we have attempted to reduce the equations to their most logical forms, i.e. to examine only those elements which clearly contributed to cost. However, as we move into the area of Maintenance Costs, we are forced to consider a more detailed level. Where, for example, we considered UF in Eq. (8) to be units of fuel consumed annually, we must, at the next level of detail, write UF_i as:

$$UF_i = (UF_h)(H_i) \tag{11}$$

where

UF_h = Units of fuel consumed per hour
H_i = Hours of operation in year "i"

In the consideration of Maintenance Costs, we must resort to this level of detail (considering both H_{S_i} and H_{B_i}) since the number of failures and the resulting maintenance will be a direct result of the operational time. Indeed, ignoring the subscripts in Eq. (1), we can say that for either M_S or M_B:

$$M_i = (H_i)(FF)\left[(MATF_i)+(LABF)(LR_i)\right] \tag{12}$$

where

H_i = Hours of operation in year "i"
FF = Failure frequency per hour
$MATF_i$ = Average materials cost per failure in year "i"
LR_i = Average labor rate in year "i"
LABF = Labor hours per failure repair

Once more, if we assume that we have a reasonable engineering knowledge of both the solar and backup systems and have an acceptable Weather Model, we can place reasonably certain values on everything except $MATF_i$ and LR_i. These two elements will be subject to inflation and Eq. (12) should be written as:

$$M_i = (H_i)(FF)\left[(MATF_o)+(LABF)(LR_o)\right]\left[\frac{1}{VM_i}\right] \tag{13}$$

where

$MATF_o$ = Materials cost per repair in some base year
LR_o = Average labor rate in some base year

and the other variables are as previously defined.

SUMMARY

If we consider all of the above equations in the most expanded form to which we have subjected them, we find that the elemental parameters can be grouped into three categories, depending upon the external condition which controls their value. The results of such a distribution are found in Table I.

TABLE I

Engineering	Weather	Economics
P_S	KW_S	R
I_S	KW_B	VM_i
P_B	H_i	ER_o
I_B		FAW_i
UF_h		FAU_i
FF		FCU_o
MATF		LR_o
LABF		

A second examination of these parameters in terms of the "hard" and "soft" categories discussed previously suggests that, given a reasonable experience base, all of the terms in the Engineering column could be classified as "hard" as could those in the Weather column if we make the assumption that whatever weather model we use for the study is the best that is available.

In the Economic column, things become a bit fuzzier. For the initial year of any study we can be reasonably certain about ER_o, FCU_o and LR_o and for any given case we can fix R. The uncertainties are VM_i, FAW_i and FAU_i, though the latter two are so closely related that an assumption about one automatically fixes the other.

An additional uncertainty, which has so far been omitted from the discussion, is the possibility of Government participation in financing through the use of tax incentives. Used, in a negative way, to encourage the use of solar energy, these incentives might take the form of a higher tax on conventional fuels. In the equations above, this would be accounted for by an increase in the FAU_i and FAW_i terms.

Used in a positive sense, the tax incentives could take the form of an investment tax credit for the installation of a solar-powered heating or hot water system and/or allowable annual income deductions for the operation and maintenance of such a system. In the former case, the $[A_S+A_B]$ term would be decreased by some fixed amount. In the latter case, both the O_i and M_i terms would be reduced by some factor related to the tax bracket of the individual purchasing the system.

CONCLUSIONS

It is clear from the equations that a large fraction of the variables which combine to make up the Life Cycle Cost of a solar-powered heating system could, with a reasonable data base, be established with a fair degree of certainty. The limited number of variables which remain can, after simple re-arrangement of the terms of the equations, be treated as multipliers or additive factors. In this role they can be tested over a wide range of values for their effect on Life Cycle Cost without the necessity of re-evaluating the total package.

It is our conclusion, therefore, that the collection of data for estimating the Life Cycle Cost of solar energy powered systems should concentrate on those terms which can be measured with a high degree of certainty, (i.e. those in the Engineering and Weather columns of Table I). Once we have confidence in the values we assign to these parameters, we can accept the uncertainties in the remaining terms and set reasonable limits on the confidence we may have in our final estimates of Life Cycle Cost.

ACCELERATION OF SOLAR HEATING APPLICATION VIA IMPROVED DATA EVALUATION

Andrew E. Scoville
Dynamics Research Corp.
60 Concord Str.
Wilmington, MA 01887

Drew A. Gillett
Brookhaven National Laboratory
Solar Technology Transfer Program
Upton, L.I. N.Y. 11973
Chairman, New England Solar Assn.

ABSTRACT

Growth of solar applications can be accelerated by adequate evaluation of accumulating data since certain problems can be ameliorated by comprehensive data base management and analysis. This paper illustrates progress resulting from more thorough engineering analysis and suggests methods of extracting definitive information from larger data bases.

STATEMENT OF PROBLEM

It is the authors' belief that one essential element in the drive to harness solar energy is a thorough scientific evaluation of the data now being collected from solar demonstration projects as well as data from other current and future solar experience. A diversity of problems hinders the widespread application of solar techniques (see Chart A). Many of these problems can be minimized by proper evaluation of the growing data base associated with the DOE/HUD solar demonstration projects and other solar experience.

Growth to date has not occurred without significant and repeated problems, particularly with regard to performance, durability and reliability. Very little publication of the results of testing and monitoring in usable form has occurred. The difficulty revolves around the amount and complexity of the data, the diversity of data user requirements, and the inherent inaccuracies involved in distilling useful information from systems whose output is a function of so many widely fluctuating variables (see Chart B).

The lack of a coordinated method for evaluating current operating system results is unfortunate since many benefits could be derived from existing solar experience; e.g., improved system performance, reduced system cost, more immediate feedback to buyers resulting in better user selection and satisfaction, improved knowledge of maintenance requirements, more accurate performance estimates and finally, accelerated growth of solar applications and hence fossil fuel conservation.

An illustration of the significance of the problem of inadequate evaluation of operating system results can be made by considering a case where adequate monitoring and evaluation has taken place. Briefly, in 1976 New England Electric System (NEES) undertook to have 100 solar domestic hot water systems installed and monitored. The preliminary results published in June 1977 were not encouraging. No systems had met the design goals, several had frozen, incurring permanent structural damage, and some had even had a net energy loss for the year. Further, costs had been greatly underestimated and savings overestimated. Needless to say, the preliminary findings led to concern for the future of solar applications in the Northeast.

A study was commissioned by Brookhaven National Laboratory's Solar Technology Transfer Program to extract maximum information from this data base. The engineer for the study, R. O. Smith and Associates, P.E., Newton, MA, was charged to examine the mechanical performance, record a matrix of mechanical troubles versus system components and make recommendations for future actions. Much more has resulted from this study than a 100-page report. Attention has been focused on faulty conventional components and faulty installation as a major cause of system failure. Among the actions that can be traced to the study's conclusions -- HUD has initiated solar installer training courses for potential installers of HUD's hot water initiative systems, New England Solar Energy Assoc. has initiated courses for do-it-yourself installers, an installers' association has been formed to improve installer quality, guidelines for solar consumers have been issued, Massachusetts' Solar Action Office has published an installation checklist, some conventional components have been redesigned for solar use, some system types have been found unsuitable for use in northern climates, NEES has expanded the experiment to include 50 additional systems with resulting improved performance, and finally, costs, although not reduced, have stablized. In short this small project has galvanized action throughout the solar industry by improved evaluation and dissemination of operating system results. The benefits of a comprehensive evaluation of a national or a regional solar data base by methods outlined below are substantial.

SOLAR DATA REDUCTION METHODOLOGY

Extracting maximum information and benefits from the solar demonstration projects present two types of difficulties. The first type is associated with the large number of factors influencing the results and the random nature of some of these factors. Refer again to Charts A and B. These problems would exist even with ideal, accurate monitoring of the projects. The second type of difficulty is always present when working with data collected in the "real world"; for example, improper placement of sensors, measurement errors and gaps in the data.

The data itself must be organized in a data base that has several key attributes including: 1. means for checking data validity before entry, 2. chronological ordering to permit time-line analysis, and 3. flexible and rapid data retrieval. The data evaluation activity requires an interactive approach between the data base and analysts who have both theoretical and practical knowledge of solar systems and their economics. Finally, the randomness associated with much of the data makes it necessary to use computerized evaluation methods based on stochastic processes.

The means for checking data validity should utilize both automatic procedures and trained data technicians. The computerized methods can check formats, data chronology and variations outside of specified brackets. Data technicians check flagged data and verify information.

Engineers further validate by considering physical models of the systems that generated the data. Confidence levels can then be assigned to the basic accuracy of the information utilizing both knowledge of the instrumentation and statistical tests of the data itself. Analysis proceeds by designing "experiments" to test various hypotheses and simulation models with the data. Model equation coefficients, correlation coefficients and influence sensitivities can be directly determined in most cases. The models thus established can be used to identify major problems, suggest areas requiring attention, determine optimum design parameters, make accurate predictions of system performance, and determine the economics associated with various tradeoffs. The methods being studied by the authors for solar data analysis, listed below, are utilized by Dynamics Research Corp. for large data systems.

Standard Statistical Methods -- include means for evaluating distributions and variability of data, and determination by 'linear regression' of the best fit line for two-dimensional data. These methods are basic to all of the techniques that follow.

Multiple Linear Regression -- provides a method to evaluate the combined effect of two or more simultaneous influences on a system. For example, the output of a solar system may be optimized to a greater cost effectivensss by considering the combined impacts of several design constants at once rather than optimizing the system for each design constant separately.

Time Series Analysis -- evolved from Fourier analysis and the autocorrelation function, provides a more realistic and accurate model for noisy, time varying functions than does linear regression. Regression only provides the coefficients for the best match to a preselected equation, whereas this method defines the equation that best matches the function including its variability. It can be used to characterize massive amounts of data; for example, weather experience, and thus could lead to faster, rigorous solar system simulations.

Kalman Filtering for Parameter Estimation -- provides a computer algorithm for setting values of an operating system, a 'plant', or an equation in order to gain a desired response; for example, maximum output, minimum error, or a specific dynamic response. It is based on the statistics of the inputs to a system and has been particularly successful for linear systems. In solar data analysis it could be used to determine coefficients or parameters for simplified reduction computations. It could possibly also be used for computer control of the operation of a complete heating/cooling system including the solar portion, backup conventional equipment, storage, air conditioning, and the distribution network.

Numerical Search Techniques for Parameter Optimization -- provides a means to determine optimum design and operating parameters for systems including those with non-linear characteristics which the other approachs cannot generally handle. There are several numerical methods available.

Statistical Experimental Design Using Factorial Analysis -- selects 'variables' in experimental design to efficiently determine their interactions and to determine the theoretical minimum number of experiments necessary to gain specific information. This is significant because of the high cost of solar 'experiments', each consisting of a system and building with specific design parameters, usage patterns, and geographic location operated and analyzed for several years. Conversely, factorial analysis can be used to maximize the information that can be extracted from a limited number of experiments.

CONCLUSION

A coordinated approach to solar system monitoring, data collection and data base management; data reduction by state-of-the-art methods and effective dissemination of the results, including accurate assessments of system performance and influence factors; hardware reliability, maintainability, life-cycle-costs, and usable information for buyers can lead to achievement of DOE goals for solar application.

CHART A
PROBLEMS THAT HINDER WIDESPREAD UTILIZATION OF SOLAR HEATING

- Initial Costs Resistant to Reduction [2]
- Marginal Return-On-Investment [2]
- Almost Infinite Variety of Approachs [1&2]
- Statistical Nature of Weather [1&2]
- No Single, Simple, Ideal Solution [1&2]
- Difficult to Focus on Best Solutions [1&2]
- Zoning, Codes, Taxes, and Craft Resistance [2]
- Retrofit Difficulties for Existing Buildings [1]
- Complexity of Solar Heating Factors [1&2]
- Commitment for Each Realistic Experiment [2]
- Time Required to Run Each Experiment [1&2]
- Experiment Results Not Universal [1&2]
- Difficult to Obtain & Disseminate Information [2]
- How to Gauge National Energy Impact [2]

1. Problem involves random events
2. Problem can be minimized by comprehensive data base/analysis

CHART B -- SOLAR SYSTEM DESIGN VARIABLES

- Active Vs Passive
- Working Fluid, Liquid Vs Air
- Flat Plate Vs Concentrating
- Number and Type of Cover Sheets
- Back Insulation Amount
- Modular Vs Architecturally Integrated
- Per Cent of Heating to be Supplied
- Ratio of Storage Capacity to Collector Area
- Minimum Temperature for Delivered Heat
- Distribution System Parameters
- Usage Patterns (Commercial, Residential, Schools)
- Sun's Path Vs Horizon Profile (Trees, Buildings, Etc.)
- Local Weather Patterns and Solar Insolation
- Fuel Prices Predicted for Economic Comparisons
- System Costs, Initial & Life Cycle

TECHNIQUE AND INSTRUMENTATION FOR MEASURING THE PERFORMANCE OF INTEGRATED SOLAR HEATING/COOLING SYSTEMS

Calvin M. Wolff
Northrop Services, Inc.
16915 El Camino Real
Houston, Texas 77058

INTORDUCTION

A technique is proposed for measuring the performance characteristics of integrated solar heating/cooling systems. The technique uses an instrumentation/control package that is easily installed and removed. Briefly, the features of this technique may be characterized as follows:

- limited to forced draft distribution systems, but may have pneumatic or hydronic heat transfer media
- includes air conditioning and heat pumps
- does not require ideal solar conditions (but at least average)
- dwelling may be occupied during testing
- average building load required
- requires six days of running
- automated; data and programs recorded on cassette tape which can be forwarded to a central data reduction system (e.g., NBS, DOE) for reduction
- may be run manually
- journeyman level personnel required to install and operate pack.

This measurement package and technique is being designed to rate a solar system in a manner that will ultimately establish an acceptable rating standard (e.g., ASTM, ASHRAE). The package will evaluate the following parameters:

- collector subsystem efficiency and loss rates
- fraction of collector subsystem loss attributed to non-collector components
- storage capacity and loss rate
- distribution subsystem efficiency
- distribution subsystem energy delivery as a function of storage temperature and duct return air temperature, for heating and cooling, including heat pumps
- energy delivered per energy absorbed (conversion efficiency)
- useful per annum energy deliverable by the system.

SYSTEM DESCRIPTION

The system consists of thermocouples, flowmeters, wattmeters, a pyranometer, humidity transducers (for cooling only), auxiliary electric heaters (230 volt, 6 kilowatt), and a microprocessor based data acquisition/control system (See Figure 1). Data acquisition is performed using multiplexers reading single programmable gain amplifiers through an analog to digital (A/D) converter. The thermocouple (T/C) reference block temperature is measured with an RTD. The duct outlet T/C's (TDi) (see Figure 2 for deployment of instrumentation) are thermopiled, with reference junctions being at the return air inlet (TAR).

A crucial device is that for measurement of air circulation (mass flow) rate in the ducting. One method is described as follows: A differential

FIGURE 1 MEASUREMENT PACKAGE

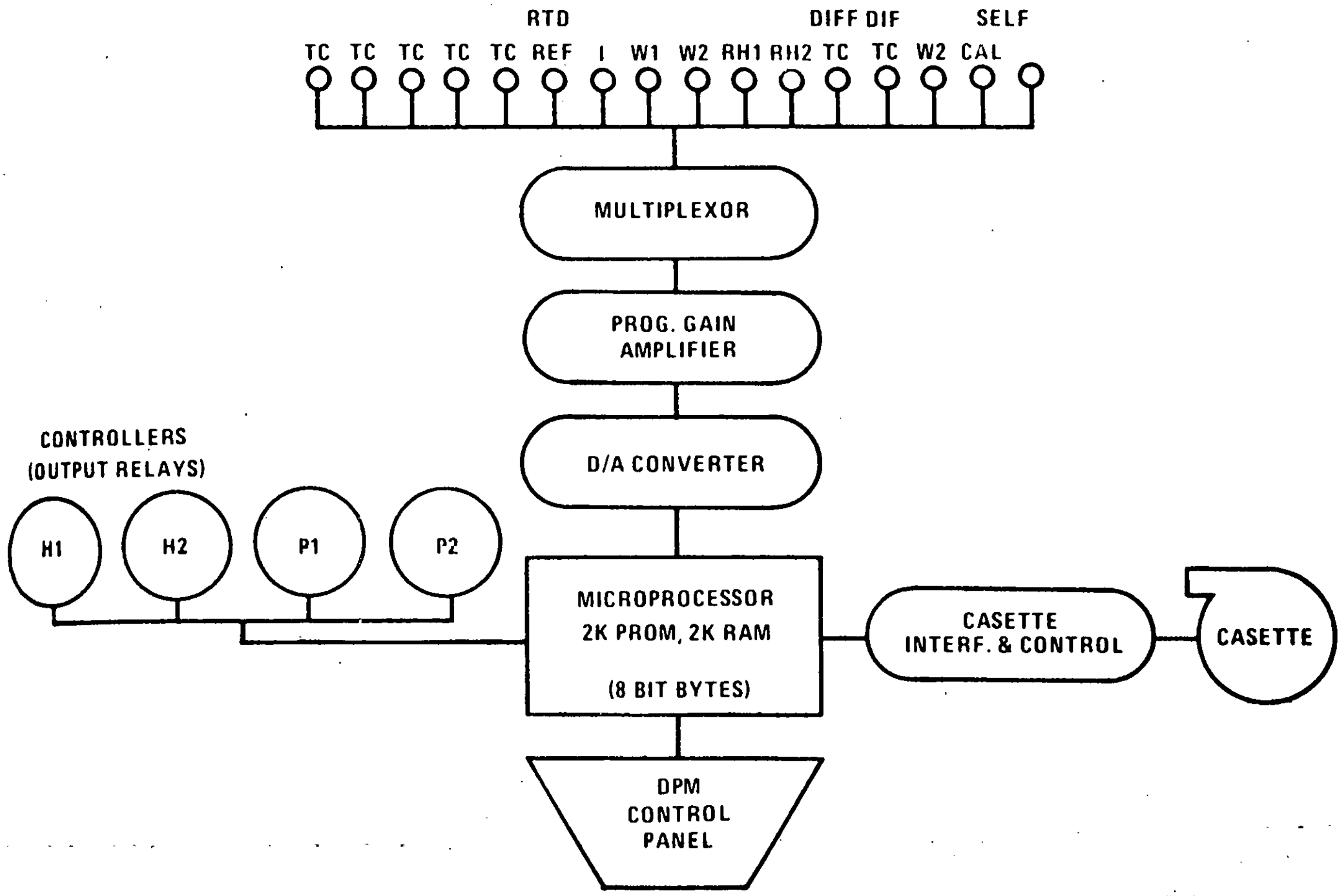
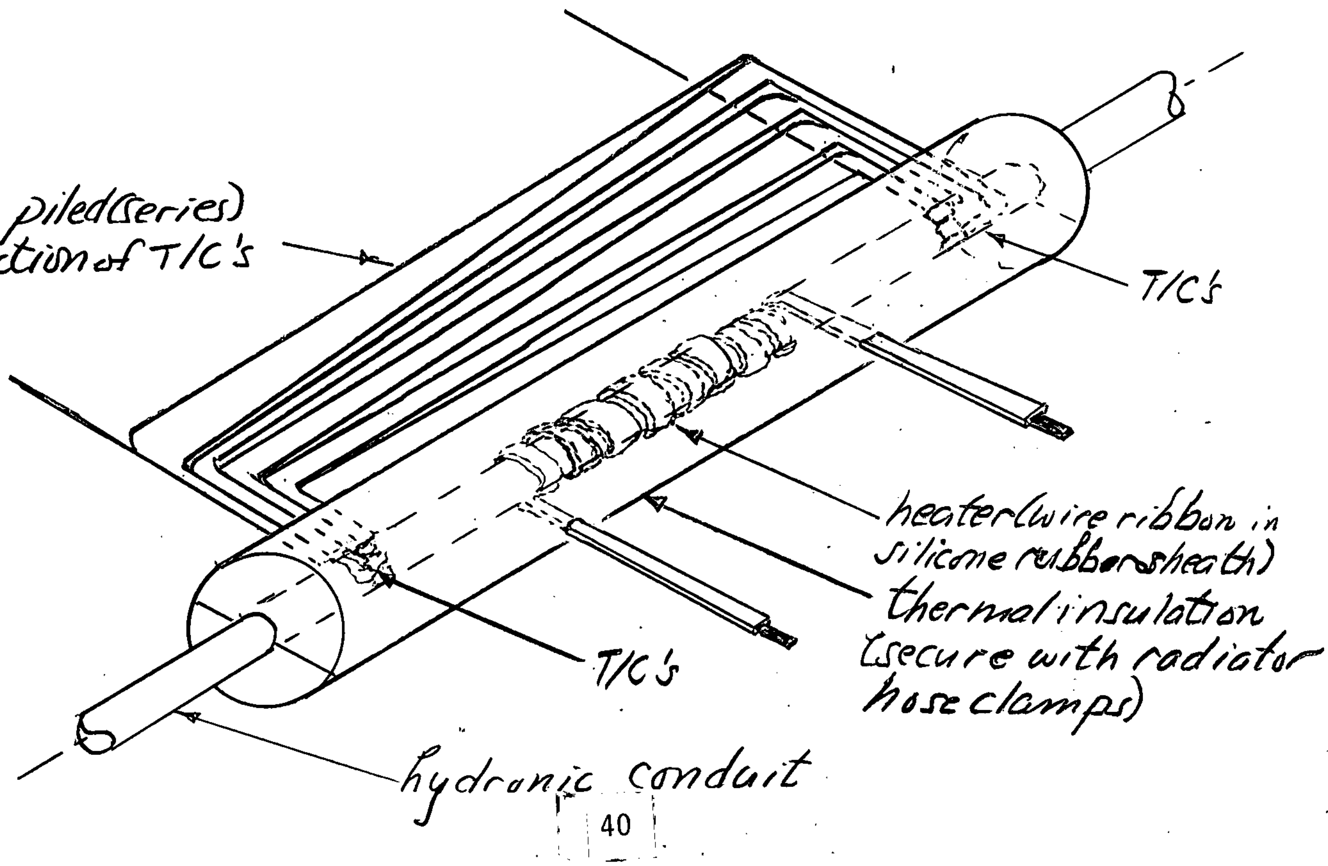


FIGURE 3
HYDRONIC FLOWMETER



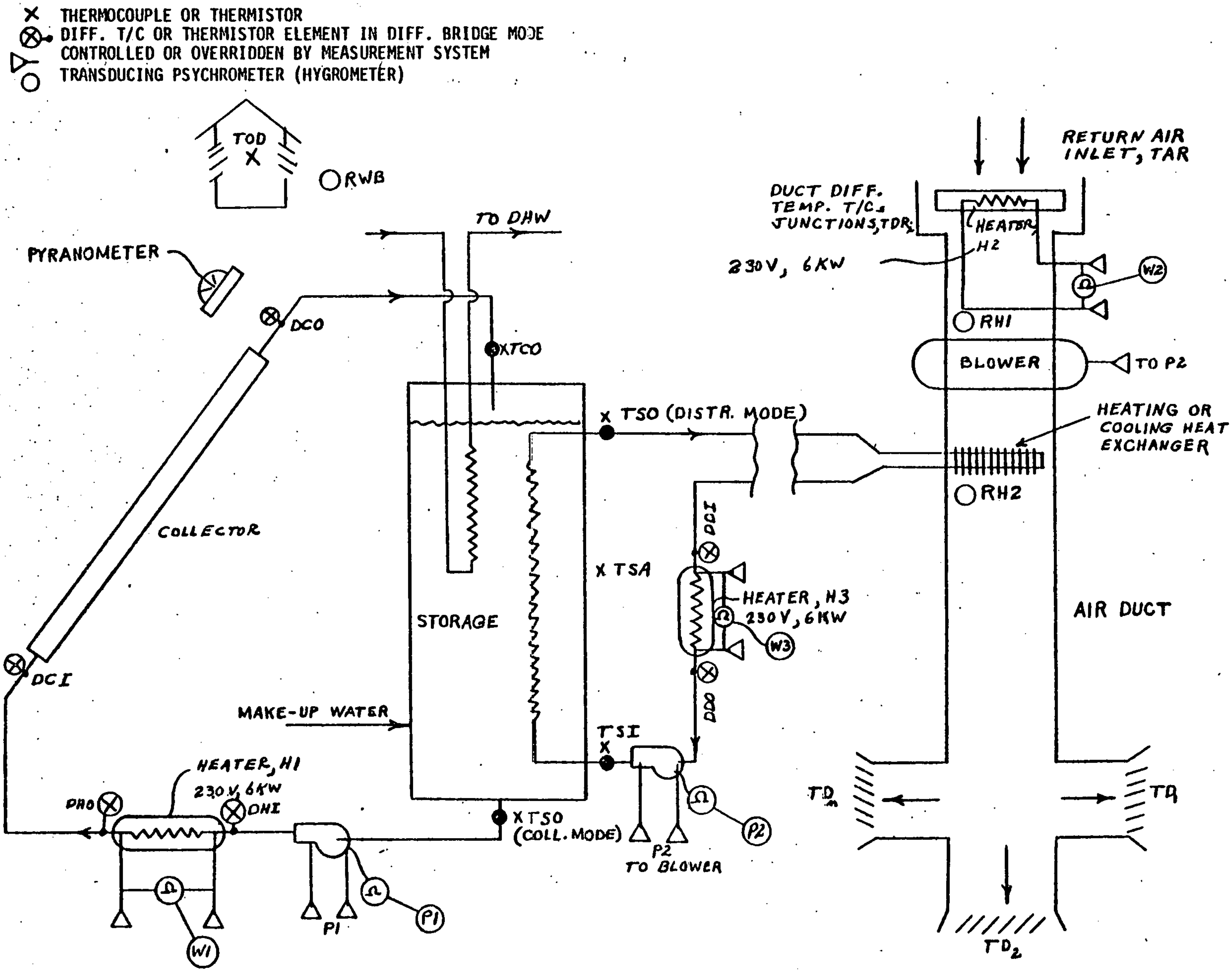


Figure 2. TYPICAL DEPLOYMENT OF SYSTEM

thermocouple is made by placing T/C's at the outlet vents, with reference junctions at the inlet vent, as described above. An electric heat load with a wattmeter (H2, W2) is inserted in the ducting in front of the blower (preferably) or just inside the return air vent (convenient access). The heat delivered to the duct air would then be:

$$\dot{Q}_{DUCT} = \left[\frac{W2}{T_2}\right]_{CALIBRATION} \cdot \Delta T_{OBSERVED}$$

The mass flow of air in the duct is then

$$G_2 = \left[\frac{W2}{C_{P_{AIR}} \quad T_2}\right]_{CALIBRATION}$$

Absolute temperature corrections may be made to refine the data, compensating for changes in air density. This same principle is used for measuring mass flow rate in the collector loop. An electric heater is introduced in series in the loop (H1, W1) with a differential T/C at each end (1-2" away) of the heater. Mass flow rate, G1, is then determined by $W1/(C_p \Delta T_1)$. This heater (H1) also augments solar energy in charging storage during various phases of the test and provides high collector temperatures for efficiency determinations. In a similar manner, the distribution loop mass flow, G_3, is measured by insertion of a heater (H3) and differential thermocouples, the flow being

$$G_3 = \frac{W3}{C_{p_{air}} \Delta T_3}$$

The technique just described is in lieu of making the more accurate mass flowrate measurement using flow meters in liquid systems and pitot rakes in air systems. The accuracy of the technique described will be determined during this effort.

PROCEDURES

The procedures described in this section were written for the most prevalent solar heating and cooling systems, i.e., those that use flat plate liquid collectors, liquid storage, and an air circulation subsystem for delivering energy to, or from, the occupied space. However, it is not intended that these procedures be restrictive. As the effort proceeds it is anticipated that the procedures will be expanded to encompass other systems and subsystems.

A key feature of the procedures outlined is that many of the major energy performance factors (collector subsystem loss ($\dot{Q}_{CL}$), storage outlet temperature (TSO), air heating rate ($\dot{Q}_{HTR}$), air cooling rate ($\dot{Q}_{A/C}$), etc.) will be characterized in the form of simple polynominals. The coefficients of these polynomials will be determined from measurements taken during the following outlined procedures.

1.0 Install Measurement System

1.1 Install heater H1 in collector loop. This may be facilitated if the collector loop is equipped with fittings to directly install and divert flow through H1.

- It is not necessary to "break into" a hydronic loop to install H1. This can be achieved by attaching inexpensive, flexible "strip" heaters to the conduit exterior. The insulation must of course be removed to do this, and must be replaced by sufficient insulation to have an "R" value of 4 over the heated section, and half the heater section length of either side of the heater. The heater could remain permanently installed. It is very important to maintain good thermal contact between heater and conduit. For temporary installations, thermal grease may be placed between heater and conduit, the heater then covered with a metal sheath, and the sheath secured with clamps, spaced approximately 4" apart. See Figure 3.

- For forced air collectors, immersion heaters of a length at least 2/3 of the conduit width may be deployed. Three of these heaters should be evenly spaced (one in the center) in the cross sectional plane. The conduit should be well insulated in the region of the heaters.

- For hydronic or forced air collectors, the heater H1 should be placed in a straight section, remaining so for at least one heater length either side for hydronic systems, or four feet in length for air systems.

1.2 Install H2 at the outside of, or just inside, return air register.

- If more than one return register exists, extra H2's may be deployed or they may be masked off.

- If strip heaters are already an integral part of the system, it may be possible to use them rather than installing any additional heaters.

- Heater H2 may not be required if duct air flow rates are measured by pitot rakes on either side of the duct blower. The pressure differential may be read by hydraulic or electronic manometers, and be read at the beginning and end of this procedure, or at Step 4. This procedure, if possible, if preferable to that described in the System Description.

1.3 Install thermocouples in collector loop.

- o If thermowells are not provided in a particular hydronic system, bondable thin film thermocouples may be bonded directly to the collector loop conduit at the desired locations. The insulation for 6" on either side of each such thermocouple must be at least R20.

- o For forced air collectors, thermocouple "rakes" may be inserted into the conduit. Each "rake" would have at least five thermocouples, evenly spaced. The rake length must be at least 2/3 the conduit width. The thermocouples may be piled or averaged, in either case the thermocouple terminations must be outside the conduit.

1.4 Install thermocouples in duct system.

- It is suggested that at least six outlet registers be instrumented with differential thermocouples, and if more outlet registers exist, a representative distribution of thermocouples must be considered and deployed.

1.5 Install heater H3 and differential thermocouples DDI and DDO in the distribution loop as the H1, DCI, and DCO were installed in the collector loop, as described in steps 1.2 and 1.3.

1.6 Install remaining thermocouples and transducing hygrometers. NOTE: Differential thermocouples DCO and DCI are used only when it is desired to isolate conduit losses from collector losses.

1.7 Install pyranometer in same plane as collector, at top center of collector. If reflectors are used, the plane of pyranometer is to be parallel to that of the <u>absorbing</u> collector.

1.8 If reflectors are used, measure and record the following:

1.8.1 Reflector dimensions (length and width)

1.8.2 Distance nearest edge of reflector to collector.

1.8.3 Elevation of reflector off the horizontal (in degrees).

1.8.4 Evaluation of collector off the horizontal (in degrees).

1.8.5 Orientation of collector, azimuth (in degrees).

1.8.6 Visually estimate specularity and reflectivity of reflector (e.g., new aluminized Mylar™ has a specular reflectance of approximately 85%).

1.9 If reflectors are used, cover them with black plastic film, firmly attached with cloth tape. <u>NO NOT ATTACH TAPE TO REFLECTIVE SURFACE</u>. Be very protective of reflective surface.

- The reason for covering the reflective surfaces is so that the absorbing surfaces of the collector only may be analyzed. The contribution of the reflective surfaces will be approximated analytically for different sun angles.

1.10 Connect pump and blower power to measurement system through system output controller relays, so that measurement may override the dwelling's control system commands when necessary. Note that distribution pump P2 and blower are energized simultaneously.

1.11 Verify system operation via routine resident on cassette tape.

2.0 MEASURE COLLECTOR PERFORMANCE (AUTOMATIC)

2.1 Perform this step on day with less that 40% cloud cover. Further, cloud cover should be relatively stable; i.e., little movement.

2.2 Drain or charge (using H1) storage to achieve downpoint temperature (TDP, temperature at which no useful heat may be obtained), indicated by TSO.

2.3 Using H1 and insolation, bring TSO up to or near maximum (TSS, saturation temperature of storage) by 4 PM solar time (system determines rate of addition of H1 heat by approximation of storage capacity during charging). This step should begin at approximately 8 A.M. solar time. Clock on microprocessor determines time. (Data is automatically taken during this phase).

2.4 Measure collector loss rates (automatic).

2.4.1 Using insolation and H1, complete saturation of storage, concluding at dusk.

2.4.2 Turn on pump P1 and pump P2, collect data automatically until downpoint temperature (TDP) is reached. It may be necessary to open windows or turn on air conditioning to keep direct return temp. below 85°F (above which P2 will automatically shut off).

3.0 MEASURE STORAGE LOSS RATE (AUTOMATIC)

3.1 On the day following step 2.4, saturate storage again, using insulation and H1. Record TSO prior to shut off of P1 (at saturated storage).

3.2 Isolate domestic hot water stream (DHW) from storage, using storage bypass valving, if present. Otherwise shut off DHW supply valve.

- Step 3.2 is a manual operation.

3.3 Turn pumps P1 and P2 off, allow to remain in this condition for 24 hours. (Data is taken automatically, including measurement of temperature adjacent to storage (TSA).

3.4 Turn on P2 for 5 minutes and record TSO and TCO. This is to obtain a representative value of the storage temperature. TSO.

3.5 Return DHW to normal configuration.

- Data from steps 2 and 3 can be used to yield storage capacity.

4.0 MEASURE SPACE HEATING DELIVERY RATE (AUTOMATIC)

4.1 This step begins immediately after 3.4, and is summoned automatically by the measurement system.

4.2 Operate heater system until storage downpoint temperature (TDP, for space heating) is achieved at TSO. Do not charge storage during this period. System will shut down automatically if duct inlet temperature exceeds 85°F. Windows may have to be opened to keep dwelling comfortable.

4.3 If there is no air conditioning equipment, proceed to step 6. If there is air conditioning equipment, use insulation and H1 to charge storage to capacity and proceed to step 5.

- o If a solar assisted heat pump is employed, useful storage temperature (downpoint) will be extended significantly downward. The heat pump power will then be monitored by W2, in which case an initial measurement of the duct flow rate will have been made by H2, and the watt meter W2 will be connected to the heat pump power source. The data system, and consequent data reduction scheme, can distinguish between direct heating (e.g., through a water-air coil in the duct) and the heat pump mode, by referring to the heat pump power level during heating.

5.0 MEASUREMENT AIR CONDITIONING COOLING RATE (AUTOMATIC)

5.1 This step begins immediately after step 4.3.

5.2 Operate the air conditioner continuously until storage downpoint temperature for air conditioner is achieved at TSO. If temperature of duct inlet is 65°F or less, H2 will come on automatically to compensate and maintain comfortable conditions. As in the measurement of other parameters, data will be recorded automatically all during this period.

5.3 Terminate data collection and measurement system controlled operations.

6.0 REMOVE MEASUREMENT SYSTEM

- Verify that the solar heating/cooling system is in the original configuration and is operating properly.

7.0 SEND CASSETTE TO CENTRAL DATA REDUCTION FACILITY

- With additional software, system could reduce its own data (software would be cassette resident).
  The Data Reduction Scheme is as follows:

7.1 Functional Parameters

7.1.1 Collector efficiency (from step 2 data)

7.1.1.a Determine collector subsystem loss ($\dot{Q}_{CL}$) rate as function of (TCO - TOD) (step 2.4)

$$\dot{Q}_{CL} = G_1 C_{p1} \text{ (TCO-TSO)} = C_1 \text{ (TCO-TOD)} + C_2 \text{ (TCO-TOD)}^2$$

- This method implies the determination of collector subsystem loss by nocturnal cooling (step 2.4). However, the accuracy of this method has not been established and requires evaluation. Another way to obtain the collector subsystem loss is to compare the incident solar insolation (as monitored by the pyranometer) with the energy delivered by the collector as measured during step 2.3.

7.1.1.b Determine collector absorption function from step 2.3 and $\dot{Q}_{CL}$

$$\dot{Q}_{COL} = G_1 C_{p1} \ (TCO-TSO) = C_o I - C_1 \ (TCO-TOD) - C_2 \ (TCO-TOD)^2$$

(extract constant C_o, absorption function = $C_o I$)

where $\dot{Q}_{COL}$ is the collected energy transferred to storage.

7.1.2 Storage Parameters

7.1.2.a Storage Loss Rate (from step 3 data). Determine the heat required to recharge storage after 24 hours of stagnation. Heat to recharge is $\int G_1 \ C_{p1} \ (TCO-TCI)dt$. Storage loss rate is denoted herein as $\dot{Q}_{SL}$, which is expressed as

$\dot{Q}_{SL} = C_3 \ (TSO-TSA)$. To calculate C_3, the mean

value of TSO at the beginning and end of step 3 is used, and the mean value of TSA measured during step 3.

7.1.2.b Storage Capacity (data from steps 2 and 3) Total storage capacity is determined by the sum of the heat input during charge and the heat loss rate. Thus, from the data taken during charging of storage:

$$Q_{STM} + \int (G_1 C_{p1} \ (TCO-TSO) - \dot{Q}_{SL}) \ dt,$$

where the time interval is that of charging storage from downpoint to saturation.

7.1.2.c Storage Outlet Temperature as a Function of Stored Energy. Evaluate stored energy during discharging (see step 2.4.2) at fixed values of TSO and incorporate these data in a least squares determination of a third order polynomial (fifth order for phase-change type storage) to achieve TSO = $A_1 + A_2 Q_{ST} +$

$A_3 Q^2{}_{ST}$.

7.1.3 Air Heating Rate (data from step 4.) The net solar heating delivered at any time is

$$\dot{Q}_{HTR} = G_2 C_{P2} \ \left(\frac{\sum TD_i}{n} - TAR\right) - W2$$

where W2 is the thermal equivalent of the electric power drawn by the heat pump and C_{P2} = 0.24 BTU/lb^{o}F. G_2 was measured at the onset of this procedure, when W2 was monitoring H2 heater power. Then, determine the heat delivered to air as a function of (TSO-TAR) from data recorded at selected values of TSO, applied to a least squares formulation of a polynomial

$$\dot{Q}_{HTR} = A4\ (TSO-TAR) - A5\ (TSO-TAR)^2 + A7\ (TSO-TAR)^3 + A7\ (TSO-TAR)^4$$

The A5, A6 and A7 terms may be omitted if no heat pump is employed.

7.1.4 Air Cooling Rate (data from step 5)

7.1.4.a Calculate cooling rate of air conditioner, $\dot{Q}_{A/C}$, at selected values of TSO, as a function of (H_1-H_2), where H_1 and H_2 are enthalpies of entering and exit air as determined by hygrometers RH_1 and RH_2. Thus,

$$\dot{Q}_{A/C} = G_2\ (H_1-H_2).$$

7.1.4.b Determine cooling rate of air conditioner as a function of (TSO-TWB), where TWB is outdoor wet bulb temperature, determined from RWB. Similar to 7.1.3.b, determine cooling rate $_{A/C}$ as a polybomial

$$\dot{Q}_{A/C} = A8\ (TSO-TWB) + A9\ (TSO-TWB)^2 + A10\ (TSO-TWB)^3.$$

- If cooling tower is not used, but forced air only as heat rejection, then determine $_{A/C}$ as a function of (TSO-TOD).

7.1.5 Collector loop loss rate, excluding collector. The fraction of collector loop losses attributed to non-collector conduits is determined by

$1 - \frac{DCO - DCI}{TCO - TSO}$ from data taken during step 2.4.

7.1.6 Determine distribution loop efficiency. This efficiency is the ratio of useful heat delivered to the dwelling versus the heat drawn from storage. Using data from step 5, calculate

$$\eta_H = \frac{\dot{Q}_{HTR}}{G_3 C_{P3}\ (TSO-TCO)} = b_0\ (TSO-TAR) + b_1\ (TSO-TAR)^2$$

$$+ b_2\ (TSO-TAR)^3 + b_3\ (TSO-TAR)^4$$

The flow rate G_3 being calculated from W_3 (H_3), DDI, and DDO.

Similarly, for air conditioning, the factor

$$\eta_{A/C} = \frac{\dot{Q}_{A/C}}{G_3 C_{P3}\ (TSO-TCO)}$$

$$= b_4(TSO-TWB) + b_5\ (TXO-TWB)^2 + b_6(TSO-TWB)^3$$

7.1.7 Determine overall system efficiency; i/e/. energy delivered per energy incident:

$$\text{system} = C_O \eta_H, = C_O \eta_{A/C}$$

7.2 Performance Predictions

These predictions are determined from the functional parameters determined in 7.1, climatic data for the given region averaged over ten years (for each day and hour), building thermal characteristics and average domestic hot water consumption for a similar dwelling and family size for a given region.

7.2.1 Useful Per Annum Energy Deliverable by the System

7.2.1.a Determine hourly domestic hot water energy consumption. This will be available from local utilities, based on family size, at least on a daily or monthly basis. For daily patterns, peak use periods are 6 A.M. to 8 A.M. and 6 P.M. to 10 P.M.

7.2.1.b Calculate building thermal load parameters, from drawings or by measurement which include

- o UA product for East, West, North and South Walls
- o UA product for East, West, North and South Windows
- o net transmittance of windows, N, W, S, E.
- o UA product for roof-ceiling
- o color (hue) of walls, roof
- o shading of roof, windows
- o lighting and appliance wattages
- o window and door perimeters for infiltration
- o quality of window and door seals
- o occupancy
- o latitude

- desired indoor temperatures for heating and cooling.

7.2.1.c Forward data of steps 7.1 and 7.2.1.a and 7.2.1.b to the central computing facility, wherein that data and a weather tape indigenous to the site location will be processed by the HISPER-M program.

- (typical data processing CPU time for hydronic systems is 20 seconds, for forced air collector systems is 60 seconds. The data processing includes one year of operation under averaged (10 + years) conditions, at 20 minute intervals).

The processing will yield total annual heating and cooling load, annual heating, cooling, and DHW load and total annual load furnished by solar, and the fraction of the total annual loads furnished by solar heating, cooling and DHW.

- (HISPER-M is a special application of a streamlined version of the TRNSYS solar heating/cooling analysis program. Test cases have shown results of HISPER-M to deviate an average of only 7% from results of the same analysis performed with TRNSYS. The advantage of HISPER-M is reduced input data requirements and 150 fold reduction in CPU time).

7.2.2 Useful Energy Deliverable from a Cloudless Winter Day (Applicable to non-concentrating collectors only).

- This step can be performed manually or with a programmable hand calculator.

7.2.2.a Set TAR as the desired indoor temperature

7.2.2.b Let TOD be the average daily value for Jan 21.

7.2.2.c Set TSO = TDP + 2/3 (TSS-TDP)

7.2.2.d Calculate from Appendix ______ the hourly insolation on a horizontal surface, I_H, for January 21.

7.2.2.e Calculate hourly insolation on collector:

$$I_S = I_H \frac{\cos(\theta_c - \theta_e)}{\cos \theta_e}$$

7.2.2.f Calculate energy delivered to storage from the collector subsystem:

$$Q_{COLL} = C_o I_s - \left[C_1 (TSO-TOD) - C_2 (TSO-TOD)^2\right] \Delta t$$

where Δt = 1 hour, and the value in brackets is set to zero if its calculated value is negative.

7.2.2.g Set TSO = TSS

7.2.2.h Calculate heat delivered to the house in ten equal increments of daily collected heat, assuming that heat is delivered to the house in a 36 hour period. (A better approximation of the time to use Q_{COLL} is to divide Q_{COLL} by UA (65-TOD), where UA is the overall heat transfer factor for the building, as determined from building design data. Refer to ASHRAE Handbook and Product Directory, 1977 Fundamentals, and HUD Min. Prop. Stds. for Solar Heating and Domestic Hot Water Systems (NBS IR 76-1059) for details of this method).

- Calculate net stored heat over the delivery period

  from $Q_{net\ stored} = Q_{COLL} - Q_{DHW} - \frac{C_3}{2}(TSS+TOP)\Delta t$

  where Q_{DHW} is the DHW energy consumed over the time period t, which is 36 hours or that calculated using building UA data and TOD. The average daily Q_{DHW} is obtained from local utility companies.

- Calculate $TSO_j = A_1 + A_2 Q_{ST} + A_3 Q_{ST}^2$ for $Q_{ST} = Q_{STSAT} - \sum_{n=0}^{j} \frac{n}{10} Q_{net\ stored}$ for j = 0 to 10

- Calculate useful heat delivery rate for each TSO_j

  $$\dot{Q}_{HTR_j} = A_4 (TSO_j - TAR) + A_5 (TSO_j - TAR)^2 + A_6 (TSO_j - TAR)^3 + A_7 (TSO_j - TAR)^4$$

- Calculate useful heat delivered:

  $$Q_{DEL,HTG} = \sum_{j=1}^{9} \sum_{k=0}^{3} b_k (TSO_j - TAR)^{k+1} \quad t + Q_{DHW}$$

7.2.3 Calculate useful energy delivered from a cloudless summer day.

7.2.3.a Perform step 7.2.2 for the following conditions:

- TWB, TOD, I_H, θ_e that for July 21.
- TAR for air conditioning setting.
- $Q_{DEL,CLG} = \sum_{j=1}^{9} \sum_{k=4}^{7} b_k (TSO_j - TWB)^{k-3} \Delta t + Q_{DHW}$

7.2.4 Calculate overall system efficiency (ratio of heat to delivered to energy incident on a cloudless day).

7.2.4.a for heating

$$\eta_{HTG} = \frac{Q_{DEL,HTG.} \cdot \cos \theta_e}{\Sigma I_H}$$

7.2.4.b for cooling

$$\eta_{CLG} = \frac{Q_{DEL,CLG} \cdot \cos \theta_e}{\Sigma I_H}$$

- The values HTG and CLG are figures of merit for the system which can be obtained at any time insolation conditions are met for this measurement procedure, and thus correlations can be made throughout the life of the system.

LIST OF SYMBOLS

A_1, A_2, A_3	- polymomial constants for determining temperature of storage from heat in storage
A_4, A_5, A_6	- polynomial constants for determining heating rate from storage and air duct temperature differential.
A_7, A_8, A_9	- polynomial constants for determining air cooling rate, from storage and wet bulb temperature differential.
C_o	- collector absorptance
C_1, C_2	- collector loss rate polynomial constants
C_3	- storage loss rate constant
Cp_1, Cp_2	- heat capacity of collector loop fluid, air
DCO, DCI	- collector loop calibration differential thercouples
DDI, DDO	- distribution loop calibration differential thermocouples
DHI, DHO	- collector loop heater (H1) calibration differential thermocouples
G_1, G_2, G_3	- mass flow rate in collector loop, duct, distribution loop - lb/hr
H1, H2, H3	- calibration heaters for collector loop, air duct, distribution loop
H_1, H_2	- enthalpies of entering and exiting air in duct system, BTU/hr.
I_S, I_H	- insolation incident on collector plane, horizontal surface - BTU/ft^2 hr.
$N_H, H_{A/C}$	- distribution loop efficiency for heating, air conditioning
P1, P2	- collector, distribution loop pumps
Q_{COLL}	- total energy delivered to storage from collector - BTU
$\dot{Q}_{CL}, \dot{Q}_{SL}$	- heat loss rates for collector loop, storage - BUT/hr.
$\dot{Q}_{A/C}, \dot{Q}_{HTR}$	- actual heating rate delivered for air conditioning, heating - BTU/hr.

$\dot{Q}_{DHW}$	- domestic hot water heating rate - BTU/hr
Q_{ST}	- heat in storage, reference temperature = "drawdown"temp. - BTU
Q_{STM}	- maximum storage heat capacity - BTU
Q_{del}	- useful heat delivered to building from solar system - BTU
RWB, RH_1, RH_2	- relative humidity transducers for outdoors, return air, conditioned air
T_{AR}, T_{CI}, T_{CO} T_{DP}, T_{OD}, T_{SA}, T_{SO}, T_{SS}	- temperatures: return air, collector inlet, collector outlet, storage downpoint, outdoor, storage exterior, storage outlet, storage saturation, - deg F.
T_{DR}, T_{D1}, T_{D2} ..., T_{DN}	- duct differential thermocouples - deg F.
T_{WB}	- outdcor wet bulb temperature - deg F
W1, W2, W3	- collector loop, airduct, distribution loop calibration heater power - BTU/hr.

CONSIDERATIONS IN CHOOSING SOLAR ENERGY MONITORING SYSTEMS

Michael R. Jacobs
Acurex Autodata
485 Clyde Avenue
Mountain View CA 94042

1.0 ABSTRACT

Low cost microprocessor-based systems have created a new era in solar data collection, monitoring and control. This paper addresses the general characteristics that should be considered when choosing a monitoring system for a particular application. In addition, two applications and their selected monitoring systems are discussed.

2.0 APPLICATION CHARACTERISTICS

Each application defines the requirements for its monitoring system. Flexibility to respond to change is characteristic of many microprocessor-based systems and is key in most situations. Some important characteristics are discussed below.

2.1 Sensors

Each application has its own set of measurements and their associated sensors. The data system must as a minimum be able to measure the selected sensors and also be able to add both additional input channels and other sensor types. Some special sensor types and their measurement requirements are listed in the following table.

SENSOR	REQUIREMENTS
Thermocouples	Ice point compensation, low level input, open circuit detection
RTD's	Bridge completion, 3-wire inputs, internal power supply
Differential RTD's	Dual polarity, 3-wire inputs, internal power supply
Other Low Level Signals	Noise rejection, resolution and sensitivity

2.2 Processing

Depending on the application, the processing is usually shared between the monitoring system on-site and eventual computer processing of the data. On-site processing allows a local, immediate look at the collected data. Areas for on-site processing include the following.

2.2.1 Engineering Units Conversion - Sensor inputs should be converted from raw input levels to engineering units for on-site evaluation. For example, thermocouple inputs in millivolts are linearized and converted to temperature in degrees (F or C). Other sensors, both linear and nonlinear, should be easily accommodated.

2.2.2 Averaging - For many kinds of inputs (e.g., solar insolation), an average value is more useful than an instantaneous sample. In addition, averaging can reduce the on-side data storage problem. For example, a single value can be recorded for the insolation average for a given hour. This on-line data averaging is preferable to recording the instantaneous value every 5 minutes and later calculating the average off-line with subsequent processing. The selected averaging technique should be digital for accuracy and flexibility. Different and multiple averaging periods should be available for assignment to various input channels.

2.2.3 Limit Checking - Although not generally required, limit checking is highly desirable in some applications to compare measured data with alarm limits and to have the data system respond in a certain manner when these limits are exceeded. For example, the data recording rate could increase when the solar insolation level increased above a certain point, or a high temperature limit could cause a contact output to defocus a concentrating collector.

2.3 Data Output and Recording

Many options are possible with a primary consideration of how much data should be available at the site for evaluation. Some output possibilities include the following.

2.3.1 Displays - Local displays provide the channel number, the reading and its engineering units. Some systems allow selection of one channel without affecting the data being recorded. These local displays are almost essential for set-up, calibration, failure detection and sensor checkout. Displays of both raw input levels and engineering units are useful for system checkout.

2.3.2 Printing - Small, inexpensive, built-in printers allow local recording for data checking and limited performance monitoring. Printers can be set-up to record data automatically at periodic intervals to provide a time-correlated summary of the system performance.

2.3.3 Terminals - Both CRT and hardcopy terminals can be used for local or remote data collecting and system checkout. In local operation a hardcopy terminal serves many of the functions of the built-in printer with better data formatting and possibly some diagnostic checking capability. From a remote location (via phone lines) data can also be collected and the system performance checked with a standard terminal.

2.3.4 Cassette Tape - Small and economical cassettes are a logical choice for recording data for subsequent processing. The data may be collected manually by retrieving the cassettes or automatically over phone lines. Capacity is on the order of 100,000 data points, depending on formatting.

2.3.5 Magnetic Tape - Open-reel tape (1/2") offers larger storage for direct computer processing (IBM Standard) with capacity in the range of 1,000,000 data points, depending on reel size and formatting. The large data storage is generally used for manually collected data systems, especially where direct computer processing is desired.

2.4 Control

In certain applications it may be desirable to control parts of the solar collection system from the monitoring system. Relay outputs can be provided from the monitor to control functions, either from the stored program or in response to remote commands.

2.5 Communications

For remote systems, communication using phone lines may be desirable to avoid the necessity of periodically visiting the sites. Remote communication is possible using modems and (usually) an automatic dial-up at the central location. In addition, provision for local operation should be considered for troubleshooting and local data checking.

2.6 Data Integrity

This can be separated into two areas: analog errors that occur as the point is being measured, and digital errors that result during data handling.

2.6.1 Analog Errors - Since many signals are low level and electrical noise may be present, the following characteristics should be considered:

- Basic accuracy - including low level resolution
- Common mode noise rejection
- Normal mode noise rejection
- Voltage protection - and overload recovery
- Time stability - automatic calibration
- Temperature stability

2.6.2 Digital Errors - These can be nearly eliminated with techniques that include error checking as the data is stored and processed. Generally a balance must be reached between the overhead required to check the data and the consequences of undetected errors. In general, the reliability of the microprocessor itself reduces the digital errors without extensive checking.

2.7 Other Factors

Certain other considerations should be made, depending on the application and site location. These include the following:

- Power failure recovery
- Battery power - entire system or just clock
- Size
- Flexibility - for changing applications
- Future usefulness of system

3.0 APPLICATION: SDAS FOR THE NATIONAL SOLAR HEATING AND COOLING DEMONSTRATION PROGRAM

This application requires remote data collection and transmission of the data over phone lines for central processing. Following the order in Section 2, the following are the major characteristics.

3.1 Sensors

Any mix of various sensor types including RTD's, differential RTD's and various voltages.

3.2 Processing

Linearization and scaling for about 100 different sensors with front panel selection.

Averaging assignable to various input channels from the front panel.

3.3 Data Output

Displays in both engineering units and raw data with front panel channel selection.

Cassette Tape with transmission to central station over phone lines.

Optional printer, terminal, magtape and other peripherals as required.

3.4 Control

None required.

3.5 Communications

Over phone lines to central station for data and commands.

Over phone lines to Acurex for diagnostics.

Local operation with front panel.

3.6 Data Integrity

BCH error checking.

Automatic calibration.

3.7 Other Factors

Automatic Power Fail recovery.

Battery-protected clock.

Flexibility to add options.

4.0 APPLICATION: LASL - PASSIVE SOLAR HEATING AND COOLING PROGRAM

Data monitoring systems with manual collection of data stored on cassettes. Can be upgraded for automatic central collection. Characteristics are:

4.1 Sensors

Voltage inputs.

Thermocouples.

4.2 Processing

Linearization for thermocouples.

Averaging - including selectable periods, multiple periods, and channel assignments from the front panel.

4.3 Data Output

Displays - front panel selection of any or all channels.

Printer - built-in for local recording

Cassette - initially for manual retrieval.

4.4 Control

None required.

4.5 Communications

Local set-up using front panel controls.

4.6 Data Integrity

Automatic calibration

Basic accuracy ±0.02 percent of full scale.

4.7 Other Factors

Automatic Power-Fail recovery.

Battery-protected clock.

Flexibility to add other options.

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DATA ACQUISITION USING A MODULAR DATA LOGGER*

Robert L. Woell
Graduate Research Assistant
Agricultural Engineering Department
North Dakota State University
Fargo, North Dakota 58102

Abstract

A modular data acquisition system is used to monitor the performance of a solar heated building, as well as gather wind and insolation data. The system is very versatile in that it is semi-programmable, field portable, and can store data on cassette tape.

Introduction

Most research facilities are engaged in many projects at one time. These projects vary in complexity and duration of study, with some projects lasting only one season. Also, these projects are being carried out at many locations. All of these factors plus, of course, budget influence the type of and quantity of data to be gathered and the equipment used to gather it.

If all the data from a project is of the same type, for example, temperature, the problem is fairly simple. Multi-channel strip chart recorders work quite well for this, although reading the numbers off the chart can be tedious. If other types of data are to be gathered at the same time another set of equipment is required. Something such as manually reading daily total solar radiation does not add much to the complexity of the problem. However, if a correlation study of the temperatures and solar radiation were desired on a more frequent basis, there would be problems of synchronizing these two units. The problem of monitoring and synchronizing the system goes from difficult to impossible as the number of units increases and the scan frequency increases. What is needed is one system which is semi-programmable to handle all of the data.

In order to look at the small details of an experiment it is often necessary to take a large number of data scans or scan at a high frequency. This can mean mountains of data which may have to be sorted and punched on computer cards. It is easier if the system is printing numbers instead of printing on charts or graphs but still this can be a limiting factor in an experiment. The solution is a system which is able to put the data into a form readable by a computer.

The data acquisition equipment must be easily portable in order to be moved from one site to another. It isn't always easy to control the environment around the equipment, particularly temperature and humidity and this should be taken into account. Finally, it may be desired to operate at remote sites where 110 volt power is not readily available so the ability

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to operate with batteries is an advantage.

The Project

When the data acquisition system was ordered the project to be instrumented was a large solar heated maintenance building for a government agency. Shortly before the instrumentation arrived, the building project was cancelled. Since other solar projects were being planned the equipment was still needed although it would serve different functions.

The project being monitored is a warm beef confinement barn on one of the university's research farms. The barn is divided equally into two sections. One side has a solar collector connected to the inlet of the ventilation system. The collector is used to heat the incoming air for purposes of humity control. The other side of the barn has a heat exchanger connected to the ventilation system. Heat is collected from the exhaust air and is used to temper the incoming air.

Both systems are being monitored at numerous points with copper-constantan thermocouples. The air temperature within the confinement pens is being monitored at 32 locations in an effort to evaluate the air flow within the building. It was also desireable to know the amount of time the two systems were operating. Whether the fans are operating or not will affect the temperatures at some locations therefore an indicator was needed to tell if the fans were running at the time a scan was made.

In conjunction with this project, a study is being made of solar radiation and wind velocity and direction. The solar radiation data will be used in evaluating the collector's performance. It will also be used in a correlation study of the energy available from the wind and the energy available from the sun.

The collector and other systems were to be monitored over a period of many months; therefore, it was felt scanning all the channels once every hour would be sufficient. The exception was the wind data, which was to be read every 15 minutes.

The Data Acquisition System

The data acquisition equipment being used is based around the system developed and built by Campbell Scientific of Logan, Utah. The basic and most important features of the system are that it is a modular system and it uses CMOS electronics throughout.

There are separate modules for each function of the system. Modules for power supply, printer, and system controller-time clock constitute the mainframe. The clock module controls the timing of scans and setting of the day and time counters. Scan rates are selectable from 5 minutes to 24 hours. When a scan is initiated, channels are scanned and data printed at the rate of 100 channels per hour. The print format is a two digit channel number and a three digit plus sign data entry.

Other transducer interface modules are added as required and in the order desired. Modules purchased for the original project include: 50 channel scanners for copper-constantan thermocouples, volt integrators, millivolt integrators, temperature integrators, pulse counters, a processor unit for the wind data, a module to translate the data and put it on cassette tape, and a module for scanning some channels at a higher rate than others.

Since the system is modular, it is somewhat programmable. Most of the modules themselves are also programmable to a degree, i.e., the 50 channel scanner can be used for sampling thermocouples, thermistors, voltages, and other functions. This scanner can also be programmed for two functions at the same time. Some of the 50 channels can be used for one function and the rest deleted or used on another function. Another example of programmability is the millivolt integrator, which has an adjustable full scale reading and a zero offset in case negative voltages were to be input.

The wind processing unit is actually made up of two modules, the data processing module and an input module. The data processor module contains a microprocessor for handling data. Another module, in this case a wind translator, is connected to it. A 16 line parallel digital input module is also available.

Data in the system is stored digitally so there is no problem of inaccuracy at very long scan intervals, particularly with the integrating modules. Each module contains its own analog to digital converter and signal conditioner. This simplifies the mainframe and also makes the system more flexible.

The power requirement is very low because the unit uses CMOS circuitry. On the current project the system is scanning 59 channels, eight of which are integrating, with a power consumption of only about 5 milliamps. The low power consumption means it can operate on batteries for weeks or months at a time. How long the batteries last depends somewhat on how often scans are made because the printer is the main power user. The voltage requirement is flexible and can be between 10 and 16 volts, so no expensive, sophisticated power supply is required.

The weight and size of the system has been kept down by the extensive use of integrated circuits. The low power drain means that the power supply can be small and light, consisting of 8 D size dry cells. The operating temperature range is from -25 degrees to +50 degrees C so an environmentally controlled instrument room is not required. The system, as purchased, is contained in aluminum brief cases which have synthetic rubber seals around the covers and it is reasonably dust and weather proof.

The system controller-time clock module keeps track of the calendar and clock. This data becomes the first three channels of the scan. When the controller initiates a scan, the day and time are printed, then the next module in the line is enabled to transmit its data to the printer. When that module has transmitted, it signals the next module to transmit and so on. This method of enabling the modules allows for an unlimited number of channels to be connected together.

Other parts of the system required for the project are for recording data onto cassette tape and playing that tape back to the computer. A module for transferring the data to tape is added to the other modules. It has a buffer memory which stores data temporarily. When this buffer is full the module turns the recorder on and transfers the data to tape in record lengths of 10 channels. ASCII characters for carriage return, line feed, and rub out are added to each block. These characters are needed for communication to the computer.

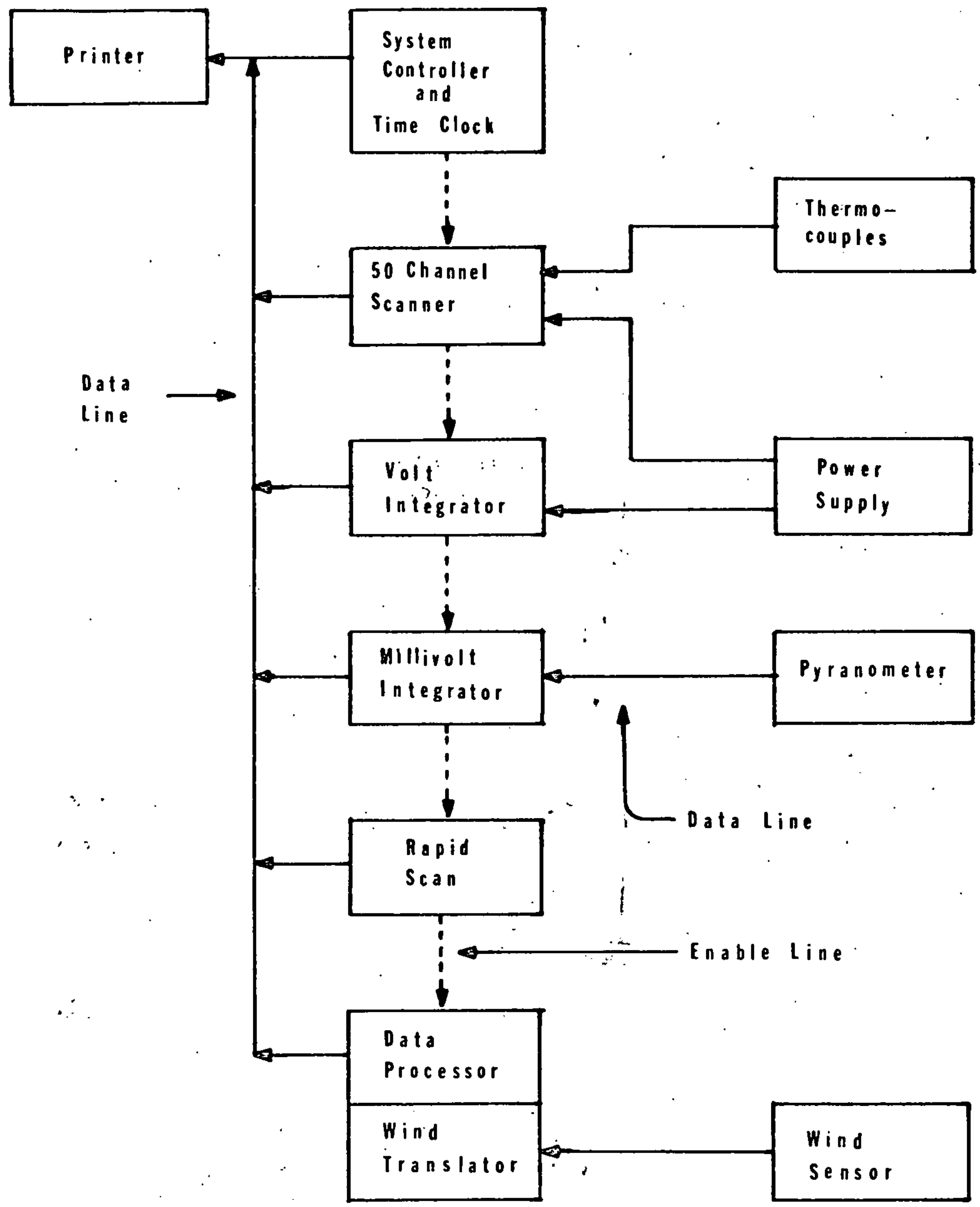

Figure 1. Each module enables the next one in line to transmit its data to the printer.

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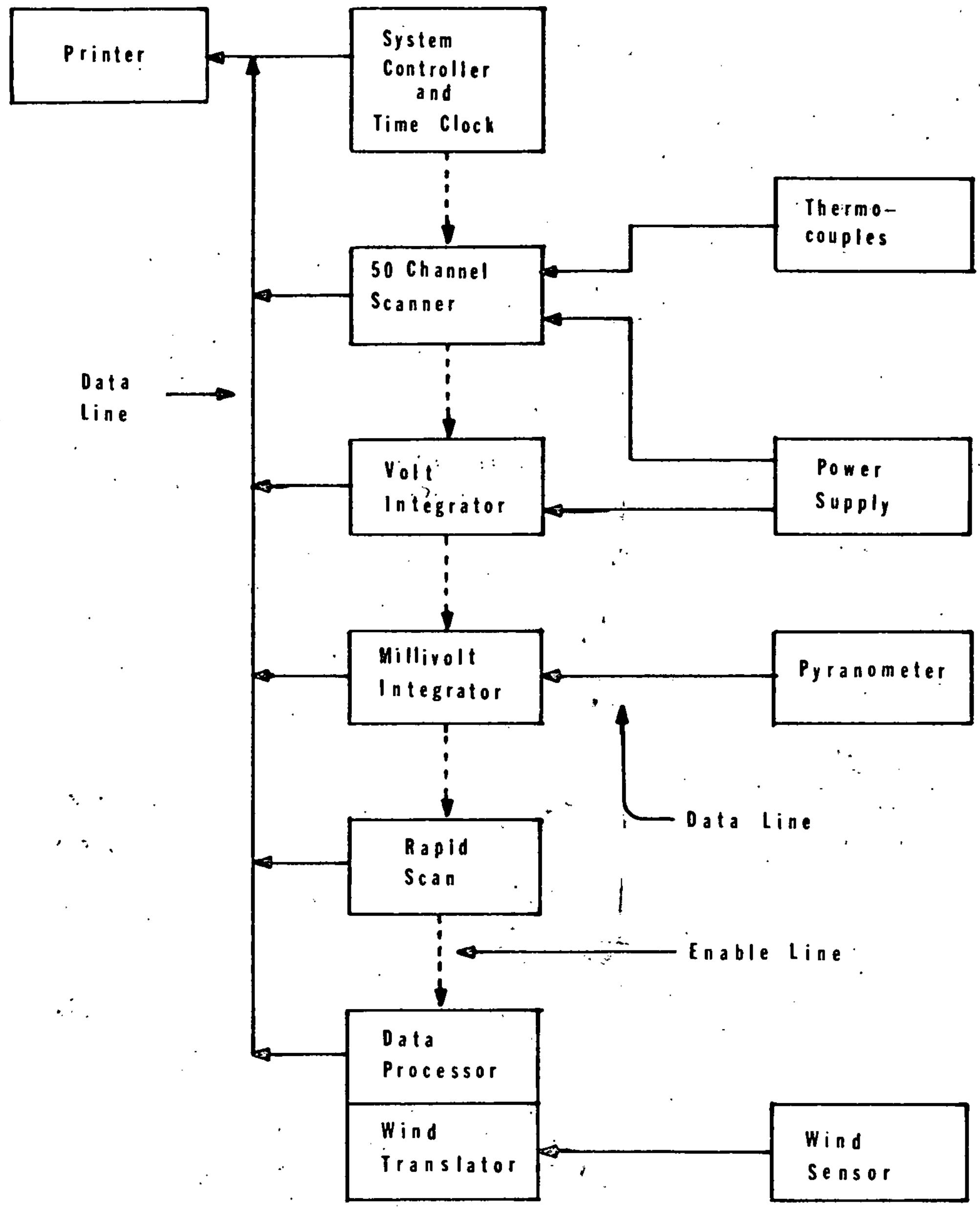

Figure 1. Each module enables the next one in line to transmit its data to the printer.

The recorder used is a standard cassette recorder. It was modified so that the electronics shut off with the drive motor. This would greatly extend battery life if the recorder is used without a battery eliminator.

A cassette-terminal interface module provides the communication link between the cassette recorder and the computer terminal. It has two RS-232 connectors so the unit can be inserted in the line between the terminal and the modem or computer for playback to both units. Either can be used without the other as well. The terminal interface module can also be used to record data from the computer or terminal for mass storage for other applications.

The terminal interface module is controlled by a program stored on a read only memory (ROM). This memory includes the control characters to be used in communication with the computer. The computer currently in use at NDSU is an IBM 360-50 and it requires special control characters to transfer information to and from the terminals. To meet these requirements, Campbell programmed a new ROM.

To complete the data acquisition system, an Epply Precision Pyranometer and a TechEcology wind speed and direction sensor were purchased. The wind speed sensor is a light chopper device which sends a 10 volt square wave signal to the wind processor module. The wind direction sensor transmits a voltage which is proportional to the direction of the wind. The voltage ranges from 0 to 5 volts. Both wind units require 12 volts to run the electronics and to power small resistance heaters to keep things from freezing in very cold temperatures.

Using the System

The type of data to be collected required that some components and interface pieces had to be built specifically for the project. Some parts were built because it was faster and lower cost in this case to do so.

North Dakota winter temperatures are often well below freezing so the heaters are needed on the wind sensors. The cable from the wind unit to the recorder was over 400 feet long. To avoid signal interference as well as make the heaters switch controllable two 12 volt supplies were used. One supply is for the heaters, the other for the electronics.

The power required for the electronics was about 20 milliamps, and about 660 milliamps were required for the heaters. This small requirement meant that a simple power supply using integrated circuit voltage regulators could be used. The specifications sheets indicated that the LM7812 voltage regulator used for the heaters would have to have a heat sink. This was accomplished by mounting the regulator to the power supply case. That regulator also has a switch on the input side so it can be shut off during warm weather.

To determine the amount of time that the ventilation systems were running, the 10 volt integrator modules were used. A variable IC regulator, LM723, was set up to provide 10 volts DC. This regulator is switched on and off with the ventilation fans by the use of a relay. By feeding the 10 volts into the integrator the value printed would be in proportion to the time the system was on. Since 10 volts is printed as

100 the data could be interpreted as the percent time on.

A way was also needed to indicate if the ventilation systems were running at the time of the scan. This was accomplished with the use of a 10 volt supply also. A set of dropping resistors was used to obtain 2 mv DC from the 10 volt output. The 2 mv is fed into a thermocouple channel and simulates a high temperature, approximately 50 degrees C over ambient. If a high temperature is recorded, it means the ventilation system was on.

Figure 2 shows how the original power supply was built. Most of the resistors and capacitors have been left off the diagram but are given in linear data books. This supply was built to monitor only one side of the barn. For the other side a second supply was built to give only 10 volts and 2 mv. These voltages were controlled in the same manner and fed into other integrator and thermocouple channels.

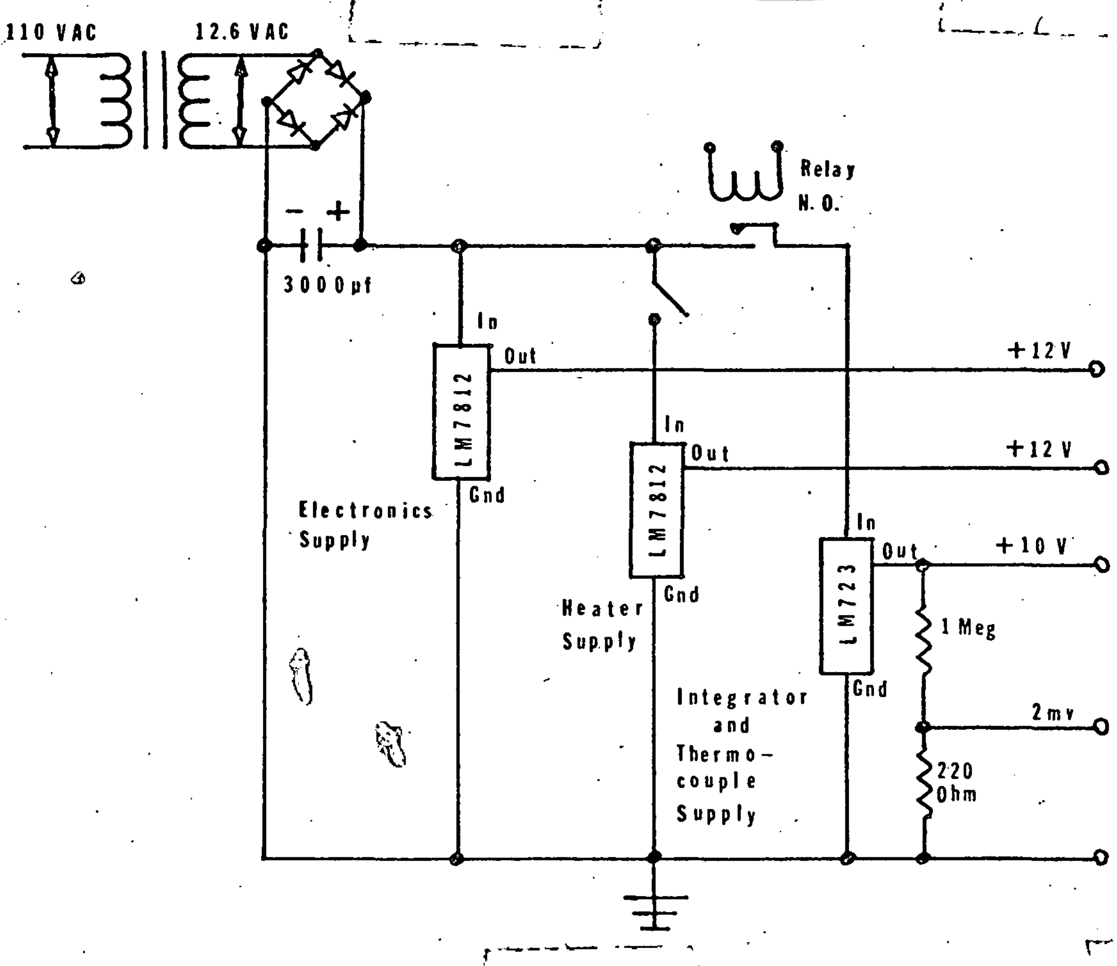

Figure 2. The power supply shown contains the 12 volt sources needed for the wind sensors and the 10 volt and 2 millivolt sources used as data.

The Millivolt Integrator Module is used with the pyranometer to gather solar radiation data. This module has an adjustable gain and zero offset so it can be programmed according to the instrument in use and the data required.

The pyranometer output is zero during nighttime so the zero offset was adjusted to read zero. The pyranometer has an emf of 13.34 mv at the solar constant of 4871 KJ/m^2 hr. Since data was to be recorded in KJ/m^2 hr a millivolt source equal to 13.34 was connected to the module and the gain adjusted so that the printed value was 487. Data interpretation would require only a shift of the decimal point.

Wind data are being recorded continuously and integrated with the processor module. It is integrated over a 15 minute interval and printed at the end of the interval. To do this while the rest of the system operates on a one hour scan interval requires the use of the Rapid Scan Module. This module counts time from the main clock and is set to scan at fractions of the main clock interval. The shortest time interval possible between scans is 6 seconds. Intervals range in multiples of 6 seconds up to 12 minutes 42 seconds or in multiples of 1 minute up to 127 minutes.

The Rapid Scan Module is latched as the other modules are. It is inserted in the line of modules and all the modules which follow it will be subject to the scan interval set by it. These modules are also scanned whenever the main clock initiates a scan.

Data are being recorded on both the paper printer and the cassette tape. The paper record helps when checking the system and looking at selected events. To analyze the major portion of the data the cassette tape is read into the computer and a data file is created. Through the use of proper format statements the file can be accessed either from a terminal for limited analysis or by card programs for more extensive statistical and graphical analysis.

Conclusion

The data acquisition system was bench tested in the department's labs and used in a class lab exercise before being set up on the research project. It has been in operation for over six months and the results have been satisfactory.

The modular construction has proven very useful. The ability of the system to accept a wide variety of transducers is very important to the many projects in which the department is involved.

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DATA ACQUISITION AND MONITORING SYSTEM FOR LOS ALAMOS NATIONAL SECURITY AND RESOURCES STUDY CENTER

by

Michael A. Trump
Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, New Mexico 87545

ABSTRACT

The National Security and Resources Study Center, a modern, three level building containing 5574 m^2 of temperature controlled space and an integral solar energy heating and cooling system is in operation at Los Alamos, New Mexico. This report describes the instrumentation system used to measure the energy production (solar energy system) and consumption (HVAC system) in all the building operating modes. Included are descriptions of the sensors (temperature, mass flow, power, etc.) and the data acquisition system.

I. INTRODUCTION

The National Security and Resources Study Center (NSRSC), located at Los Alamos, New Mexico, has been heavily instrumented as part of a research program into the use of solar energy for the heating and cooling of large commercial and public buildings. The Study Center is a three level building containing approximately 5574 m^2 of temperature controlled space. The solar energy system, designed to supply up to 96 percent of the building's heat and 76 percent of its cooling requirements, is an integral part of the building. Other energy saving features include extensive use of insulation, heat recovery from the ventilation exhaust, and the use of both evaporative and mechanical cooling. The energy storage system is designed so that it may be split between hot, pressurized water and chilled, low pressure water during the cooling season.

For the purpose of instrumentation, the Study Center may be considered as three interconnected systems. These are the solar energy system, the heating, ventilating, and air conditioning (HVAC) system, and the control system. In the following sections of this report, the instrumentation of each will be described in detail.

II. INSTRUMENTATION

A. Solar Energy System

Figure 1 is the simplified mechanical schematic of the system. Instrument locations are marked by type (i.e., Temp, Flow, Power, etc.). This instrumentation is the minimum required to yield energy balances for the basic system components. Thus the energy input from the solar collector to the primary heat exchanger, H1, is determined by temperature measurements at its inlet and outlet, and a mass flow measurement in the collector coolant loop. The other system components are instrumented in a similar manner.

With the exception of the solar collector manifold temperatures, all temperature measurements are made with 100 ohm platinum resistance probes (RTDs). With the RTD probes in LASL designed bridge completion networks, temperatures are read with a resolution of 0.025°C to an accuracy of 0.12°C. The collector manifold temperatures are measured with copper-constantan (Type T) thermocouple probes referenced to 65.5°C. Resolution and accuracy are 0.1 and 0.25°C.

Flow measurements are made by turbine flowmeters (TFMs) and equal area pressure-drop (Annubar*) probes. The TFMs are used on 1/2 in., 1 1/4 in., and 3 in. diameter pipes while the Annubar probes are used on the 4 in. and 6 in. diameter lines. The TFMs and the Annubar probes are typically 1 percent devices. Each TFM is provided with a pulse rate to dc converter, which transmits a 4 to 20 mA signal to the data acquisition system. The Annubar differential pressure signals are translated by means of individual differential pressure transducers, which send 4 to 20 mA signals to the data acquisition system.

Auxiliary energy is supplied to the building in the form of steam at 862 x 10^3 Pa. When this auxiliary energy is required for heating or cooling, the pressure is reduced to 172 x 10^3 Pa and it is allowed to flow through two small heat exchangers and the condensate is returned to the central power plant. For the purpose of energy determination, steam pressure and temperature, and the condensate flow and temperature are measured. The pressure and flow measurements produce 4 to 20 mA signals.

The electrical power consumed by the major pumps in the solar energy system is measured by three-phase watt transducers whose 4 to 20 mA outputs are sent to the data acquisition system. The watt transducers are 480 volt delta connected and each reads the current in two legs of the three phase line. Accuracy is better than 1 percent.

Weather data in the form of ambient temperature, wind speed, and wind direction is gathered from a small weather station located on the roof. In addition, the solar flux is measured in both the horizontal and collector planes by two pyranometers designed for this purpose.

The solar energy system instrumentation occupies 68 analog channels in the data acquisition system and permits the determination of energy balances, efficiencies, and overall system performance.

B. Heating, Ventilating, and Air Conditioning Systems

Figure 2 is a simplified HVAC system schematic in which typical instrumentation locations are shown. Two types of air temperature measurements are made. Copper-constantan (Type T) thermocouples are used in all air supply and return ducts as well as in the fan discharges. The accuracy of these measurements is within ± 0.5°C with a resolution of 0.1°C. The reference system is shared with the solar energy system instrumentation. When air temperature measurements must be made in ducts of large cross-sections, an averaging temperature probe is used. These applications include the air washers, cooling coils, and a heat recovery unit. The probe consists of a 1000 ohm Balco resistance thermometer with an active length of 6.6 m, which is suspended across the duct so that it may respond to the average air temperature. Excitation and read-out of the probe is accomplished through a conventional bridge network. The accuracy and resolution of the measurement is similar to the thermocouple measurement described above.

*Ellison Instrument Co., Boulder, CO

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Air flow measurements within the supply and return ducts are made by precision propeller anemometers pre-calibrated to provide an output of 1 volt at an air speed of 180 m/s. As a means of checking the in-place calibration of the anemometers, each is provided with a Duct Air Monitor Device (DAMD)* permanently mounted in the duct up stream of the anemometer. Each DAMD consists of a honeycomb air straightner section followed by an array of static and total pressure sensors interconnected in an averaging configuration. The output lines (static and total pressure) from each DAMD are routed to a central jack panel where the differential pressure across a selected DAMD may be measured by means of 0 to 1 torr differential capacitance manometer. The electrical output (0-10 volts) of this instrument is connected to one channel of the data acquisition system so that on-line calibration of the propeller anemometers may be made during system operation.

Dew point temperature measurements are made in the return air ducts and at selected locations in the air handling equipment. The device used is a DewProbe,** an electrically heated, self-regulating, lithium chloride dew point hygrometer. The DewProbe temperature is sensed by a 500 ohm nickle resistance thermometer. A conventional bridge network is used for excitation and read-out of the resistance thermometer. The actual dew point temperature is related to the measured temperature by a nearly linear function. This conversion is done in the data reduction program.

Air flow in the HVAC system is controlled by variable position dampers, which respond to pneumatic outputs from the control system. The relative positions (0 to 100 percent) of 14 of these dampers are measured by potentiometers coupled to the actuator shafts. The potentiometers coupled to the actuator shafts. The potentiometers are excited with 5 volts dc and the voltage at the arm of each potentiometer is read by the data acquisition system as a measure of the damper position.

Electrical power to the two supply and two return fans is measured by three phase delta connected watt transducers, which provide 4 to 20 mA signals to the data acquisition system. In a similar manner, the building lighting loads are measured by 7 additional watt transducers. The total electrical load of the building is measured by a cam-driven contact installed in the main kWh meter. This contact, which provides one transition per kWh, is used to generate interrupts in the data acquisition program; these interrupts are counted to provide a measurement of the electrical energy consumed in the building.

C. Control System

The controls for the solar energy system and the HVAC system are based on conventional pneumatic proportional control systems. The solar energy system has two heating modes (normal and auxiliary) and three cooling modes (normal, auxiliary, and night-time evaporative). Operation of the system in any one of these modes results in the closure of a contact associated with a pressure to electric transducer. The contact closures are wired to a digital interrupt module in the

*Air Monitor Corp., Santa Rosa, CA

**Honeywell, Minneapolis, MN

data acquisition system, which senses the state of the control system, and then makes any necessary changes in the data acquisition and display tasks.

III. DATA ACQUISITION

A. Requirements

Early in the project it was realized that the complexity of the system and the number of measurements needed to characterize it made it imperative that some form of on-line data reduction and display of system behavior be provided. A simple data-logging scheme would result in the generation of large quantities of data, which would be useless until further processed. Therefore, specifications were written for a minicomputer based data acquisition system with the capability for simultaneous data acquisition, reduction, display, and program development. The specifications also provided for system expansion, both in the number of data acquisition channels and in the capability for analog and digital outputs, since a projected expansion of the research program will require development and implementation of programs for energy management and control of the building energy systems.

B. Configuration

The system selected, and ultimately delivered, consists of a PDP-11/34* central processor with 32K of parity core memory, 7.5 megabytes of mass storage (disk pack), a console terminal, a CRT terminal with both alphameric and graphics capability, and a fully integrated local process I/O subsystem. A communications interface and auto-answer modem are also included to permit access from remote terminals. The local process I/O is presently configured with two A/D converters connected to 160 analog channels and a single 16 channel digital interrupt module. All but 5 analog and 6 digital channels are presently in use.

The system software, RSX-11M,* is a real-time, multi-user, multitask operating system. All program development is done in FORTRAN IV. The system permits task scheduling as a function of time and specific events; this permits the system to operate around the clock with a minimum of operator intervention.

C. Capabilities

Each A/D converter is capable of sampling analog channels at the rate of 200/s. By using the two converters in parallel, an effective sampling rate of 400/s is achieved. The full scale range of each analog channel is programmable between ±10 mv and ±10 volts in a 1, 2, 5 sequence with 12 bit resolution. The gain programming and channel selection are accomplished by FORTRAN subroutine calls to the process I/O. At present, the system samples all the channels once every 15 s and converts the readings to appropriate engineering units (°F, gal/min, etc.) and stores these values in a common block accesible to other programs. A second program, running at the same interval, then calculates the energy balances appropriate to the building's operating mode (heating, cooling, etc.) and updates a disk file with the current and

*Digital Equipment Corp., Maynard, MA

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integrated values for these balances. Every one-half hour during the day (hourly at night) a summary of these balances is printed on the system console and also written in a disk file. In addition, mode changes sensed by the digital interrupt module will force summaries to be printed. Once a day, at midnight, a disk file, located on the removable disk pack, is updated with the day's summaries and all integrations are reset to zero. This disk pack holds up to one month's summary data and serves as long term archival storage. During the day additional summaries and information regarding the individual channels may be requested without interrupting the system operation.

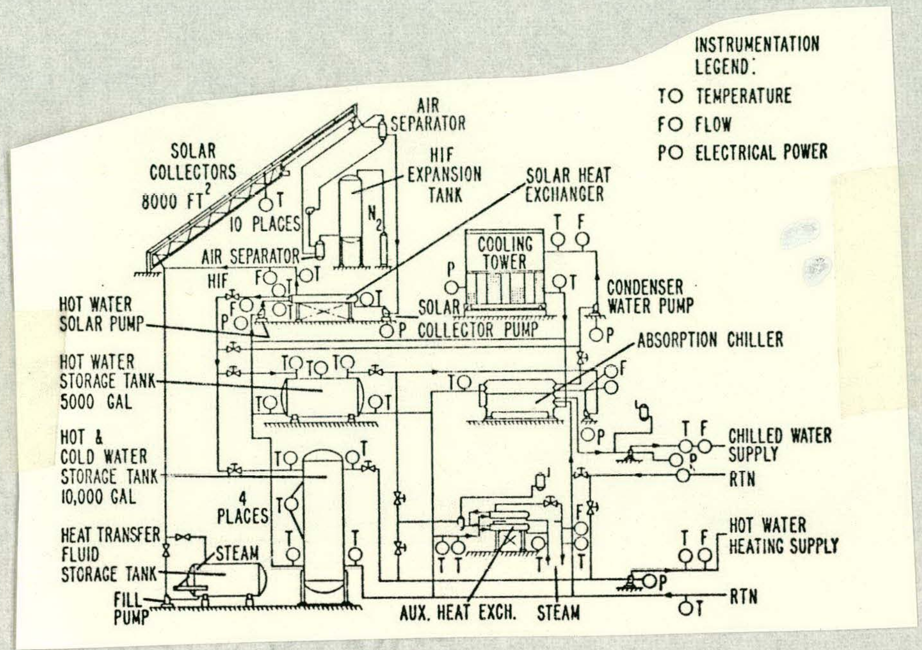

Fig. 1. Simplified mechanical schematic.

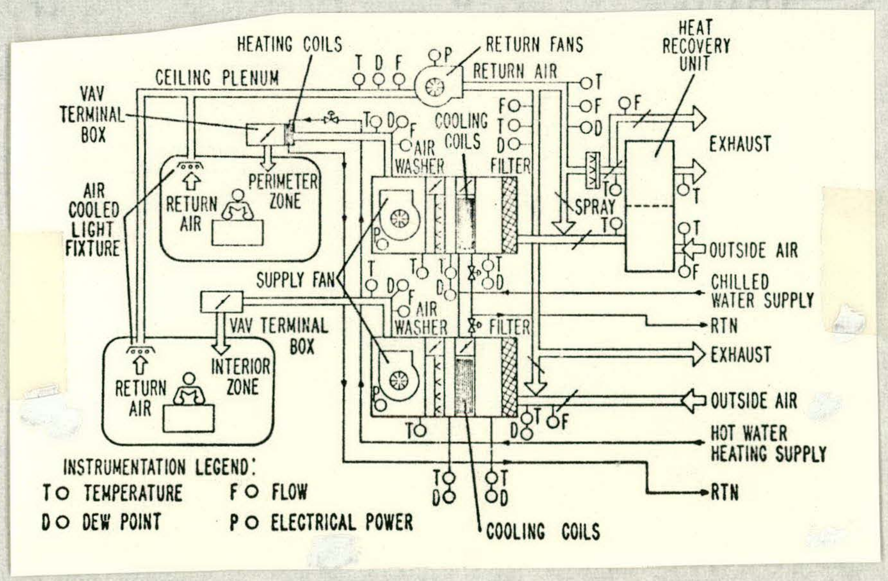

Fig. 2. Simplified HVAC schematic.

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ON-LINE PERFORMANCE CALCULATIONS FOR THE LOS ALAMOS NATIONAL SECURITY AND RESOURCES STUDY CENTER

by

Hugh S. Murray and James C. Hedstrom
Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, New Mexico 87545

ABSTRACT

The National Security and Resources Study Center at Los Alamos, New Mexico, has been heavily instrumented to permit monitoring of the performance of the solar heating and cooling system. The monitoring system includes a computer, which provides the capability for doing real-time engineering calculations. This capability permits data compression and allows the researcher to interact with the system and to see immediately the results of changing the system parameters.

I. INTRODUCTION

The solar heating and cooling system of the National Security and Resources Study Center (NSRSC) at Los Alamos, New Mexico, incorporates a number of energy conserving features and represents the use of a solar energy system integrated into the design of a modern commercial building.

Studies of the NSRSC system include a performance evaluation of the solar heating and cooling system and overall optimization of the energy system. Cooling experiments include a comparative study of absorption refrigeration versus a solar Rankine cycle cooling unit. Several different modes of operation of the system are available, and the control system has numerous set points and parameters, which may be varied to optimize system performance. About 160 measurements are made in the system to analyze the performance.

In order to conduct the necessary experiments on the energy system effectively, a computer-based data acquisition system was required. The additional computational power offered by a computer over more conventional data acquisition systems allows the researcher to interact with the system and to see immediately the results of changing the system parameters in a comprehensible format. Changes in the operating mode of the system and the occurrence of other significant events can be detected by the computer and the effect of these changes can be summarized. The researcher is able, with minimum effort, to add or modify engineering calculations using the basic data from the system, to display the results, and to save the results in a summary form. By performing the calculations necessary to determine system component energy balances in real time, the amount of data that must be stored is reduced considerably, and the need to do additional post-processing of data to determine system performance is totally eliminated.

II. SYSTEM DESCRIPTION

A description of the building energy system and a detailed view of the installed instrumentation is given in another paper by M. A. Trump.[1]

The computer system consists of a PDP-11/34* central processor with 32K words of core memory, a 5 M byte fixed disk, a 2.5 m byte removable disk pack, a system console, a CRT terminal with limited graphics capability, and a process I/O subsystem. A communications interface is also available to permit access to the computer from remote terminals.

The operating system software for this computer is RSX-11M,* a real-time, multi-user, multi-task system. This system provides for the building, scheduling, and running of the real-time programs (tasks). A number of utilities are provided to perform program text editing, file management, and high-level language processing. All programs are written in FORTRAN IV, and the system provides FORTRAN callable subprograms to service the I/O subsystem.

Because of the limited size of the computer, only one task may be in memory at any time. The user may assign priorities to the various tasks and the system allows competing tasks to run on the basis of their relative priorities. A task may also be assigned the attribute of "checkpointability," which will allow the system to remove that task to run a time-critical task and then to restore the checkpointed task so that it may run to completion. The system utilities are checkpointable, allowing program development to be accomplished concurrently with and without interfering with the running of the real-time tasks.

III. SYSTEM FUNCTIONS

The system basically provides for data acquisition, data conversion, energy calculations, interrupt processing, energy summaries, data storage, and data display.

A. Data Acquisition

The data acquisition task runs every 15 seconds at the highest task priority and may not be checkpointed by another task. All of the channels are sampled at this interval and converted to engineering units. The components of the data acquisition task are:

1. The I/O subsystem driver
2. Resistance probe conversions
3. Thermocouple conversions
4. Turbine flowmeter conversions and pressure differentials
5. Weather station (temperature, wind, and pyranometer) conversions
6. Watt transducer conversions
7. Propeller anemometer conversions
8. Dew probe conversions

The converted values are stored in a permanently core-resident common data area, which provides the link for communication among the various tasks.

At the conclusion of a complete data scan, a task that performs the energy calculations is activated by the data acquisition task.

B. Energy Calculations

This task uses the converted data to perform the energy flow calculations on the solar heating and cooling system components. Primarily,

*Digital Equipment Corporation, Maynard, MA these calculations consist of mass flow rate times specific heat times temperature differential calculations, and include mass flow rate calculations based on pressure differentials, fluid density, and temperature, and corrections to specific heats and functions of temperature. The instantaneous energy flows as well as average values over the sampling interval are stored in the common data area. The task also integrates these values to provide a total energy figure for each subsystem.

The contents of the common data block are backed up on the fixed disk every 5 minutes. This allows the system to be stopped for maintenance and restarted without losing integrated energy information. This feature also protects against loss of data in the event of a system "crash."

C. Interrupt Processing

A task is linked to the interrupt module in the I/O subsystem, which is activated upon the occurrence of any interrupt. The total electrical power is tallied in the common data block using interrupts from the main watt hour meter, and system operating mode changes are stored for examination by other tasks to determine which components should be analyzed.

D. Energy Summaries

A summary of all of the instantaneous heat flows, and integrated energies, weather data, and system temperatures and flow rates, is written on the fixed disk automatically every one-half hour from 6 a.m. to 6 p.m., and every hour otherwise. Additional summaries are written in response to any operating mode change.

At the end of the day (midnight), all of these data are copied to the removable disk for permanent storage. One month's worth of data typically uses about two-thirds of a disk pack's capacity. At this time all of the energy integrals are reset for the next day and the periodic summaries are printed on the system terminal. An additional file is then created that contains integrated energy values for the entire day as well as other pertinent information such as maximum and minimum storage and ambient temperatures. The condensed daily summary is also printed during the night. The daily summaries are saved for subsequent examination and display.

III. DATA DISPLAY AND RESULTS

Figure 1 is a typical printout from the periodic summaries taken during the day. In addition to being recorded on disk automatically, this information may also be displayed or printed on any terminal at any time in response to an operator request. This particular record was written at 1 p.m. on March 4, 1978. All energies and heat flows are in BTUs per square foot of collector area. Temperatures are in degrees Fahrenheit, and electrical powers in killowatts. A few of the significant variables shown in this table are:

1. Instantaneous collector insolation (QSUN35)
2. Integrated collector insolation for the day (ESUN35)
3. Storage tank vertical temperature stations (T1-1, 2, 3, and 4)
4. Solar collector output (COLL, SUPPLY)
5. Solar collector flow rate (COLL,FLOW) in gallons per minute

6. Domestic hot water energy consumption (DHW, SUPPLY)
7. Pump instantaneous electrical power (PUMP KW)
8. Pump integrated energy consumption (PUMP E) in BTU/ft^2

A similar summary is made for the air system.

Figure 2 is the condensed daily summry for the solar heating system only. The values are the integrated energies in BTU/ft^2/day for

QH - horizontal insolation
Q35 - collector incident
QCOLL - collector output
H1 - collector heat exchanger output
T1IN - storage tank input
T1OUT - storage tank output
H23 - auxiliary heat exchanger output
RHHW - total reheat energy
RHHWS - solar portion of reheat energy
DHW - domestic hot water
DD - degree-days of heating

Figures 3 and 4 show the computer generated daily summaries and monthly running totals for the system through March 6, 1978. Total monthly summaries are also kept on a seasonal basis (heating or cooling) to determine overall system performance, per cent solar, for example, for a full heating or cooling season. These tables to date are shown in Fig. 5.

Daily summary data may be viewed in bar graph form on the CRT terminal. An example of this is shown in Fig. 6. The hard copy feature of the CRT terminal is not of sufficiently high quality for reports, so data are also transmitted over the dial-up port to an HP 9830* system at another site for the purpose of making better quality plots. (An example of this type of plot is shown in Fig. 7.) The CRT, however, has proved extremely valuable for "snapshots" of current data.

IV. CONCLUSIONS

The computer-based data acquisition and processing system at the NSRSC has proved to be an effective tool for analyzing system performance, particularly from the standpoint of presenting system operating data in real time in a comprehensible format. This feature is virtually a necessity when system optimization studies are being conducted. The system has also proved to be highly reliable with very little downtime or loss of data.

ACKNOWLEDGMENTS

Work performed under the auspices of the US Department of Energy and funded by the Research and Development Branch for Solar Heating and Cooling, Office of the Assistant Secretary for Conservation and Solar Applications.

REFERENCES

1. M. A. Trump, Data Acquisition and Monitoring System for Los Alamos National Security and Resources Study Center, to be presented at the "Conference on Performance Monitoring Techniques for Evaluation of Solar Heating and Cooling Systems," Washington, D.C., April 1978.

*Hewlett Packard, Palo Alto, CA

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 DATE       TIME       MODE   MODE LAST     DT
3/ 4/78   13: 0: 0      1        1        0.25
  TA       WSPEED      WDIR     QSUNH    QSUN35    ESUNH        ESUN35
 40.5        1.8       -0.2     261.5     329.6    1008.2    1416.5
 T1-1       T1-2       T1-3      T1-4      T2-1      H23S
135.2      137.4      137.7     137.5      72.6     259.2
          COLL     H1   T1IN  T1OUT    H23     RH    DHW
SUPPLY   167.3  142.8  142.6  140.3  106.7  139.8  139.7
RETURN   156.9  135.1  134.9  128.8  102.1  128.4  138.7
FLOW     460.2  309.0  309.0   59.8    0.0   59.8   15.7
HEAT     152.4  153.9  152.9   44.5    0.0   44.1    1.0
HEATAV   110.3  109.0  107.7   42,1    0.0   42.7    0.9
ENERGY1  567.1  572.1  564.9  156.8  200.4  354.7    5.2
ENERGY2  220.1  335.2    0.0    0.0    0.0  161.4    0.0
HTM 166.3 166.9 165.3 165.9 165.5 166.5 166.1 165.7 166.7 164.7
PUMP KW     9.56      1.12      1.17      0.00      0.00      0.00      0.00
PUMP E      20.0       2.4       7.1       0.0       0.0       0.0       0.0
LITE KW    48.66      0.42      0.42      0.00      0.00     11.09     19.37      0.40
LITE E    280.23      2.27      2.27      0.06      0.00     64.01    103.96     14.67
FAN  KW    10.96     12.19      5.00      2.23
FAN  E     34.84     38.50     15.85      7.03
    HTRC       PFA       IFA       TFA
   28.70     19.35     39.28     58.63
  144.53    115.13    220.05    335,18
```

Fig. 1. Periodic energy summary.

```
DATE      3/ 6/78

  QH    Q35   QCOLL    H1   T1IN  T1OUT  H23   RHHW  RHHWS   DHW
 1316  1623   564.   574.   570.   346.  209   574.   369.  12.3

TA    MAX/MIN/DD     48/28/27.
```

Fig. 2. Daily summary, solar system.

NATIONAL SECURITY AND RESOURCES STUDY CENTER

HEATING RESULTS FOR 3/78

SOLAR DATA

DAY	SUN HORZ	SUN .35	COLL OUT	HTEX IN	TANK OUT	DOM HW	AUX STM	TOT HEAT	PUMP 1+2	TSMAX F	TSMIN F
1	333	296	0	0	17	5	476	498	0	98	97
2	1456	1682	570	582	284	11	262	557	29	132	96
3	886	838	113	117	179	7	402	588	12	115	105
4	1528	1998	782	788	448	9	200	657	32	148	104
5	739	772	156	166	403	2	79	484	16	126	99
6	1316	1623	564	574	346	12	209	567	24	131	98
TOT	6258	7209	2185	2227	1677	46	1628	3351	113	125	100

UNITS: BTU/FT2/DAY

Fig. 3. Solar system daily summary table.

NATIONAL SECURITY AND RESOURCES STUDY CENTER

HEATING RESULTS FOR 3/78

BUILDING DATA

DAY	HOT WATER	TOT ELECT	TOT LITE	FANS S+R	PUMP 3+4	TOT HEAT	HTRC UNIT	FRESH AIR	TAMAX F	TAMIN F	DD F*D
1	516	1099	660	161	12	1349	369	1057	44	35	25
2	556	1099	657	162	12	1387	290	1110	46	31	25
3	596	961	649	160	13	1418	401	1237	33	16	40
4	664	605	343	165	12	1184	210	860	44	27	29
5	518	597	350	164	13	1045	198	775	47	33	24
6	573	1012	664	160	12	1409	192	930	47	28	26
TOT	3423	5373	3323	972	74	7792	1660	5969	44	28	169

UNITS: BTU/FT2/DAY

Fig. 4. Building daily energy summary.

NATIONAL SECURITY AND RESOURCES STUDY CENTER

HEATING RESULTS FOR 77/78

SOLAR DATA

MON	SUN HORZ	SUN 35	COLL OUT	HTEX IN	TANK OUT	DOM HW	AUX STM	TOT HEAT	PUMP 1+2	TSMAX F	TSMIN F
11	30833	48217	16902	19425	14476	0	1966	16442	0	133	108
12	28187	46472	15528	16360	13453	275	4909	18637	309	134	111
1	28840	43648	14413	14874	11997	394	7382	19773	683	130	105
2	33762	44895	14047	14188	11766	358	5335	17479	674	138	109
TOT	121622	187232	60890	64847	51712	1027	19592	72331	1666	143	113

BUILDING DATA

MON	HOT WATER	TOT ELECT	TOT LITE	FANS S+R	PUMP 3+4	TOT HEAT	HTRC UNIT	FRESH AIR	TAMAX F	TAMIN F	DD F*D
11	14952	0	0	0	0	14952	0	0	47	31	634
12	18249	11574	8233	2704	87	29273	0	0	45	28	859
1	19361	29183	17149	5219	391	42120	1404	3474	39	23	1018
2	17211	27286	16095	4683	346	38335	6096	17313	41	24	880
TOT	69773	68043	41477	12606	824	124680	7500	20787	43	24	3391

UNITS: BTU/FT2/MON

Fig. 5. Seasonal tables.

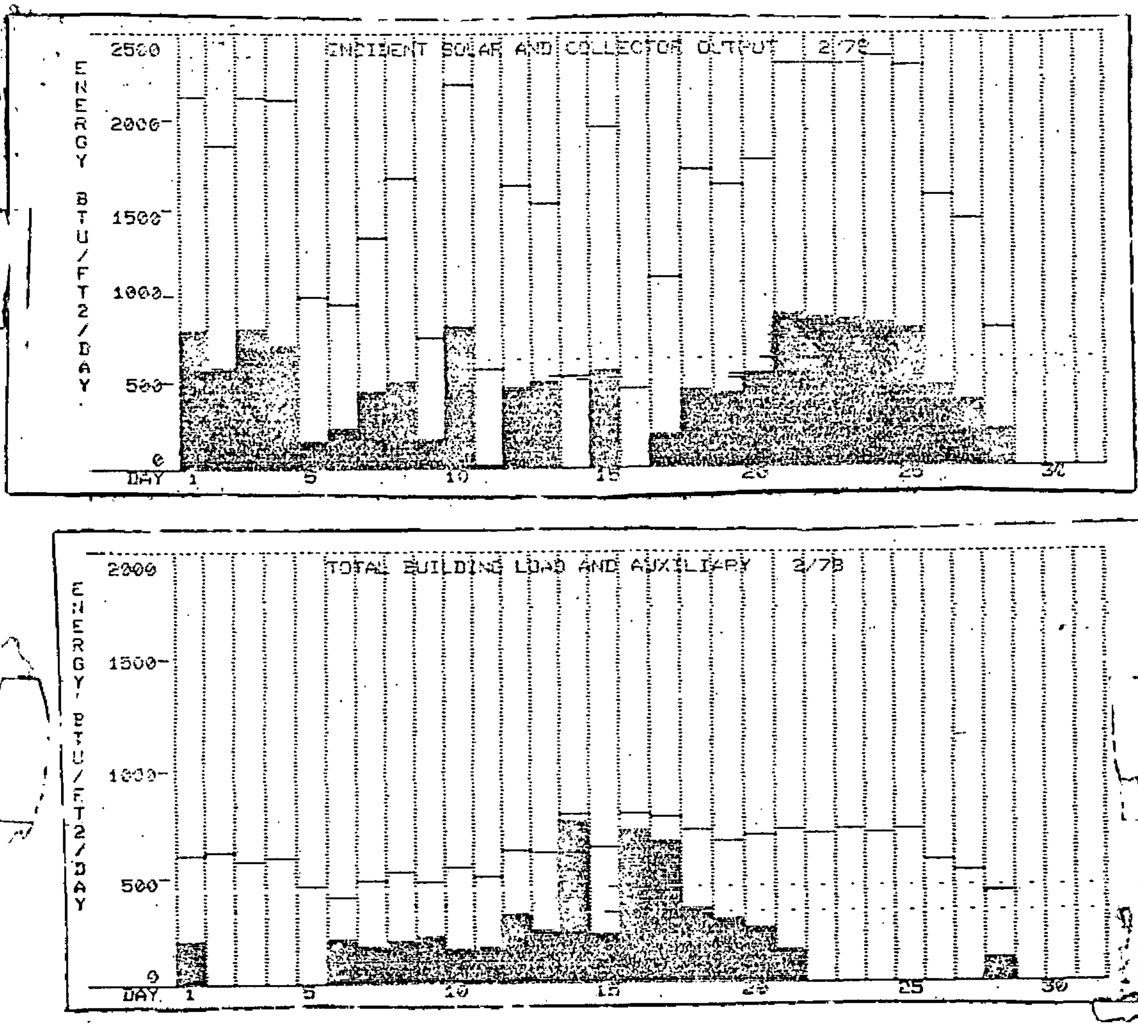

Fig. 6. Computer-generated energy summary bar graphs.

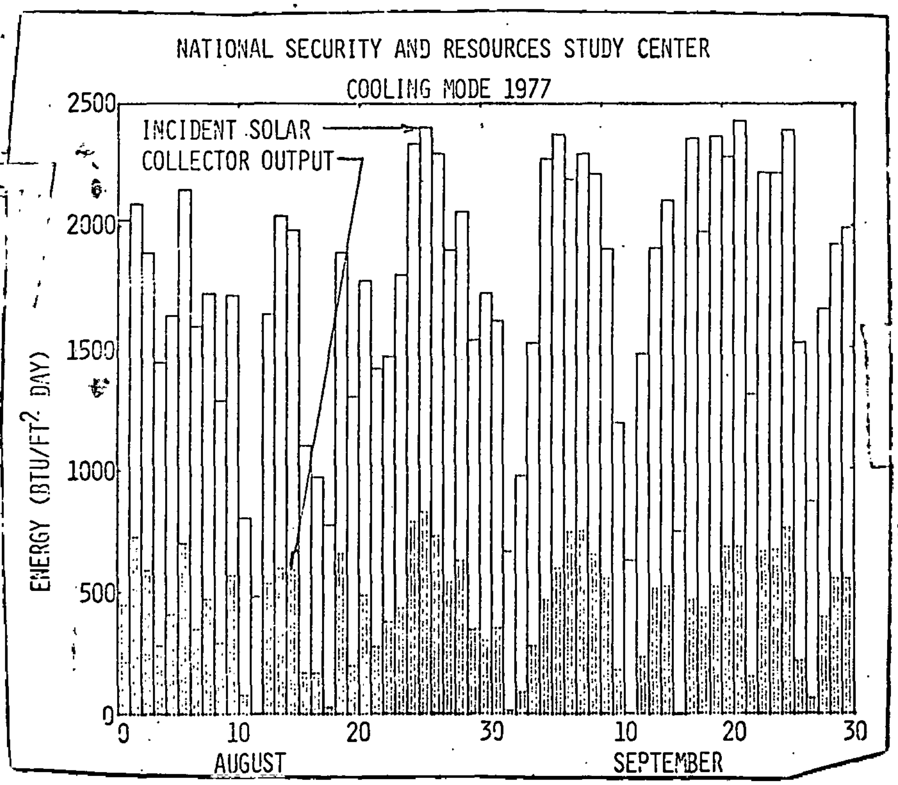

Fig. 7. HP 9830 bar graph.

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ABSTRACT

EXPERIENCE GAINED AND LESSONS LEARNED FROM MONITORING THE SOLAR BUILDING, ALBUQUERQUE

By

M. W. Wildin, Department of Mechanical Engineering
The University of New Mexico, Albuquerque, NM 87131

and

E. J. Hull, E. R. McLaughlin and S. F. Gilman
Department of Architectural Engineering
The Pennsylvania State University, University Park, PA 16802

Data were collected on the solar-boosted heat pump system in the Solar Building, Albuquerque, for the heating seasons of 1974-75 and 1975-76 and for a portion of the 1975 cooling season. An automated data acquisition system centered around an IBM System 7 was used to collect data from 72 sensors in 1974-75 and 165 sensors in 1975-76. To provide adequate time resolution to permit identification of significant events without storing unduly large quantities of data, six-minute averages or totals of the data from each channel were recorded. Files of six-minute data were transmitted frequently via a dial-up telephone connection to The Pennsylvania State University for permanent storage, display and analysis. Hourly totals and averages of the data were scanned to assess system performance and to detect malfunctions, while six-minute data were used in detailed analysis of system performance, and in data validation and diagnostic work which required finer time resolution.

It was found that assessment of validity of the data was an essential prerequisite to analysis of system performance. Furthermore, continual observation and analysis of the data were found to be necessary to maintain acquisition of valid data. Our experience indicates that it is essential to have personnel knowledgeable about both the HVAC system and the instrumentation and data acquisition systems on-site regularly and frequently and to provide them with the capability to observe both current data and data obtained at regular intervals in the past. We also found that the ability to perform energy balances regularly and frequently on components and subsystems is very desirable in maintaining acquisition of valid data on related quantities such as electrical and thermal energy flow rates. Use of redundant temperature sensors and frequent comparison of their outputs was found to be very helpful in maintaining valid temperature data. We also learned the necessity for clear communications between those whose equipment is interfaced to record and transmit data.

EXPERIENCE GAINED AND LESSONS LEARNED FROM MONITORING THE SOLAR BUILDING, ALBUQUERQUE

By

M. W. Wildin, Department of Mechanical Engineering
The University of New Mexico, Albuquerque, NM 87131

and

E. J. Hull, E. R. McLaughlin and S. F. Gilman
Department of Architectural Engineering
The Pennsylvania State University, University Park, PA 16802

Introduction

In June, 1974, a grant was given by the U. S. National Science Foundation to perform monitoring of the solar-assisted heat pump system in the Solar Building, Albuquerque. The grant was awarded for a proposal submitted by Dr. Stanley F. Gilman in the category of performance monitoring of existing solar buildings in response to the November, 1973 NSF solicitation. It should be noted that at the time of this solicitation there were few existing solar-heated buildings in the U. S. and very few solar-heated office buildings. However, the Solar Building, Albuquerque, had been in existence for seventeen years, although the solar portion of the heating system had been inactive since 1962. Thus, one of the principal objectives of the project was to renovate the solar system sufficiently to place it in regular operation again. Although minimal modification of the original system was desired by the NSF project monitor, it was decided that the collector panels would be cleaned, repainted and repaired, the controls for the solar-assisted heating and cooling (HVAC) system converted from manual to automatic operation and a heat exchanger added between the collector loop and the storage tank so that anti-freeze could be used in the collectors. These changes were designed and supervised by Bridgers and Paxton Consulting Engineers, Inc. under a subcontract from The Pennsylvania State University.

Following renovation, the objective was to operate the system and monitor its performance during the 1974-75 heating season. Subsequently, a contract was received from ERDA to extend the monitoring through the 1975-76 heating season. The principal purposes for monitoring the system were threefold. One was to determine how well the solar-boosted heat pump system performed, the second was to investigate concepts for modifying the system to improve its performance and the third was to obtain experimental data that could be used in assessing the validity of a computerized model to be developed for solar-boosted water-to-water heat pump systems applied to office buildings.

Measurements Performed and Data Acquisition System Selection

To achieve these objectives, an extensive monitoring effort, based on a computer-controlled data acquisition system, was planned. The plan included automated sampling and storage of data on system fluid temperatures, inside and outside air dry bulb and dew point temperatures, electric energy use, liquid flow rates, incident solar radiation, wind speed and direction, operating mode of the system and elapsed time of door openings. The liquid temperature at the inlet and outlet of every subsystem and of almost every heat exchanger in the system was to be measured (see Figure 1).[1] Inside air temperature was to be measured at several locations; and inside and outside dew point temperature and outside dry bulb temperature were each to be measured at one location. Electrical energy use by each component of the HVAC system, including pumps and blowers, was to be measured, as was the total single-phase and three-phase electrical energy used in the building. The liquid flow rate through each pump and each water-to-air heat pump was to be monitored. The diffuse and total insolation on the plane of the collectors and the total insolation on a horizontal plane near the collectors was to be measured, as were the wind speed and direction. In all, 72 separate channels of data were to be recorded in 1974-75 (expanded to 165 channels in 1975-76). The instrumentation used to make these measurements was installed by the Department of Mechanical Engineering at The University of New Mexico, which subsequently provided on-site services to Penn State by helping maintain acquisition of valid data and interpreting results.

An IBM System 7, Model A10 computer with twin disk pack storage and a bisynchronous communication module was selected as the data acquisition system. This system was selected because it was being used successfully in other monitoring projects of a similar nature, principally by Professor Sepsy of Ohio State University, and because field-developed programs for data acquisition applications were available. It is a very powerful system, since it is fully programmable, its computational speed is high and its disk storage capacity is large.

The computer sampled the inputs, digitized the data and stored it temporarily in core. Inputs were sampled at intervals ranging from 1/2 second for rapidly-varying quantities such as wind speed and direction to 6 minutes for room temperatures, which varied slowly. Most inputs were sampled at intervals of one, ten or sixty seconds. The data from each sensor were summed to produce six-minute totals, termed records, prior to storage on disk. Thus, the minimum time resolution of the recorded data is six minutes. The six-minute records for all items of data were formed into files after several hours of continuous data collection. Twelve-hour-long files were used in 1974-75 and three-hour-long files in 1975-76. To avoid confusion in reducing the data and recovering it from permanent storage, only continuous files were retained; so if data collection was interrupted for any reason prior to completion of a file, all the data in the file were lost. This produced excessive losses of data in the first heating season, for reasons to be discussed later; so the file lengths were reduced thereafter.

To reduce the rental charges for the data acquistion computer, no provision was made for on-site data reduction. Hence, the only data output that could be obtained locally from the data acquisition system as originally configured was the most recent set of samples, in the hexadecimal number system. An associated decision was to transmit all the data via the telephone system to The Pennsylvania State University computer system for permanent storage and subsequent manipulation, display, reduction and analysis. Although an IBM 1130 could have been

[1]All figures are taken from: "Field Study of a Solar Energy Assisted Heat Pump Heating System," by S. F. Gilman, M. W. Wildin and E. R. McLaughlin, ERDA Document COO-2704-4, December, 1976.

available for on-site data reduction at the initiation of our project, the building owner anticipated replacing it soon, so no provision was made for its use. Thus, the only way to obtain a comprehensive view of the data was by transmitting it to Penn State, printing it on hard copy and returning it by mail to the site.

This type of arrangement may be satisfactory for monitoring if no problems occur, but it was found to be quite unsatisfactory for initial check-out and for diagnostic work. For these purposes, quick output of recently-sampled data is essential. It was found that the utility of data for trouble-shooting decreases rapidly with time. Also, it was found to be desirable to have data from redundant sensors, for purposes of checking the sensors' outputs. And it is desirable to have essentially simultaneous data from several sensors that measure related variables, for purposes of computing an energy balance on an item of equipment or a subsystem. Furthermore, to gain an understanding of system and component operating patterns, it is desirable to output data from a few key sensors at regular, periodic intervals or upon command, for trouble-shooting. To fulfill this need, a data logger was borrowed from the Mechanical Engineering Department at The University of New Mexico and installed at the site early in the check-out phase. It remained on site for the duration of the first year of the project, at which time it was replaced by a data logger purchased with project funds. Although only a few essential channels of temperature data were monitored with the data logger, it proved to be a valuable complement to the capabilities of the data acquisition computer for purposes of check-out, diagnostics and quick scans of the operating pattern and the status of system operation. Thus the importance of providing a capability for local output of data at regular, periodic intervals and instantaneously, upon command, was learned.

In retrospect, it would have been desirable to transfer the data to an on-site or near-by computer, at least for conversion to engineering units and display. This would have permitted inspection of a more complete set of data by on-site personnel at an earlier time. This, in turn, would have facilitated diagnosis of problems by enabling earlier correlation of a broader set of observed events with the data. Also, transfer of the data to Penn State on magnetic tape would have aided in reducing losses of data associated with the transmission process, which losses are discussed in the following section.

Data Transmission and Losses

Data were transferred from disk storage on the System 7 to the Penn State central computer and subsequently to storage on 9-track tape. Each set of data was also stored on a second tape, to avoid losses of data due to destruction or erasure of the first tape. Transfer of data occurred nominally once a day, and was implemented by means of a dial-up long distance telephone connection between the site in Albuquerque and the Penn State computer. Transfer of data took place at 120 characters per second and was effected by a Bisynchronous Communications Module attached to the System 7 computer. Only complete data files, comprised of 12 hours of continuous 6-minute records in 1974-75 and 3 hours of records in 1975-76, were transmitted. Since it was desired to make provision for temporarily saving on the System 7 disk storage files that had been transmitted, pending their output and inspection at Penn State, it was necessary to mark the files on disk storage according to whether they were "empty," denoted E, and therefore ready to receive data, or "filled," denoted F, and therefore ready for transmission or "transmitted," denoted T, but being held temporarily pending inspection. Also, provision was made to automatically and immediately retransmit any portion of a file that was not received properly at the other end. If successful transmission was not achieved after 5 attempts, a time-out error occurred, which halted transmission.

In general, this scheme for transmitting data and marking files yielded quite satisfactory results when the interface between the data acquisition computer and the telephone system performed well. However, for about three months at the start of data acquistion in 1974-75 and again in the summer of 1975, serious problems were encountered with this interface. At times, transmission would occur without interruption. At other times, it was essentially impossible to transmit data, due to failure to establish an adequate connection, or due to time-out errors, or due to the System 7's "going down," i.e., ceasing to operate. These failures were frequently interactive, thus tending to compound the difficulty of transmitting data on some occasions. They were interactive in the sense that time-out errors tended to occur when it was difficult to achieve a satisfactory telephone connection, and repeated attempts to reestablish communication and transmit data tended to cause the System 7 to go down. Shut-down of the System 7 prior to completion of a file caused loss of data, due principally to the fact that incomplete files were not saved. Of course, no data were collected when the computer was shut down, thus increasing the losses. Data losses due to failure to complete a file increase with increasing length of the file, so the 12-hour file length used in 1974-75 was reduced to three hours in 1975-76. The longer file length in 1974-75, combined with the difficulties encountered with transmission early in this period, caused significant losses of data. The losses due to unplanned shut-downs were increased by the occasional need to shut down the System 7 to permit diagnostic work on it. Whenever possible, the computer was shut down just after a file had been completed, but this was not always possible, particularly with the 12-hour file length, due to the need for key personnel at both ends of the line to be available. Very little data was lost from storage or in the actual transmission process, due to the capability of the computer to automatically store information on disk in the event of a power failure and due to the provision to re-mark and save files that had been transmitted, if it was felt that the transmission had been unsatisfactory. The principal problems with the transmission process were noisy telephone connections and a lack of mutual understanding of interface requirements on the part of IBM and Mountain Bell Telephone personnel; the latter being the dominant factor. Thus, the importance of clear communication between the parties responsible for each side of an interface was learned.

Techniques for Checking and Validating Data

The simplest technique for validating data, and one that is extremely useful in monitoring systems that should operate continuously, is use of redundant sensors. Implementation of redundancy checks may require use of duplicate sensors or instruments, but such checks can be performed by comparing readings obtained during certain operating modes from sensors that are not redundant in the usual sense. For example, the readings from two temperature sensors in a fluid stream on opposite sides of a heat exchanger may be compared under conditions in which flow continues but negligible heat is exchanged. Such conditions occur when an item of equipment cycles off, but the system remains in the same basic mode of operation. This type of redundancy check was implemented both during normal system operation and during special check runs, to be described later. It was especially helpful to be able to perform these checks during normal system operation by regular, at least once daily, observation of data output from the data logger. It was found that enough cycling occurred to permit checking most of the critical temperature sensors in this manner. Use of six-minute average data returned from Penn State was helpful in performing redundancy checks on additional sensors.

Longer-term checks were performed on the readings obtained from the watt-hour meters, by performing visual readings over periods a few hours in length and comparing the differences in these readings with the energy use indicated by the automated data acquisiton system for the same period. Shorter term checks were performed by counting revolutions of the watt-hour meter disk for six minutes and comparing with the computer output. These checks are on the data acquisition system alone, and do not constitute redundancy checks. Although it was planned to implement redundancy checks on water flow rate readings by comparing outputs from turbine flow meters with rotameter readings, only one turbine meter was obtained late in the second heating season, so these checks were performed in a very limited fashion. However, it was possible to perform redundancy checks on three of the rotameter readings during much of the first heating season, since two of the water streams joined to form a mixed stream, and there was rotameters in each of the three lines. These checks were performed frequently during the first six weeks of the 1974-75 heating season, when visual readings were made hourly during occupied hours due to lack of receipt of watt-hour meters with pulse outputs. These readings also established that the various water flow rates for each of the modes of operation were relatively stable, which alleviated the perceived need for automated measurement of water flow rates. But it would have been helpful to have had such measurements at times, such as when portions of the control system malfunctioned.

Since redundancy checks were not performed on electrical power, it was considered doubly important to implement, wherever possible, energy balance checks to validate simultaneous measurements of temperature, flow rate and electrical energy use. This was felt to be the case particularly for the water-to-water heat pump. However, our initial attempt to obtain an energy balance on this unit lasted for several weeks. In the process, every temperature sensor, watt-hour meter and water flow meter associated with this heat pump was recalibrated or checked by all the measures we would identify and implement. By the time the problem producing the failure to achieve an energy balance was identified and remedied, the necessity for performing energy balances had been deeply engraved in our thinking. Incidentally, the problem was primarily due to a missing check valve and not the instrumentation. An energy balance on the subsystem of water-to-air heat pumps, termed the heat pump loop, was considered important, since this loop was a major source of thermal energy for the 6,000 gallon storage tank. This occurred due to the continual need for cooling the computer room. Such a check was performed by measuring the water flow rate through, and the temperature difference across, each water-to-air heat pump, evaluating the rate of heat flow to or from the unit, and comparing the net heat flow to the water obtained by algebraically summing the heat flow rates to the five units with the net heat flow obtained by multiplying the temperature difference across the entire loop by the total water flow rate through the loop. Although the difference in temperature between the loop inlet and outlet was frequently on the order of 2 F, this check generally yielded satisfactory results due to careful selection and insertion of the temperature sensors at the inlet and outlet of the heat pump loop.

Following our difficulty in obtaining an initial energy balance on the water-to-water heat pump, we adopted a procedure of performing special runs to check out critical items of instrumentation and sensors. These runs were subsequently performed at fairly regular intervals during a period when the building was not normally occupied, such as at noon on Friday. The first step was to manually force the system into a certain mode of heat pump operation to maintain operation of the pumps, by resetting the main thermostat. The power to all blowers was maintained, while the power to all heat pump compressors was cut off. This step resulted in negligible heat exchange to and through all components except the collector loop, the heat exchanger and the storage tank for solar energy. After transients in the temperatures of the air and water streams had died out, it was possible to perform redundancy checks on the temperature sensors at the inlets and outlets of all heat pumps, the water-to-air heat pump loop and the heat exchanger in the main air handler. If these checks proved unsatisfactory, the sensors were checked further, frequently by interchanging the locations of sensors that should have agreed, but did not. Placement of most of the sensors in loose fitting wells filled with oil facilitated such interchanges. Faulty sensors were replaced until satisfactory agreement within 0.33 degrees F (0.18 degrees C), was achieved.[2] Following completion of the redundancy checks, power flow to all compressors was resumed. Continuous operation of the heat pumps in either the heating or cooling mode was maintained by adjusting thermostat settings, until steady state operation of each unit was achieved, as indicated by steady temperature readings. Flow rates observed visually during these runs were also recorded. The steady state data obtained from these runs on temperatures, electrical energy use and flow rates, were used to perform energy balances on the water-to-water heat pump and the water-to-air heat pump loop. Following completion of a check run, the system was returned to normal operation.

Energy balance checks were performed occasionally on the thermal storage tanks, by observing the inlet and outlet temperatures for a period of a few hours, using the temperature difference together with the water flow rate through the tank to compute a net energy flow rate and comparing the result with the change in internal energy computed from the water storage capacity and temperature change of the tank. Near-uniform tank temperature permitted use of the outlet temperature for the tank temperature. After-the-fact checks on the tank energy balance were also performed for a few periods of operation and the results displayed on plots, as will be shown later.

The only critical component on which an energy balance check was not performed was the heat exchanger between the collector loop and the main system. This type of check was not possible, since the turbine flow meter we planned to use in measuring the collector fluid flow rate was never obtained. The potential for errors in the heat flow rate through this heat exchanger was reduced, by observing redundant temperature measurements at both the inlet and outlet of the water side of the heat exchanger.

[2] Dual thermistor probes with linearized outputs, manufactured by Yellow Springs Instrument Company, were used for temperature measurements.

All of the checks described above were performed throughout data acquisition periods. Subsequent to acquisition of much of the data, extensive automated data analysis programs were developed, the results of which permitted observation of redundancy and energy balance checks for periods of normal operation. Six-minute data were used in these analysis programs, and results were produced in terms of six-minute and hourly energy flow rates and performance factors and hourly average temperatures.

Examples of the results obtained from these programs are presented in the format of energy balances in Figures 2, 3, 4 and 5. Figure 2 shows a comparison between values for the net heat flow rate to the water-to-air heat pump loop, using the two methods for evaluating this heat flow rate described above. Each point represents a corresponding pair of hourly total values computed from the data obtained during a 40 day period in 1976. If perfect agreement existed, all the points would lie along a 45 degree line. The scatter observed in the data is considerable, but does not seem unusual, considering the low differences observed between the heat pump loop inlet and outlet temperatures and the transients which occurred in these temperatures due to equipment cycling. Figure 3 shows a comparison of thermal energy output and the sum of the thermal and electrical energy inputs to the water-to-water unit, for the heat pump heating mode of operation. It is observed that the data exhibits a systematic deviation between the output and input energies. Similar disagreement was observed in the results from the special check runs, which involved steady-state conditions. The difference could be due in part to thermal losses from the compressor, since the input energy is higher than the output. But an estimate of such losses indicates that this mechanism could not account for all of the difference. Hence this difference remains unexplained. Figure 4 shows a comparison between the heat input to the water-to-water heat pump evaporator and the difference between the heat output from the condenser and the electrical input to the compressor, for the heat pump cooling mode of operation. Fewer data points appear, since less cooling operation occurred during the portion of the year to which this data pertains. The agreement is considered satisfactory, except for the points which lie along a line with a slope of about three. These points were obtained during a period when a portion of the control system malfunctioned, so that the water flow rates which occurred were quite different from those used in the data analysis program, which were the normal values. Figure 5 displays plots of measured (uniform) tank temperature and the temperature computed from an energy balance on the tank. Although differences developed between the computed and measured temperatures, particularly on date 51, the two curves exhibit the same behavior. The difference developed due to drift of a temperature sensor. Thus the agreement is considered to be acceptable, in general.

The above results indicate that, despite the transients which occurred in normal operation, the temperature, flow rate and electrical energy data obtained were generally valid. But it would have assisted in obtaining valid data if we had performed automated data analysis on a continuous schedule during data acquisition, to help identify problems.

Pyranometer outputs were checked using a comparative test, twice during the project. One such check was performed about midway through the first heating season when a new set of pyranometers was installed, after obviously invalid readings were obtained from the used instruments originally installed. The new instruments were Epply Black and

White pyranometers. This check consisted of placing all the pyranometers side by side on a horizontal plane having an unrestricted view of the sky. Their outputs were compared with each other and with the output of an Epply PSP Pyranometer. The agreement was within about three percent initially, and the difference was only slightly larger at the end of data collection, about 14 months later.

Conclusion

The principal conclusion we have reached from our experience is that the price of good data is continual vigilance, using personnel at the monitoring site who are thoroughly familiar with the operating patterns of the HVAC/Solar and the data acquisition systems. A second major conclusion is that a variety of checks must be utilized to maintain acquisition of valid data. These checks include observations of data from redundant sensors and calculation of energy balances. To achieve the steady state conditions essential for performing rigorous energy balances, it may be necessary to override an automatic control system; and this may require setting aside test period intervals. A third major conclusion is that capability for prompt local output of recently-sampled data in an easily-interpreted form is essential for diagnostic work. It is also helpful to have a capability to output all the data locally on a continuing, periodic schedule. This aids in gaining an understanding of system behavior more rapidly and therefore aids in interpreting results and diagnosing problems. Finally, when transmission of data over a distance is necessary, it is desirable either to provide a mechanism for temporarily storing all transmitted data until satisfactory transmission has been ascertained, in the case of telephone transmission, or to transfer the data on a more permanent medium such as magnetic tape.

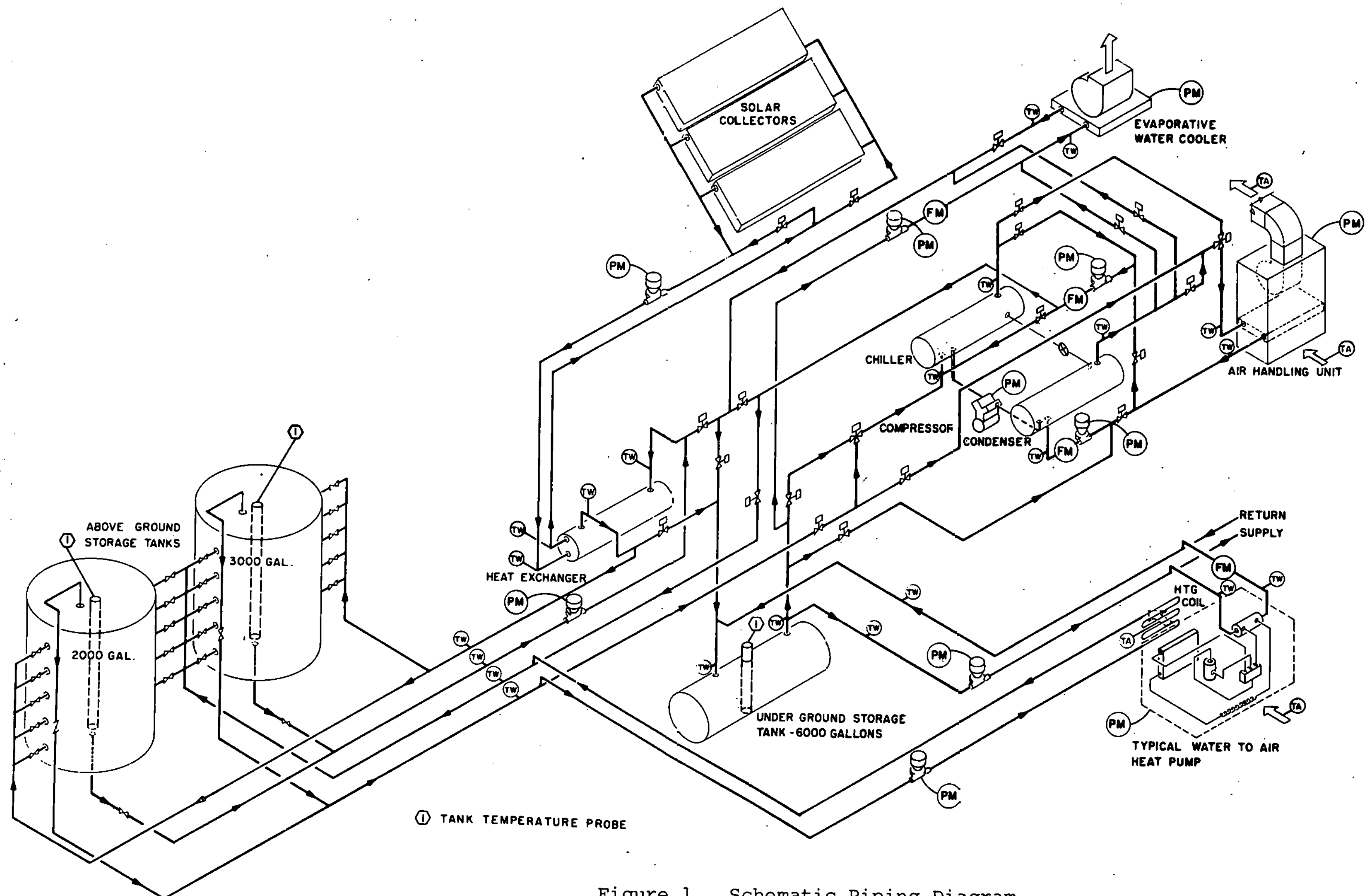

Figure 1. Schematic Piping Diagram

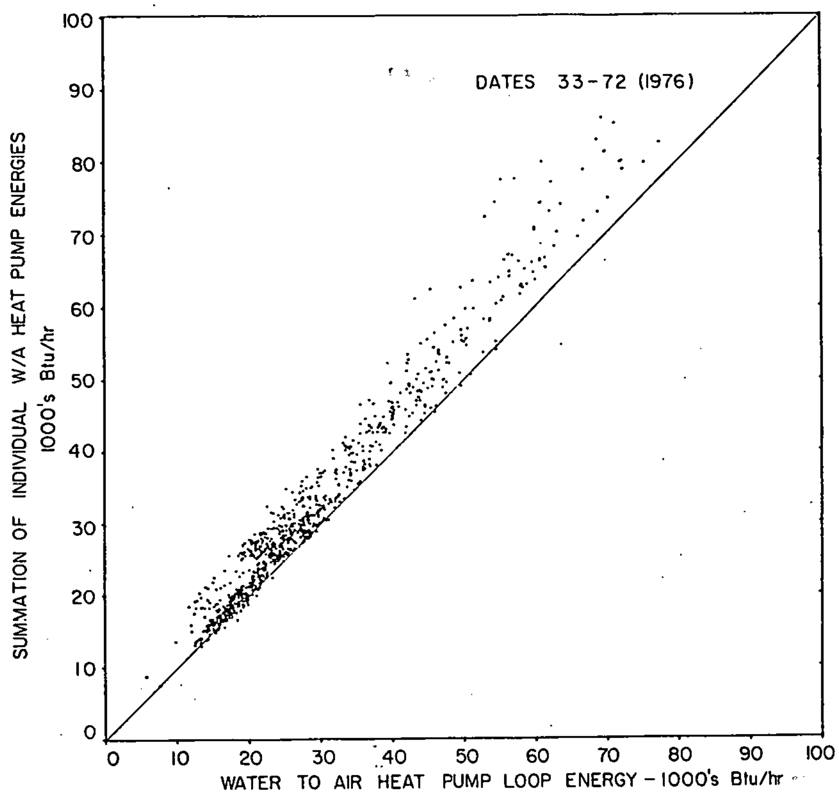

Figure 2. Energy Correlation for Water-to-Air Heat Pump Loop

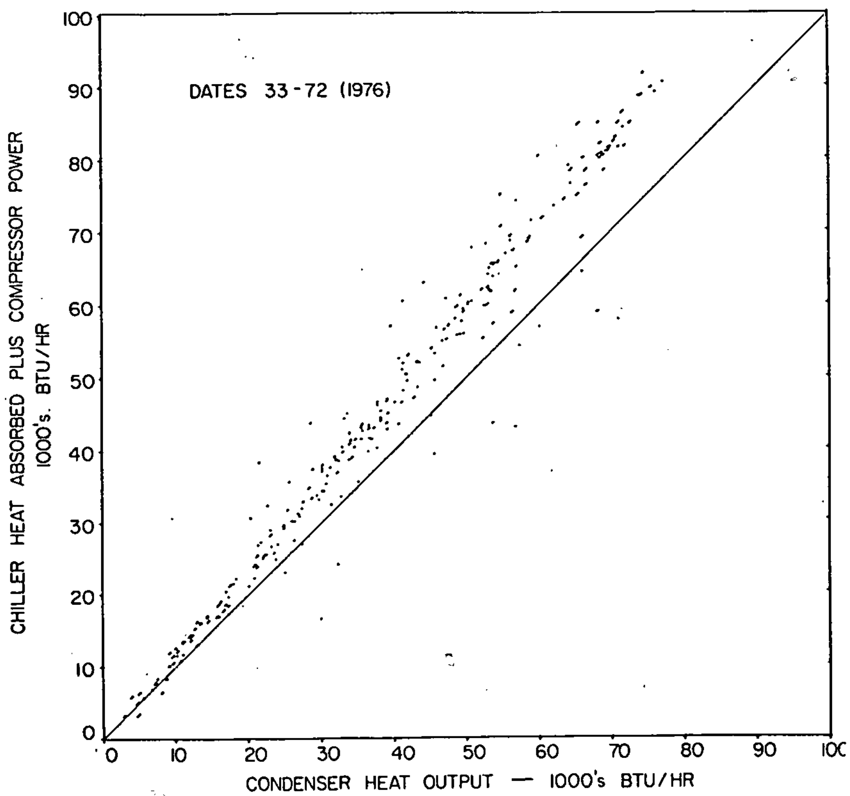

Figure 3. Energy Correlation for Water-to-Water Heat Pump Condenser

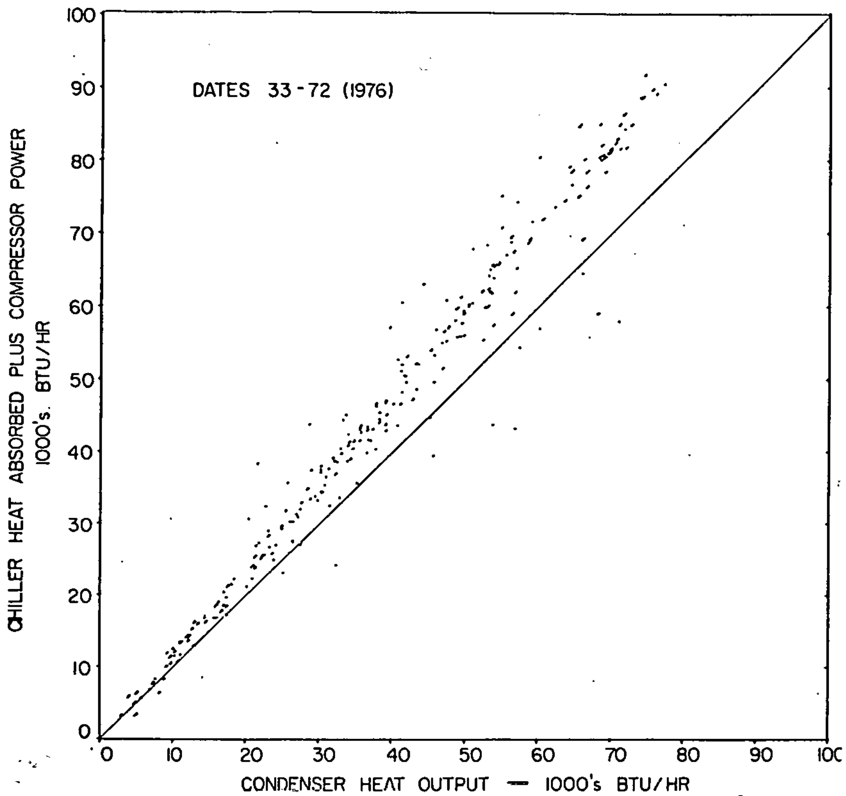

Figure 4. Energy Correlation for Water-to-Water Heat Pump Chiller

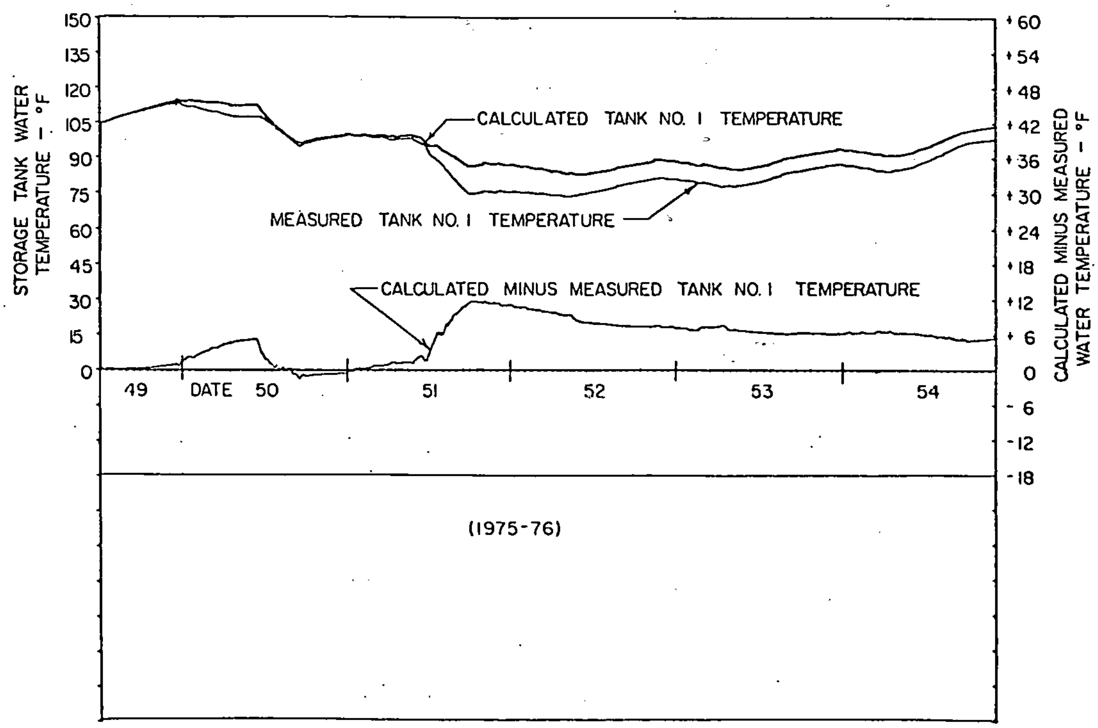

Figure 5. Calculated Versus Measured Temperatures for Tank 1

The Use of Computer-Controlled Data Acquisition Systems in Determining Solar Heating and Cooling System Performance

by

Thomas E. Richtmyer
Thermal Solar Program
Center for Building Technology
National Bureau of Standards
Washington, D.C. 20234

Abstract

For the past few years, NBS has been conducting a number of solar energy related projects. Two, in particular, are solar heated and cooled buildings that use computer controlled data acquisition systems. This paper describes those buildings, their data acquisition systems and discusses problems that have been experienced. Finally, a list of recommendations and suggestions are offered based on those experiences that should help prevent similar problems on future projects.

THE BUILDINGS

The Norris Cotton Federal Office Building (NCFOB)

The Norris Cotton Federal Office Building (NCFOB) is a medium-sized 7-story, government office building of approximately 11,000 m^2 total floor space. It is located in Manchester, New Hampshire and has been designed to demonstrate a number of energy saving concepts.

The building shell is nearly cubical in shape thus providing a low surface to volume ratio. Its walls are of heavy masonry construction with insulation on the outside rather than inside. This creates a thermal "flywheel" effect which reduces peak heating and cooling loads. Since windows tend to be net heat losers in northern climates, overall window area makes up only about 10% of the total exterior wall. Each window is double glazed and surrounded by granite fins that reflect sunlight in, provide shading in summer, and reduce convection losses due to wind.

The building's mechanical system consists of a number of interconnected subsystems. On the first three floors, various types of water-to-air heat pumps handle the heating and cooling. In a building of this size, excess heat which is generated in its relatively large core by lights, office machines and occupants is usually removed by ventilation or air conditioning and rejected to the outside air. Here, however, core heat pumps transfer this excess heat to water which is then returned to a large, 38 m^3, storage tank so that it can be used by perimeter units to heat outer office areas. Thus, the only heat that must be added to a given floor is the net difference between the core cooling and perimeter heating requirements. The core of the upper three floors and the entire fourth floor are cooled by a combination of outside air and chilled air from central chillers through the main ventilation ducts. The perimeter areas of floors 5, 6 and 7 are heated and cooled by fan coils and the fourth floor perimeter is heated by finned tube radiators.

In addition to purchased electricity, other energy comes from solar collectors, gas-fired modular boilers, oil-fired boilers and heat recovery from a special condenser on the main electric chiller. Also, a natural gas-powered engine/generator provides power for the electric chiller and simultaneously produces waste heat which is recovered and used to drive an absorption chiller. Using ordinary design procedures, the mechanical equipment would seem undersized to meet peak loads. However, by making use of hot and cold storage tanks and the thermal capacity of the masonry walls, the equipment, especially the chillers, have been sized more for average loads.

Other energy saving concepts incorporated into the building include various types of lighting systems and heat recovery from ventilation exhaust.

The building was occupied in September 1976, the data is being collected at the present time on the performance of the mechanical and electrical systems in the building.

The NBS Solar House

The NBS Solar House is a lightweight wood frame dwelling of 111 m^2 gross floor area that has been retrofitted with a solar heating, cooling and hot water system. Its major components are: 45 m^2 of roof mounted flat plate collectors. 5.7 m^3 total storage (1.9m^3 plus 3.8 m^3 water tanks that are interconnected), an absorption air conditioner, a liquid-to-air heat exchanger for space heating, a liquid heat exchanger for preheating domestic hot water and a 20KW electric boiler for auxiliary energy. Though simple by comparison to the government office building described above, it is somewhat complex in that a number of different piping schemes have been incorporated in a single system. Thus, by merely opening and closing valves, it is possible to examine several different system configurations and storage capacities.

The NBS Solar House was tested during 1975 and 1976 to determine the performance of the complete solar heating and cooling system. At the present time, it is being used as a test bed for special experiments on the thermal storage tanks.

THE DATA SYSTEMS

Norris Cotton Federal Office Building Data Systems

The heart of the present system in the NCFOB is a 64K minicomputer. It gathers information from approximately 1000 sensors throughout the building and includes such things as dry-bulb temperature, flow rate for both liquid and air, dewpoint temperature, weather data, and equipment status information. The sensors do not feed directly into the computer; instead, they are wired to remote terminals. These terminals accept various types of sensor output signals such as voltages, resistances and currents and, after proper conditioning, convert them to digital data. The computer, through a single I/O port, can interrogate a remote terminal to obtain each sensor value. From an instrumentation point of view, the remote terminal concept offers the following advantage: By placing the

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terminals near their respective sensors, the lengths of the interconnecting signal wires are reduced. This helps to eliminate much of the voltage loss and noise interference associated with long cables. Since the remote terminal transmits digital data, voltage loss and interference in the main return line are of little or no consequence. This is because the computer needs only to discern between high and low logic levels which it can usually do over a relatively wide range of variation.

A computer data scan of every point occurs several times a minute. For selected data point, the computer compares their valves with preset limits that are stored in memory. One purpose for these limits is to determine if any conditions exist which may require action. For example, if a temperature is too high or a piece of equipment which should be operating is not on, an alarm can be sounded and a warning message will be displayed at the operator's console.

Another use for these limits is to provide control capabilities. However, because the computer is intended primarily as a data collection device, its control functions are presently limited to making a few basic decisions concerning the use of solar and auxiliary energy and whether to operate in a heating or cooling mode. The computer has no direct control over the individual pieces of equipment; instead, it sends mode selection signals to a pneumatic controller which, in turn, effects the necessary changes.

Although data is read in at a rate of several times a minute, much of it was ignored until recently. Originally, a special subroutine that provided NBS with its required data would be called in only about once every 20 minutes. This subroutine retrieves data from the disc, computes a running average and, once an hour, records the data on magnetic tape. However, the 20 minute interval was judged to be too long in some cases where rapid variations occur. As a result, plans are currently underway to reduce some of the sampling times to as short as one minute.

The NBS Solar House

The NBS Solar House uses a slightly different approach in its data collection. Whereas the NCFOB uses remote terminals with separate amplifiers for each sensor, the NBS Solar House makes use of a single, high resolution, digital voltmeter. A set of mechanical relays switch different sensors (mostly thermocouples) onto the voltmeter. The advantages of using a single voltmeter are that it not only reduces cost, but it also minimizes certain calibration errors. In particular, errors that occur when attempting to measure the often small temperature differences between the inlet and outlet of solar collectors, heat exchangers and other system components. This difference rather than the absolute inlet and outlet temperatures, is of prime importance since energy transfer is mainly a function of temperature difference. There is only a secondary dependence on overall temperature in as much as it has a slight affect on specific heat.

To illustrate the difficulties in trying to measure the difference between two large quantities, consider the case where the inlet and outlet temperatures are measured using separate meters. Furthermore, assume that these meters exhibit a straight line deviation between indicated and actual temperature (T_{ind} and T_{act}, respectively) such that

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$$T_{ind} = A + (1 + K)\, T_{act} \qquad (1)$$

where A is the instrument zero offset and K accounts for an error which is proportional to the reading. When computing the temperature difference (ΔT) by subtracting the inlet (T_{in}) from the outlet (T_{out}),

$$T_{ind} = T_{out,ind} - T_{in,ind}$$

$$\text{or } \Delta T_{ind} = \Delta T_{act} + A_{out} - A_{in} + K_{out}\, T_{out,act} - K_{in}\, T_{in,act} \qquad (2)$$

Now, assume the following condition exists: $T_{in,act} = 99°C$, $T_{out,act} = 101°C$, $A_{in} = -0.1°C$, $A_{out} = +0.1°C$, $K_{in} = -.002$, $K_{out} = +.002$. In this case, the apparent temperature difference would be 2.6°C when it is really only 2.0°C which represents an error of 30% higher than the actual difference. However, with a common meter, $A_{out} = A_{in}$ and $K_{out} = K_{in}$ so that equation 2 becomes:

$$\Delta T_{ind} = \Delta T_{act}\, (1 + K)$$

Thus, assuming a value for K comparable to the case for two meters, the error would be a mere 0.2%. What is more, not only can the voltmeter be removed periodically for calibration, it can also be checked continually by making one of the scan points a known reference such as a D.C. transfer standard.

The voltmeter and scanner in the NBS Solar House are both controlled by a small 16K computer. Within the limits of the instrumentation, the computer can be programmed to select the scan rate, sequence, and number of points in a scan. However, for this particular application it has been found to be sufficient to set the scan interval at a constant two minutes. The number of points scanned have been varied somewhat between 150 and 200 points but in reality the maximum number of points ever used during data analyses is something less than 100.

After each scan, the computer has in its memory, voltmeter readings that represent the following: thermocouple EMF's, solar radiation, modulating valve settings, weather data, switch status, relative humidity, and supply voltages. In addition, digital information from pulse counters used for fluid flow measurement is also input. This information is recorded directly on magnetic tape along with system status information. Note that the data is recorded in its most basic form, unaveraged without conversion to engineering units. So doing, it is felt, affords the greatest possibility of correcting data that may later be found to be subject to a significant but correctable error due to an instrumentation problem.

The control capabilities of the NBS Solar House data system are much more extensive than those of the Norris Cotton Federal Office Building. Virtually every piece of mechanical equipment is under direct control of the computer. This has proved to be an ideal situation: control problems could be easily rectified through "soft" changes, different control strategies could be implemented quickly, and since the computer makes all control changes, it can record the exact time that each piece of equipment starts, stops or changes status. Thus, on-off sampling errors are eliminated.

PROBLEMS AND EXPERIENCES

The problems associated with both projects can be grouped into two categories: computer and non-computer. Computer problems have generally involved software and the computer itself while non-computer problems include such things as sensors, transducers and electronic circuits. In most cases, the non-computer problems are things that would affect all data systems, no just those that use a computer controller.

Computer

Of the computer oriented problems, the most annoying have been computer halts. These have been caused by such things as power loss, core memory failure, CPU failure, excessive dust, dry air, low temperature, and miscellaneous random failures. These problems can be minimized by providing proper environment and preventive maintenance; but, occasional failures are inevitable. Therefore, in cases where equipment could be damaged by loss of control, the designer should install emergency overrides and alarms which are independent of the computer. As examples, the NBS Solar House utilizes a timer that must be reset every three minutes by the computer; if a halt should occur, the entire mechanical system will shut down and an alarm will be tripped automatically. At the NCFOB, each piece of equipment has its own safety interlock that protects it from damage. (In addition, the pneumatic controller can handle the equipment independently of the computer, but, this is an atypical situation. Ordinarily, two control systems would not be used.)

Another important aspect is to make certain that the data being collected is sufficient and is being properly stored. One experience at the NBS Solar House will serve to demonstrate this potential problem. It involved one of the earlier sets of tests conducted. After each scan, an entire data array was stored by what appeared to be a perfectly valid command that would write several hundred characters on magnetic tape. Unfortunately, the standard I/O software could handle no more than 120 characters at a time; any remaining characters were simply ignored. At the conclusion of the test, it was discovered that only a small and insufficient amount of data had been recorded. Fortunately, though, there were enough back-up instruments such as chart recorders, thermocouple indicators and integrators which provided enough hard copy data to permit analysis by hand. Thus, it is important to make sure the data tapes can be read before starting an experiment and, if feasible, use back-up equipment. Admittedly, extra equipment may seem rather costly; but, on a project of this nature where an intensive study revolves around a single facility, the additional instruments can become essential insurance against the possibility that several weeks of data will be lost.

At the NCFOB, the data that are recorded are, at present, unacceptable to meet energy analysis needs. The scan interval is too long, the resolution is too low and there are a few locations where needed sensors do not exist. Much of the reason for this, it is felt, is that the system is actually intended primarily for control rather than data collection. These problems, however, are expected to be worked out as the system is still in the process of shake-down and debugging.

There are, of course, a number of obvious advantages to using a computer: they are fast, highly flexible and can provide real time data analysis. However, another particularly powerful advantage of a computer is that it can perform real time, continual checking of data in order to locate possible hardware problems. Some ways in which data can be checked are as follows:

1. Limit checks - Under steady conditions, most sensors will usually operate within a specific range. For example, at the NBS Solar House, collectors operate between 15°C and 100°C, space heater (liquid side) between 25°C and 70°C, domestic water heater between 15°C and 60°C and absorption air conditioner between 88°C and 95°C. Temperatures that appear out of these bounds could be the result of faulty instrumentation or equipment malfunction.

2. Rate of change - Except for transients (which a computer can be programmed to ignore), most thermal devices exhibit an inertia effect. For many quantities, a maximum expected rate of change can usually be established fairly easily. Faster change rates could be the result of dirty relay contacts, loose connections or electronic failures. A computer can easily calculate time derivatives and flag those that seem excessive.

3. Balance checks - With most solar energy equipment, real time calculations can be applied to insure that there are no violations of physical laws, especially simple energy balances. For example, the heat output from a heat exchanger should very nearly equal but never exceed the input. However, to avoid complications, balance checks should only be performed on equipment operating under steady conditions.

By automatically performing the above checks and reporting problems as soon as they occur, sensor malfunctions that otherwise might go undetected until the end of a test can be quickly corrected.

<u>Non-Computer</u>

Voltmeter Scanner

The voltmeter/scanner arrangement at the NBS Solar House has worked well for the most part. The most common problems have been broken thermocouples, loose or dirty connections, and voltmeter malfunctions. Depending on the nature of the problem, one or more of the following could result: (1) the inoperative sensor, if used in the control logic, would cause improper system operation (particularly troublesome with intermittent sensor), (2) the recorded value would be meaningless and of no use or, (3) in the case of voltmeter failure, the computer could become hung up resulting in a complete system shut down. However, these problems can be greatly minimized by making use of the computer's ability to make real time error checks as previously described.

Temperature Measurements

The rationale for justifying the use of two thermocouples and a single voltmeter for measuring temperature differences at the NBS Solar House has already been discussed. The analysis, however, assumes that the sensors themselves are perfectly matched. Initially, it was thought that this was the case: all of the critical probes had been carefully calibrated and divided into matched pairs. But, inconsistencies that appeared during data reduction caused a reexamination of the thermocouples. The approach was simply to remove each pair and place them together in a temperature bath. By subjecting both sensors to an identical temperature, it was not essential that the bath temperature be measured precisely; but only to verify that for any temperature, there was no difference in readings between the two sensors. It was found, however, that this was not the case; as the bath temperature was raised from ambient, differences appeared that increased with temperature. These differences could be applied retroactively to the data. The fact that the discrepancies were found proportional to bath/ambient temperature differences was the result of an additional thermocouple effect created at the junction between the probe and its extension wire (even though the extension wire and probe are of the same materials, there may be slight differences in their alloys).

In the case of the NCFOB, the concerns for accurate temperature measurements were even greater. Not only are temperature differences computed from absolute measurements, but in addition, each sensor has its own amplifier. Once again the constant temperature bath technique was applied to determine correction factors for the data. This task, however, proved to be of monumental difficulty. Many of the sensors are located above suspended ceilings over occupied offices and in other equally inaccessible areas. On future projects, provision for easy field calibration will certainly be included to the maximum extent possible. Also, since computed temperature differences are potentially much less accurate, consideration will be given to direct differential measurements, specifically the use of thermopiles.

Flow Measurements

At the NBS Solar House, fluid flow measurements are accomplished through the use of positive displacement meters that drive mechanical registers (very similar to a household water meter). In addition, however, the meters are also geared to pulse generators. As fluid passes through the meter, pulses are produced which coincide precisely with the mechanical register (at a rate of 1000 pulses/U.S. gallon). These pulses are counted by electronic totalizer and are fed directly into the computer during each data scan. Positive displacement meters usually have good accuracy over a wide range of flow rates and they are generally insensitive to velocity profiles, flow disturbances, and changes in fluid temperature. Furthermore, there are no errors associated with any intermediate transducer. Barring stray or missed pulses, the computer's reading will agree exactly with the register. Thus, total system error is ideally dependent only on the reliability of the sampling chamber.

However, some difficulties with the pulse counters were experienced. For one thing, their input sensitivities were too high. This caused them to pick up a low level 60 Hz hum which would sometimes be present during no flow conditions. Also, their outputs were too low to meet the input requirements of the computer. As a result, they would not always read in. Fortunately, both of these problems were avoidable through software changes: stray counts were ignored when devices were known to be off and missed readings were repeated until successfully input. Nevertheless, this experience points out the need to insure that there is compatibility among the various components of the data system.

As for the overall calibration of the positive displacement meters, checking is relatively easy. In most cases, two or more meters can be valved in series to provide a quick internal check.

Furthermore, each meter is installed with a by-pass so that it can be removed quickly and easily for repair and calibration without shutting down the system.

The measurement of fluid flow rates at the NCFOB is done entirely differently. The positive displacement meters which worked well in the NBS Solar House have two significant draw-backs: they create high pressure drops and require much maintenance. With only six meters, such disadvantages represent no real liability. However, the NCFOB requires nearly 70 meters. With pumping cost already high and with proportionately less maintenance personnel, a simpler metering system was chosen, namely static-pitot tubes. These tubes have no moving parts, require little space, and are easy to install. However, installation does require some care. The manufacturer assumes that the meters will be subjected to a well-defined velocity profile such as would be found in a long straight length of pipe. Therefore, specific installation recommendations are set forth that should eliminate or reduce errors due to a local disturbance in the fluid stream such as may be caused by elbows, tees, valves, etc.

Unfortunately, the realities of the HVAC plumbing in this building required that most of the pitot tubes be installed in close proximity to an upstream disturbance, usually a thermometer well, without proper flow straightening devices. After the discovery of this problem, much discussion followed aimed at finding a solution. One thought was to remove and reinstall the pitot tubes in precise accordance with the manufacturer's recommendations. However, besides the fact that such a job would be costly and might require closing the already occupied building, another serious problem existed. This particular installation involves several intermediate transducer conversions, namely from velocity, to a pressure difference, to a mechanical displacement, to a resistance, and finally to a voltage that drives an A to D (analog to digital) converter. Once digitized, the quantity becomes unchanged (other than software conversions to engineering units); however, the long chain of transformations ahead of the A to D converter created much concern that, even with properly installed pitot tubes, flow rate measurements might still be subject to significant calibration errors.

A final solution was to install by-pass fittings on 7 main feeder trunks throughout the building. Thus, assuming that the indicated flow will be a repeatable function of actual flow, it will now be possible to obtain calibration factors for each meter by installing a carefully calibrated flowmeter at the by-pass and valving off all but one pitot tube at a time and observing the two meters simultaneously. This procedure will permit checking the entire transducer chain.

RECOMMENDATIONS

Based on the NBS experience in the two solar heating and cooling projects described which have used mini-computer data acquisition systems, the following recommendations are made:

1) If a computer data system is used simultaneously for building HVAC control, design the system to be as flexible as possible. A control program that cannot be changed or can be changed only at great time and expense does not take full advantage of the computer. If control is essential and it appears that the data gathering functions may interfere, it may be worth considering a separate data-only system.

However, in such a case, the data system should have access to all the information used by the controller including equipment status and set points.

2) Collect all data in its most basic form. If data are manipulated before being recorded, it may be impossible to reconstruct an event. For example, if one of the values used in an hourly average was erroneous because of an electrical short, the entire averaged value might be affected. Without knowing each term in the average, it would be impossible to make a correction. However, if each point is recorded (tape and money permitting), a faulty value can then be identified and deleted with little overall effect.

3) Check data as it is collected by
   a. limit checks to make sure values are in their expected range
   b. rate of change checks; sudden changes could indicate sensor problems
   c. energy balances; provides a double check

4) Provide an adequate means of calibrating sensors:

a. For temperatures, make the sensor easily removable by using a thermometer well or locating sensors between valves. Furthermore, paired sensors such as inlet and outlet probes should be able to be calibrated simultaneously. Also, if possible, when removing a probe which is to be calibrated in place, an attempt should be made not to disconnect signal wires. Changes in resistance and galvanic reactions from perspiration can sometimes have a significant effect.

b. For liquid flow meters, install by-passes around positive-displacement meters so that they can be removed for calibration and repair. For other types of meters where the by-pass would create a disturbance, consider installing a calibration by-pass loop elsewhere in the system.

c. If possible, locate sensors where they can be easily reached.

d. Prior to installation, make sure that the recommended installation practices are followed. This may require either close supervision and/or advice to individuals doing the work or a lengthy and detailed description in contract specifications.

e. Perform regular calibrations. The frequency of calibration, of course, depends on the importance and stability of the equipment. In the case of the NBS Solar House, the central digital voltmeter has been removed for calibration at least annually and is spot-checked continually by scanning a reference voltage along with the other data.

5) Protect equipment from damage due to loss of control. Equipment which could be damaged if a computer should hang up or otherwise lose control should use safety interlocks that are independent of the computer.

6) Maintain proper environmental condition around the instrumentation. Heating and air conditioning of computer rooms are obvious requirements; however, humidity control is also important. If humidifiers are used, make sure they will not contaminate the air with substances found in the supply water. Also, remote equipment in unconditioned spaces such as basements or attics may be subject to temperature effects.

7) Make sure data tapes can be read before beginning an experiment. It may also be useful to provide a means of reading tapes during a test. This will permit repositioning of a tape which has, for some reason, been taken off line or rewound.

8) Use back-up equipment, if available, to get secondary readings of critical values. Often a simple thermocouple indicator and thermocouple switch will suffice. This not only can provide additional measurements for double checking but can also be used to collect primary data when the computer is down for short periods.

9) When building a system with individual components, make sure that the equipment is compatible. Not unlike a stereo system, impedances, voltage outputs, etc. of the sending device should meet the requirements of its respective receiver.

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System Performance Measurements for a Packaged Solar Space Heating System Equipped With Air-Heating Collectors

by

Dennis E. Jones
Thermal Solar Program
Center for Building Technology
National Bureau of Standards
Washington, D.C. 20234

Abstract

This paper describes the approach and instrumentation used at the National Bureau of Standards for determining system performance of a packaged solar space heating system equipped with air heating collectors. A method of measuring air flow rate accurately without disturbing system performance through use of the collector as a flow measuring element is the major unique feature of the experimental approach.

1. INTRODUCTION AND BACKGROUND

Beginning in 1974, the National Bureau of Standards (NBS), with support from both the National Science Foundation (NSF) and later the Energy Research and Development Administration (ERDA), began a program of developing thermal test procedures for solar heating and cooling equipment. The primary results to date have been ASHRAE Standards 93-77 and 94-77 for solar collectors and thermal storage devices, respectively [1,2]. NBS is now involved in examining the feasibility of developing a thermal test procedure for a complete solar space heating system. In order to conduct the study, a packaged system has been installed on a conventional single-width mobile home and data is being gathered on the performance of the system.

2. DESCRIPTION OF THE SOLAR HEATING SYSTEM

The system being tested uses air as the heat transfer fluid and rocks for thermal storage. Collector, rock bed, fans, ducts, dampers, and control system are all contained within a single unit which is connected to the existing forced-air conventional heating system of the mobile home by supply and return ducts. Auxiliary energy is supplied by the electric furnace in the mobile home.

A schematic of the system is shown in Figure 1. It has basically four modes of operation, one for charging the rock bed and three for supplying heat to the house. When the temperature sensor mounted on the collector absorber surface indicates a temperature 5.6° C (10° F) greater than the average temperature in the storage bin, the collector fan turns on and circulates air from the storage bin through the collector and back to the rocks. This continues until the temperature difference drops below 2.8° C (5° F).

When the house thermostat calls for heat, the distribution blower in the solar unit is turned on to deliver hot air from the storage bin to the house. If after 15 minutes, the house thermostat is not satisfied, the auxiliary electric heater in the house is turned on. If the temperature of the air coming from the storage bin drops below 23.9° C (75° F), the distribution fan in the solar unit is turned off altogether and all the space heating in the house is supplied by the auxiliary energy source. The unit has also been designed so that if solar collection occurs simultaneously with house heating, "short circuiting" will occur in the rock bed so that hot air can be delivered directly from the collector to the house.

The solar collector used is shown schematically in Figure 2. It is basically a double-glazed air heater in which the air passes over the absorber and under the inner glazing. The absorber is a finned metal plate coated with a black paint. A horizontal aluminum reflector is located in front of the unit so as to reflect additional solar radiation onto the collector.

The solar collector has a nominal area of 8.9 m^2 (92 ft^2) and an aperture area of 8.2 m^2 (88 ft^2). The reflector has an area of 8.9 m^2 (96 ft^2). The rock bed contains approximately 11,300 kg (12.5 tons) of crushed stone with a nominal diameter of 5 cm (2 in). The duct work used to connect the solar unit to the mobile home consists of two runs of approximately 3.1 m (10 ft) each of urethane foam-insulated square ducting. The ducting dimensions are 33 x 33 cm o.d. (13 x 13 in.) and 20 x 20 cm i.d. (8 x 8 in).

Performance monitoring of a solar heating system involves determining the energy flows in the system and in particular the fraction of the load supplied by solar. An energy flow diagram is presented in Figure 3. Instrumentation and testing of the system has involved determining the energy flows across the control volume shown in addition to some internal energy flows.

Instrumentation and testing of the solar system was divided into two phases. In Phase 1, the bare minimum of instrumentation necessary to measure solar fraction was installed so that data collection could be started immediately. Phase 1 data collection began March 1977 and will be continued through May 1978. In Phase 2, the system was completely instrumented to measure all important parameters so that system performance could be examined in detail. Phase 2 data collection began December 1977 and will continue through March 1978.

3. PHASE 1 INSTRUMENTATION AND TESTING

The heating load required by the mobile home was determined in previous tests in a large NBS environmental chamber [3]. The thermal characteristics of the mobile home were determined over a complete range of outdoor conditions and equations were developed relating heating load to indoor-outdoor temperature difference. The heating requirements of the home were found to be approximately 5000 Btu/Degree Day. Air leakage measurements were also performed [4].

The original furnace in the mobile home was a gas-fired, forced-air, sealed-combustion unit. The plenum was modified during the environmental chamber tests to contain electric resistance heaters in order to simplify energy measurements. These resistance heaters have been used as the auxiliary heaters during this solar test program and watt-hour meters provide accurate and reliable measurements of auxiliary energy used.

The three fans in the solar system have each been connected to a watt-hour meter to obtain fan operating energy requirements.

Total electric energy to the house and solar system is measured by another watt-hour meter which allows determination of internal heat generated from lights, relays, and test equipment.

Through use of watt-hour meters and monitoring of indoor and outdoor air temperature (and use of the previously-determined correlation relating heating load to indoor-outdoor temperature difference), it is possible to determine solar fraction reliably without the use of an electronic data-logging system. Insolation on the collector plane was also monitored in Phase 1.

4. PHASE 2 INSTRUMENTATION AND TESTING

Phase 2 instrumentation and testing is designed to provide detailed information about the solar system over a long term period. Table 1 is a summary of the instrumentation and sensor locations may be seen in Figure 1.

Prior to beginning long term testing, the collector thermal operating characteristics were determined by isolating the collector from the rest of the system and performing collector efficiency tests similar to those described in ASHRAE Standard 93-77.

The reflector in front of the collector complicates the determination of collector performance characteristics since it produces a non-uniform radiation field on the collector surface which is very difficult to measure. To eliminate this complication, the reflector was covered with a flat black material during the collector tests.

The collector test loop was configured similar to that shown in the schematic diagram of Figure 4. Type-T thermocouples were used to measure absolute temperatures at the inlet and exit. A six-junction type-T thermopile was used for measuring differential temperature across the collector. The static pressure drop across the collector is measured using a slant-gage manometer. The fan is located such that it "pulls" air through the collector array, creating a slight negative gage pressure on the collector. Electric resistance heaters were used to heat ambient air to the desired collector inlet temperature. The primary flow measuring device was downstream of the collector array and consists of a receiving chamber, discharge chamber, and a 3 inch A.S.M.E. nozzle. A commercial diaphram type pressure transducer continuously monitored pressure difference across the nozzle and a slant gage manometer was used to measure gage pressure at the nozzle throat.

The resulting collector performance curve is shown in Figure 5. The slope of the curve is steeper than theoretical calculations would predict and the difference is probably due to air leakage from the ambient air to the flow stream in the collector.

One of the major problems in solar system testing is measuring air flow accurately without disturbing system performance. Accurate airflow measurement with state-of-the-art methods requires either flow elements which result in high pressure losses or equipment which requires frequent calibration and careful installation. Neither of these methods is satisfactory for long-term system testing. An alternative, used in this study, is to calibrate the collector as a flow measuring element. The collector on the system being studied at NBS has a pressure drop of approximately 0.75 inches of water which allows use of reliable, inexpensive electronic pressure-difference measuring devices. The higher pressure drops also neutralize the effects of local variations in atmospheric pressure.

Following the collector tests, the collector was "calibrated" using the A.S.M.E. nozzle as the "standard" in series with the collector. A plot of air-flow versus the square root of the pressure drop across the collector divided by air density resulted in a straight line with little scatter as shown in Figure 6. The resulting equation for flow is therefore:

$$Q = 120.5 \sqrt{p_c/d}$$

where Q is flow rate in cfm

p_c is the static pressure drop across the collector in inches of water

d is the air density in the collector, pounds per cubic foot, computed from the average of the inlet and exit temperatures and the barametric pressure

Thus it is possible to continuously measure collector flow rate by monitoring of pressure drop and collector inlet and outlet temperatures.

Air flow rate in the supply duct is measured using a commercial laminar flow element which consists of a honeycomb air straightener upstream of an averaging pitot tube arrangement. This flow element was calibrated using a A.S.M.E. nozzle and was found to give good results once a correction factor was established. The correction factor, similar to the discharge coefficient in a nozzle, is a constant multiplier which corrects indicated flow rate to actual flow rate. The correction factor for this particular element was 0.93. The low pressure differentials in the flow element (0.045 to 0.055 inches H_2O) necessitated the use of a hook gage manometer for accurate pressure measurements.

After monitoring flow measuring pressures for a period of time with the system in normal operation, equations and curves were developed relating air flow rates in both the supply ducts and the collector to the respective air densities; the blowers having constant speed motors. Thus it is now possible to measure air flows knowing only duct air temperatures and the barametric pressure.

The incident solar radiation on a 60 degree tilted surface is measured by two precision pyranometers which are located away from the solar unit so as to avoid measuring reflected radiation from the reflector.

Data collection is accomplished by a standard commercial data loggor in conjunction with a reel to reel magnetic tape drive. The scan rate interval was set at two minutes, the short auxiliary heating cycle being the controlling variable. Data reduction is done on a large scale digital computer at NBS. The data logger has a capacity of 80 channels and will handle millivolt signals (0 to 400 mv) and type-T thermocouple inputs with an internal reference junction.

Temperatures are measured using laboratory-fabricated type-T thermocouples. In addition to the thermocouples listed in Table 1 there are an additional 40 thermocouples located in the rock bed.

Temperature differences across the collector and across the supply duct are measured using laboratory-fabricated six junction type-T thermopiles. A problem frequently encountered in measuring temperature differences across air-heating collectors is a poorly mixed air stream. To avoid these problems, several steps were taken:

1) A thermopile was used. A thermopile with junctions distributed over the air flow cross-section will tend to average out any uneven temperature distributions.

2) The thermopile was located far enough downstream beyond a right angle turn to insure proper mixing. Calculations showed that flow conditions were in the turbulent range.

3) Individual thermocouples were arranged across the cross-section in order to detect any uneven temperature distribution.

5. SUMMARY AND CONCLUSIONS

The test results and data collected on this solar heating system will be used as a data base for the development of a thermal performance test procedure for complete solar space heating systems. Preliminary studies indicate that a meaningful system test procedure is possible and work is continuing at NBS on this project.

The use of the collector as a flow element provides accurate and reliable flow measurement without disturbing the performance of the system.

Watt-hour meters in conjunction with an electric auxiliary heating system and an ambient temperature recorder will provide accurate and reliable information on a solar system independent of complex sensors and data logging systems. Of course the heating load thermal characteristics must be known either from environmental chamber testing or through monitoring of the auxiliary heat and the inside-outside temperature difference with the solar input isolated from the load. Many gaps in the data due to electronic data system down time have been filled in using information provided by these simple instruments.

6. REFERENCES

1. "Methods of Testing to Determine the Thermal Performance of Solar Collectors," ASHRAE Standard 93-77, ASHRAE, 345 East 47th Street, New York, New York 10017, 1977.

2. "Method of Testing Thermal Storage Devices Based on Thermal Performance," ASHRAE Standard 94-77, ASHRAE, 345 East 47th Street, New York, New York 10017, 1977.

3. Teitsma, G. J., and B. A. Peavy, "The Thermal Performance of a Two-Bedroom Mobile Home," NBSIR 76-1182, January, 1977.

4. Hunt, C. M., Treado, S. J., and B. A. Peavy, "Air Leakage Measurements in a Mobile Home," NBSIR 76-1063, August, 1976.

TABLE 1. SUMMARY OF INSTRUMENTATION FOR SOLAR AND HEATED MOBILE HOME

Measurement	Symbol	Instrument	Frequency of Measurement
Barometric pressure	P_B	barometer	daily
W-HR meter reading for collector fan	Ec	watt-hour meter	daily
W-HR meter reading for rock bed fan	E_D	watt-hour meter	daily
W-HR meter reading for trailer fan	E_H	watt-hour meter	daily
W-HR meter reading for trailer excluding auxiliary heat	E_T	watt-hour meter	daily
W-HR meter reading for adjustable electric heat	E_{XA}	watt-hour meter	daily
W-HR meter reading for fixed electric heat	E_{XF}	watt-hour meter	daily
Collector fan on/off (HRS)		relay	2 minutes
Delivery fans on/off (HRS)		relay	2 minutes
Auxiliary heat on/off (HRS)		relay	2 minutes
Average insolation of tilt W/O reflector (W/M2)	I_T	pyranometer	2 minutes
Average collector temperature gain (DEG-C)	t_c	thermopile	2 minutes
Average duct temperature difference (DEG-C)	t_D	thermopile	2 minutes
Collector fluid inlet temperature	$\Delta t_{f,i}$	thermocouple	2 minutes
Collector fluid exit temperature	$\Delta t_{f,e}$	thermocouple	2 minutes
Duct fluid temperature - hot side at trailer		thermocouple	2 minutes
Duct fluid temperature - cold side at trailer		thermocouple	2 minutes
Living room air temperature	t_r	thermocouple	2 minutes
Instrument room air temperature		thermocouple	2 minutes
Horizontal insolation (W/M2)	I_H	pyranometer	2 minutes
Rock bed centerline temperatures	t_s	thermocouple	2 minutes
Duct fluid temperature - cold side at solar furnace		thermocouple	2 minutes
Duct fluid temperature - hot side at solar furnace		thermocouple	2 minutes
Effective sky temperature	t_{sky}	purgeometer	2 minutes
Wind velocity (M/S)	Vw	anemometer	2 minutes
Wind direction		resistance pot	2 minutes
Ambient temperature	t_a	thermocouple	2 minutes
Relative humidity in trailer	rh	transducer	2 minutes
Beam insolation (W/M2)	I_B	NIP pyranometer	2 minutes
Second insolation on tilt reading (W/M2)	I_{T2}	pyranometer	2 minutes
Pressure difference across collector	ΔP_c	transducer	2 minutes

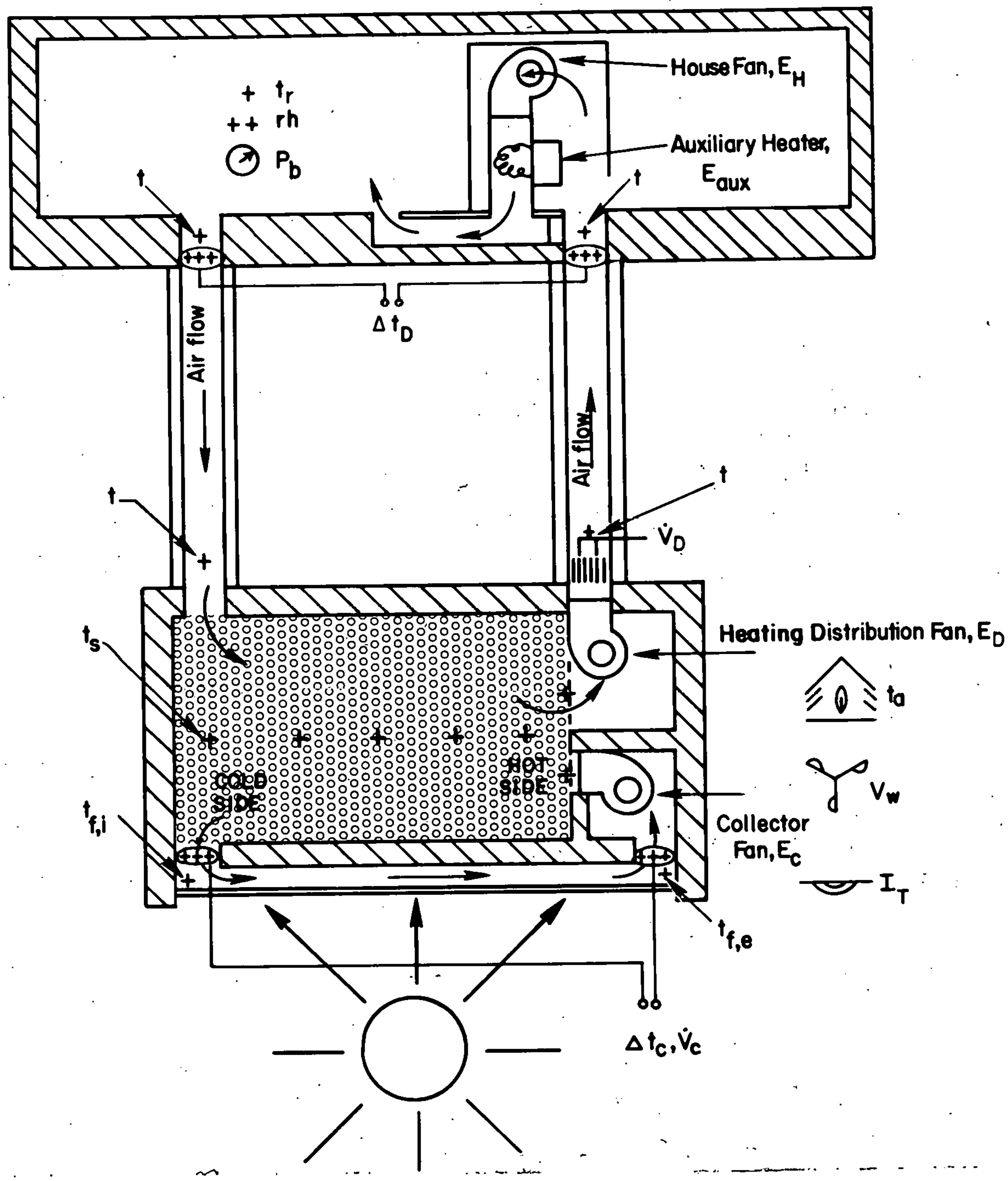

Figure 1. Schematic Representation of Solar Space Heating System and Instrumentation

SOLAR COLLECTOR OF SOLAR FURNACE

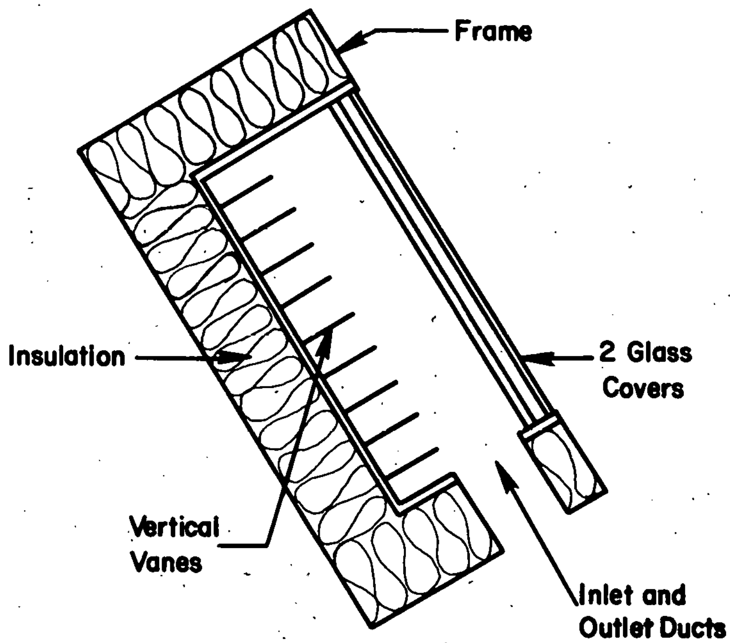

Figure 2. Schematic Cross Section of the Solar Collector

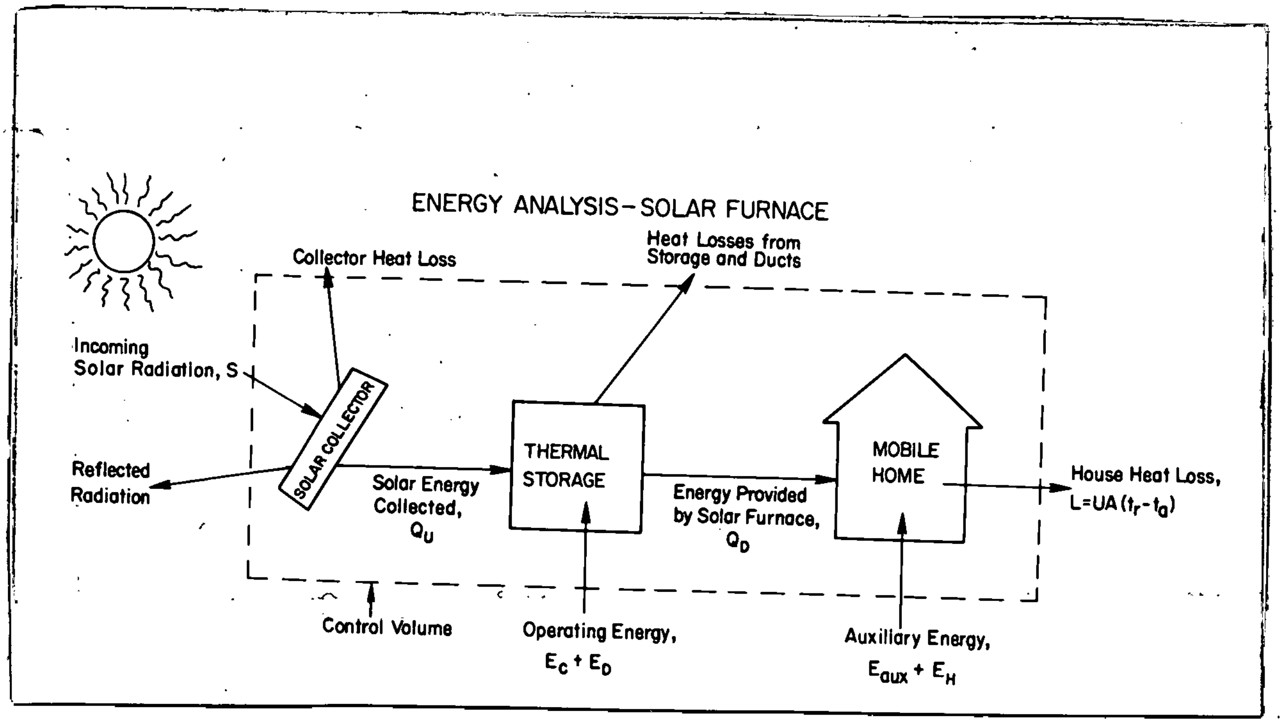

Figure 3. Schematic Representation of the Energy Balance Occurring on the Mobile Home Equipped with the "Solar Furnace"

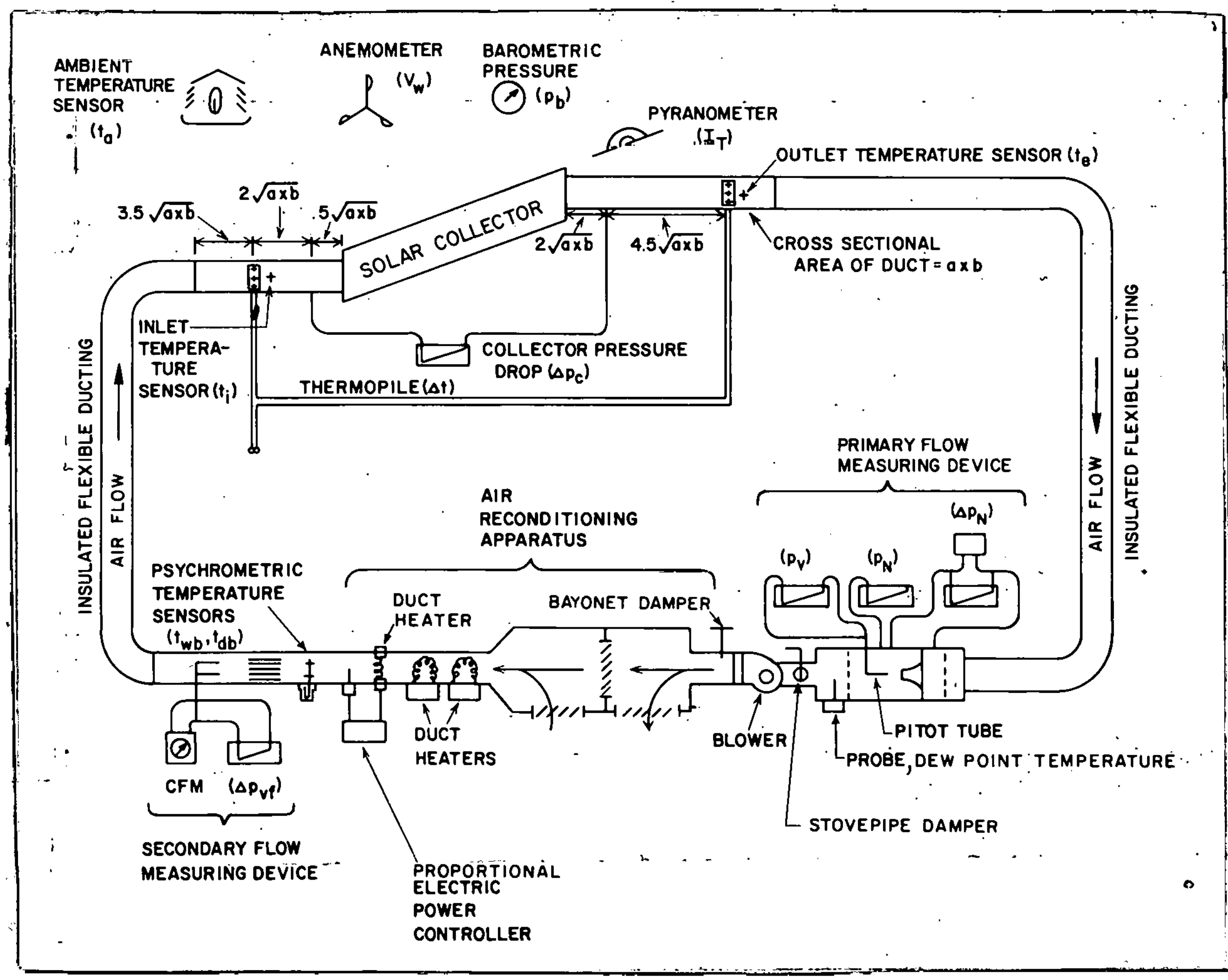

Figure 4. Schematic Diagram of NBS Test Facility for Solar Air Heaters

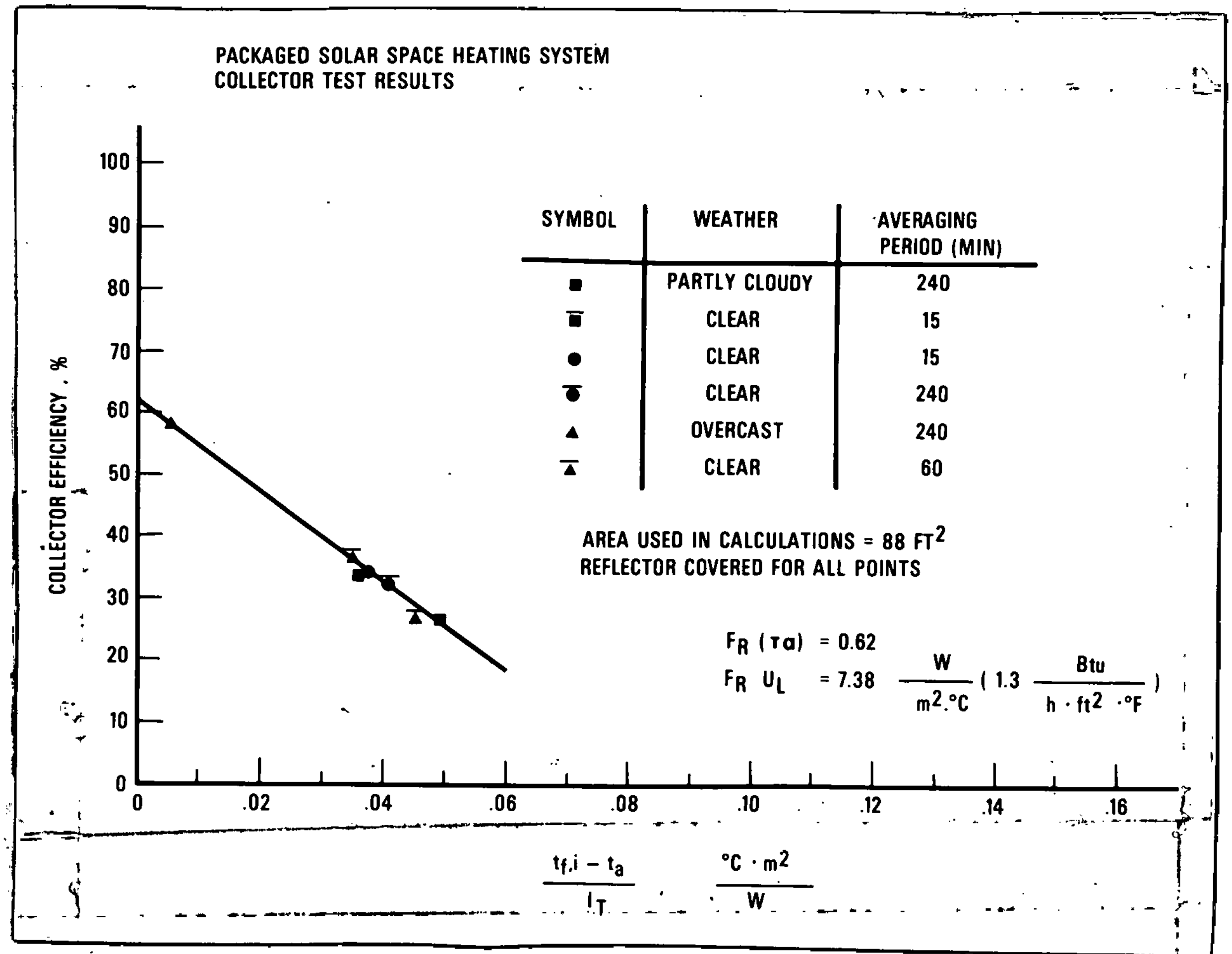

Figure 5. Packaged Solar-Space Heating System Collector Test Results

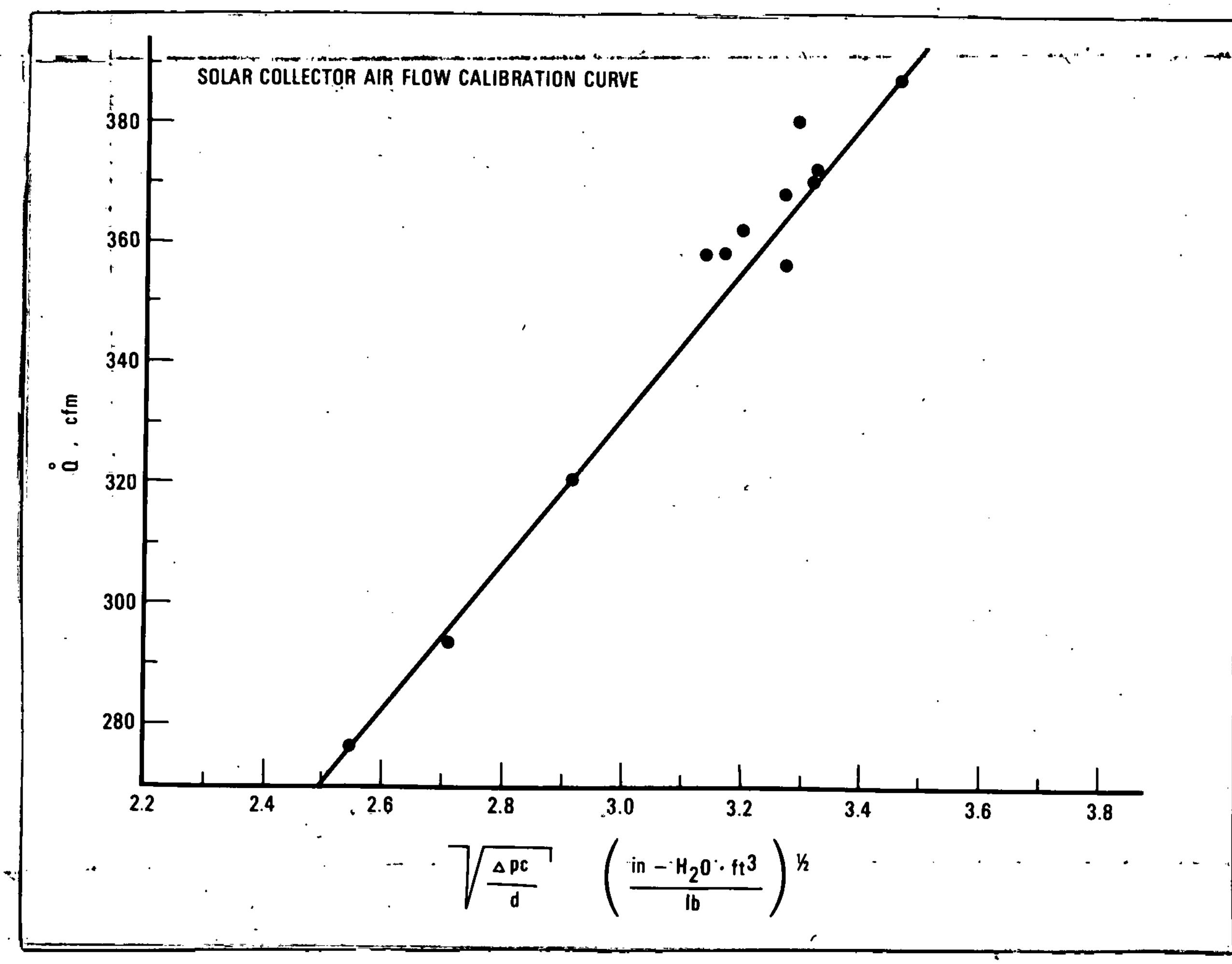

Figure 6. Solar Collector Air Flow Calibration Curve

INSTRUMENTATION, DATA ACQUISITION AND MONITORING SYSTEM FOR AN AIR HEATING SOLAR SYSTEM

by

S. Karaki and P. R. Armstrong
Solar Energy Applications Laboratory
Colorado State University
Fort Collins, Colorado 80523

ABSTRACT

The instruments and components of a data acquisition system used to monitor the performance of Solar House II at Colorado State University are described in this paper. While the calculation of heat flow quantities are elementary, difficulties in obtaining reliable values of air flow velocities and temperatures in a variable state system makes the performance analysis complex. Every system state introduces a different set of variables and when air leakage occurs at different rates with different states, the problems of heat flow calculations and heat balances are compounded. The problem of system monitoring is further made difficult by intermittent malfunction of instruments, the data logger, the processor and power failures. The experiences at Solar House II should be of assistance to other experimenters of solar air-heating systems.

INTRODUCTION

CSU Solar House II, located in Fort Collins, Colorado, is a residential type building with 130 m^2 floor space that is provided with an air-heating and nocturnal cooling system. There are 67.1 m^2 of flat-plate air-heating collectors mounted on the south-facing roof, tilted at an angle of 45 degrees. The pebble-bed storage has a volume of 10.2 m^3 and is filled with 2- to 4-cm diameter gravel. There is a solar hot water preheating subsystem, and also an evaporative cooler to chill the pebble bed during the night for daytime cooling of room air.

Fort Collins is located 40.6°N on longitude 105.1°W and is near the eastern foothills of the Rocky Mountains at an elevation of 1585 m above sea level. The climate of the region is semi-arid with continental winters and meager summer rainfall. Average precipitation in the region is 36 cm. High temperatures are generally below 40°C and low temperatures are above -30°C with average daily temperatures in July of 24°C and in January, -1°C. The normal total annual heating degree-days is 3500°C-days.

A schematic diagram of the solar system is shown in Figure 1. Heat is collected, stored and distributed to the building by a single blower with a constant speed motor, but because the pressure drops are different through different air-flow circuits, the air flow rates vary in different sectors of the system and in different modes of operation. There are nine motorized dampers in the system and because there are leakages through closed dampers, the leakages contribute to different flow rates in different sections of the duct system. More details of the system are given in a separate report [1].

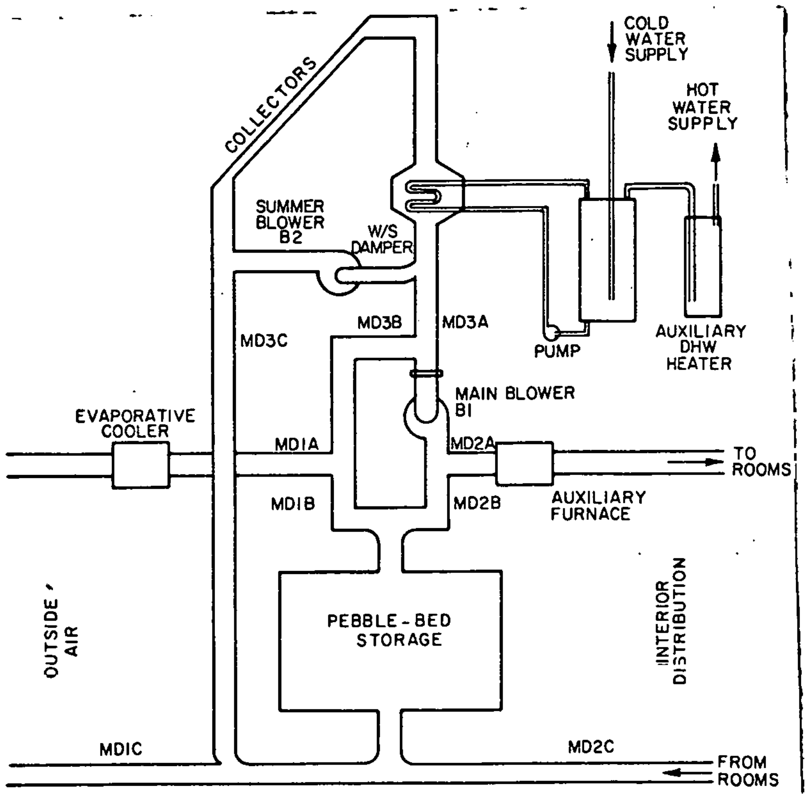

Figure 1. Schematic of the Solar Air-Heating and Cooling System.

DATA ACQUISITION SYSTEM

The data acquisition system consists of (1) instruments and transducers of various kinds to sense temperatures, temperature differences, solar radiation, air and water flow rates, pressures and pressure differences, (2) an analog-to-digital converter and data logger, (3) a magnetic tape recorder to store data in digital form, (4) an on-line mini-computer for real-time data reduction, and (5) an uninterruptible power supply. The five components of the data acquisition system are depicted in Figure 2.

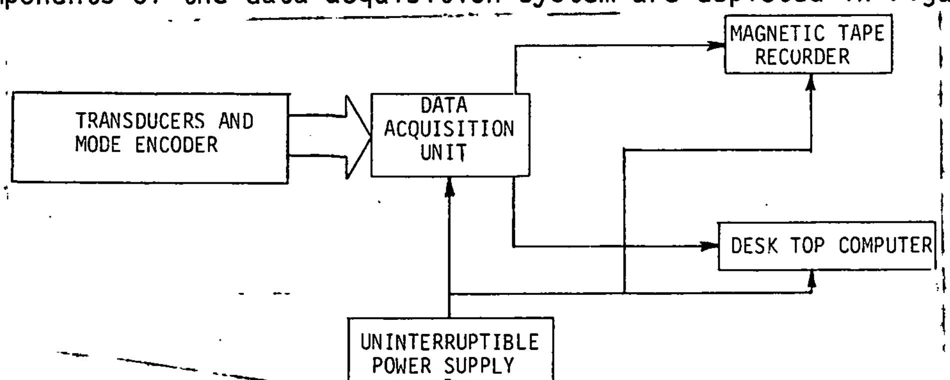

Figure 2. Block Diagram of the Data Acquisition System

INSTRUMENTS

The instruments used to monitor the performance of the solar system are listed in Table 1. Along with instrument specifications, comments are provided in the table which reflect our experiences and are intended to assist readers who plan to monitor solar air-heating systems. The location of sensors are listed in Table 2 and shown in Figures 3, 4, and 5.

Table 1. Transducer Specifications

FUNCTION	INSTRUMENT TYPE	MANUFACTURER, DESCRIPTION	QUANTITY	INSTRUMENT/ DATA RANGE	ACCURACY (1)	COMMENTS
Temperature measurement (2)	Thermocouple Type T	Leads and Northrup, Omega, ThermoElectric: 22 and 26 gage ThermoElectric, sheathed: Grounded (3) Ungrounded (3)	67 2 2	-184 to +390°C -40 to +150°C	±.4°C	Consider: Temperature gradients, heat transfer to and from the measuring junctions, thermoelectric homogeniety of wire, reference junction calibration, linearization errors, use of extension wire and connections, mechanical integrity, grounding, common mode voltage sources (including lightning).
Differential temperature measurement (2), (4)	Thermopile, Type T	Leads and Northrup, Omega 26 gage	7	-184 to +370°C ±100°C diff.	±(1%R+.05°C)	
Outside ambient temperature and humidity	Aspirator	Modified Cambridge Systems, Inc., Model #1105 - contains 1 T.C. and 1 R.H. sensor	1			
Air flow measurement (velocity pressure)	Total/static pressure tap array	Air Monitor Corp., duct air monitor device	7	+1 to +20 m/sec +1 to +3 m/sec	±(1.0%R +.02 N/m²), after calibration	More uniform pressure tap geometry and placement w.r.t. air straightener, more taps and better pneumatic averaging should give more uniform pitot coefficients between units. Suitability of materials for high temperature should be checked.
Pneumatic multiplexer	Ganged wafer valves, actuator and electrical driver	Fluid Wafer Switch SCANCO Actuator: LEDEX S2 Controller: CTLRP10/S2-56	2 1 1	10000 N/m² max operating pressure	N/A	Dessiccant needed to prevent condensation of water vapor inside tubulation, wafer valve, and differential pressure transducer.
Differential pressure	Variable capacitance diaphragm type	Datametrics (Gould) Transducer: 570D-1T-2C1-V1 Signal Conditioner: 1173-AIA-10A1-D1 Thermal Base: Model 525	 1 1 1	±133 N/m² 0 to +4N/m²	±(.2%R +.02%F) (5)	RC=5 seconds filter inserted to mask turbulence induced fluctuations. Controlled temperature transducer environment essential to maintaining quoted error limits.
Mode/air-flow-multiplexer encoder/controller		Locally made by SEAL	1	Digital	±0.1 LSB	Digital filter needed to reject transients. A resetable clock to indicate exact time of mode change between scans would be useful.
Solar flux measurement on 45° tilt	Pyranometer	Epply precision pyranometer Model PSP	1	0 to 2800 w/m² 0 to 1200 w/m²	±(1.5%R+.5%F)	Both instantaneous and integrated values of pyranometer output are logged. A "double-glazed" pyranometer with axially symmetric black and white sensing surfaces is required to maintain accuracy when measuring global radiation on a tilt.
Electric power transducers (6)	Current coil and hall effect transducer	F.W. Bell, Inc., PX-2202B	6	±1KW or ±2KW 0 to 800 w	±(.25%R+.25%F)	Models offered by Ohio Semitronics are available with offset, scale factor adjustments and in a greater range of capacities.
Water flow	Turbine meter	Cox 21-1/2-15 Cox AN8-4 with graphite bearings	1 1	0.1 to 1.0 ℓ/sec 0.1 to 0.3 ℓ/sec .015 to .15 ℓ/sec .03 to .06 ℓ/sec	±.5%F ±.5%R	Sensitive to damage or error from excessive flow, passage of entrained air or dirt.
Auxiliary fuel consumption (piped natural gas)	Conventional positive displacement meter with optical pickup	Sprague Optical pickup by SEAL	2	0 to 1.4 ℓ/sec 0 to +1.2 ℓ/sec	±(1%R+.2%F) (estimated)	Instrumented demonstration projects should employ electric auxiliary sources to ensure an accurate primary or redundant measure of the delivered auxiliary energy.
Integrators Pulse counters		AGM Electronics EA-4011-5 AGM Electronics EA-4050-2	7 4	Unipolar input/ output range specified per individual module	±(.25%R+.25%F)	Pick range carefully. Large accumulated errors due to offset avoided by setting offsets slightly negative and rejecting negative values during data processing.
Barometric pressure	Variable capacitance diaphragm; vacuum reference	Rosemont 1332A	1	0 to 15 psia .73 to .83 atm	±0.2%R	
Relative humidity	Brady Array (AC excited solid state sensor)	Thunder Scientific PC-200	3		±.5%F	Individual calibrations required.
A/D data logging	μP controlled analog multiplexing; dual slope digitizer	Doric 220-160-05-34-61-K5-TK1 KK1-31-53-4K-43-73	1	±11.0 VDC; -165 to +435°C ±1.0 VDC; -40 to 150°C	±(.03%R+.005% F +1.5μv) Thermocouple conversion ±0.3°C	Integration of computer and D/A functions should be considered now that such equipment is increasingly available. Provision for digital inputs would be helpful.

NOTES:

(1) R = of Reading; F = of Full Scale

(2) All thermocouples and thermopiles are fabricated from premium grade wire. All except sheathed junctions are twisted, electric arc welded junctions and are directly exposed to the surrounding air.

(3) The two thermopile circuits - each comprised of one grounded and one ungrounded thermocouple - potentially available in the four absolute temperature measuring thermocouple circuits specified are used. This simultaneous use of thermocouple junctions for absolute and differential temperature measurements is possible because the A/D unit (Doric) has a very high input impedance, and because its input terminals are isolated from one another and from ground.

(4) Each thermopile circuit is fabricated from a single spool of wire.

(5) ±1.0% of reading is typical accuracy achieved in this application because the readings are a small fraction of the instrument's full scale range.

(6) A pair of these transducers, each excited by a 20:1 current transformer, serve to measure the larger power intensities drawn into the house through two legs of a 3ϕ trunk line serving the solar village.

Table 2. Transducer Descriptions

43	Temp., preheat supply line
44	Temp., preheat delivery line
45	Temp., rise through preheat tank
46	H.W. delivery temp.
47	outdoor air temp. (dry-bulb)
48	temp. in room 102
49	temp. in room 106
50	temp. in room 104
51	temp. in room 105
52	temp. in room N2 (near thermostat)
53	temp. difference across auxiliary heater
54	room air supply temp.
55	room air return temp.
56	temp. difference, room return to Blower B1
57	Storage temp. (top of bed)
58	Storage temp. (0.15m)
59	Storage temp. (0.46m)
60	Storage temp. (0.76m)
61	Storage temp. (1.07m)
62	Storage temp. (1.37m)
63	Storage temp. (1.68m at support mesh)
64	Air temp., top port of storage
65	Air temp., bottom port of storage
66	Temp. difference across storage
67	Air temp. at inlet to Main Blower (B1)
68	Temp. difference, top of storage to B1
69	Air temp. at collector outlet
70	Air temp. at collector inlet
71	Temp. difference across collector
72	Air temp. before H.W. heat exchanger
73	Air temp. after H.W. heat exchanger
74	Temp. difference across H.W. heat exchanger
75	Air temp. to evaporative cooler
76	Air temp. after evaporative cooler
77	Temp. difference across evaporative cooler
78	Water temp. at top of preheat tank
79	Water temp. at bottom of preheat tank
80	Total solar flux (45 tilt)
81	Total solar insolation (45 tilt)
82	Mode indicator
83	Air monitor selection indicator
84	Dynamic pressure at air monitor
85	Quantity of hot water supplied
86	Quantity of hot water recirculated
87	Relative humidity outdoor
88	Relative humidity at main blower
89	Relative humidity at thermostate
90	Barometric pressure at site
91	Water temp. difference across H.W. heat exchanger
92	Auxiliary heater gas consumption
93	H.W. Heater gas consumption
94	Electrical power used in the building
95	Electrical power used for instrumentation and data logger
96	Electrical energy for main Blower
97	Electric energy for Blower B2 and H.W. pump
98	Electrical energy for evaporative cooler
99	Electrical energy for controller, and motorized dampers

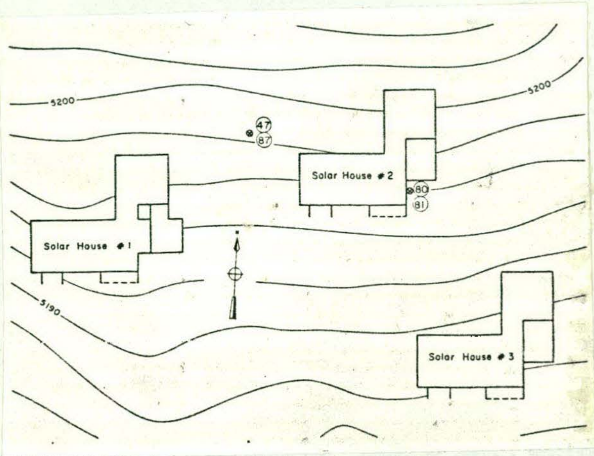

Figure 3. Transducer Locations Outside House

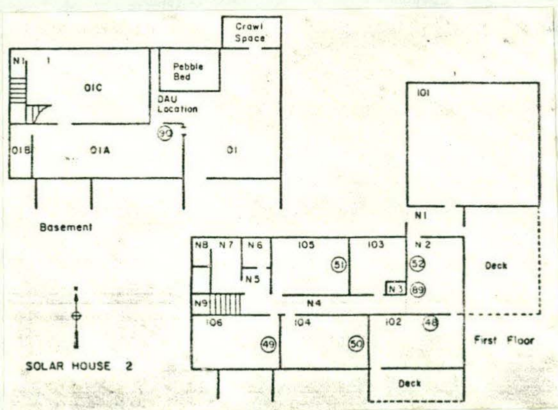

Figure 4. Room Temperature and Humidity Sensor Locations

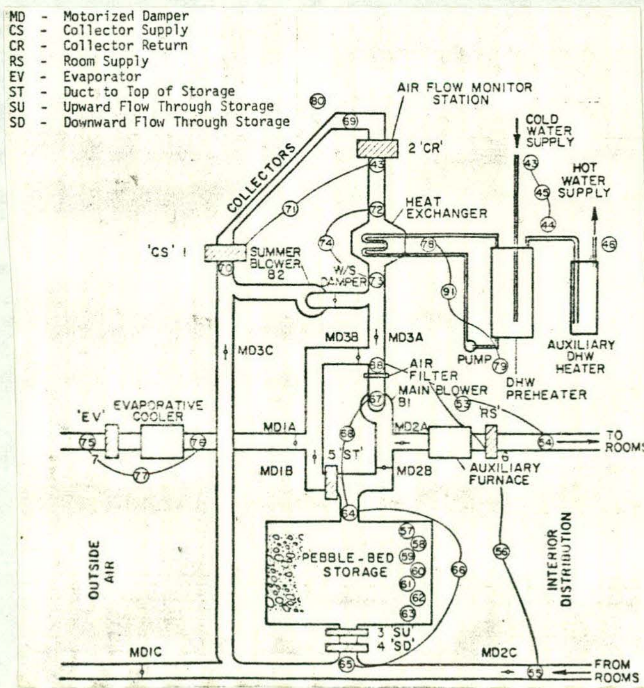

Figure 5. Transducer Locations in Heating System

Temperature

Copper-constantan (Type T) thermocouples are used to measure temperatures of both air and water. Sheathed thermocouples are used to measure water temperatures. Reference junction compensation and linearization is provided by the data logging unit and the linearization error is within ±0.11°C, [2].

Temperature differences are measured with multiple-junction thermopiles and electrical output is converted to temperature differences using standard procedures [3, 4, 5]. Because air velocities are low, the dynamic heating effect is negligible. Also the effect of radiative heat transfer between the duct walls and thermocouple junctions is negligible.

Solar Radiation

Solar flux is measured with an Epply Model PSP pyranometer placed in the plane of the collectors at a tilt of 45 degrees with respect to horizontal. Both instantaneous and integrated values are included in the data set.

Air Flow Rates

Although there are several methods for measuring air flow rates in ducts, air monitors with an array of pitot tubes and two static pressure probes were used to measure air flow rates. With honeycomb flow straighteners, straight duct runs upstream of measurement stations could be minimized, and with multiple pitot probes, flow rates at sections are pneumatically averaged. The small velocities in the ducts (less than 3 m/sec), however, result in small dynamic pressures and pressure differences between the static and dynamic probes, and requires a sensitive pressure transducer which measures small pressure differences. Because pitot tubes are air velocity meters, barometric pressure sensors are needed in addition to air temperature to determine air density to calculate mass flow rates.

There are seven air flow monitoring stations in the system located as shown in Figure 5. (Temperature and temperature difference sensor locations are also shown on the figure.) All air monitors were calibrated with an ASME standard nozzle [6] and the coefficients determined from the calibrations were used to calculate volumetric and mass flow rates. The pitot coefficients were found to differ significantly from the manufacturer's specifications.

Although it would be convenient to provide a differential pressure transducer with each air flow monitor, the cost of the transducer prohibited purchase of multiple units. An electrically controlled pneumatic multiplexer (Scanivalve) was used instead to sample an appropriate air monitor with one differential pressure transducer during each scan of the set of instruments.

Water Flow Rates

The recirculating volumetric flow rate through the preheater coil and the hot water delivery volume are measured with turbine flow meters. Pulse-count-to-voltage converters are used in the output circuitry. There have been considerable difficulties with maintaining turbine flow meters in the system. They are sensitive to damage from excessive flow rates, and require frequent recalibration. The turbine meters were replaced by a Rotameter which require manual readings.

Mode Indicator and Air Monitor Controller

A basic need for system monitoring is a characterization of the state, or mode of the solar system, so that appropriate mass and heat flow rates can be determined. The mode indicator coupled with an air monitor station controller, is illustrated by the block diagram in Figure 6.

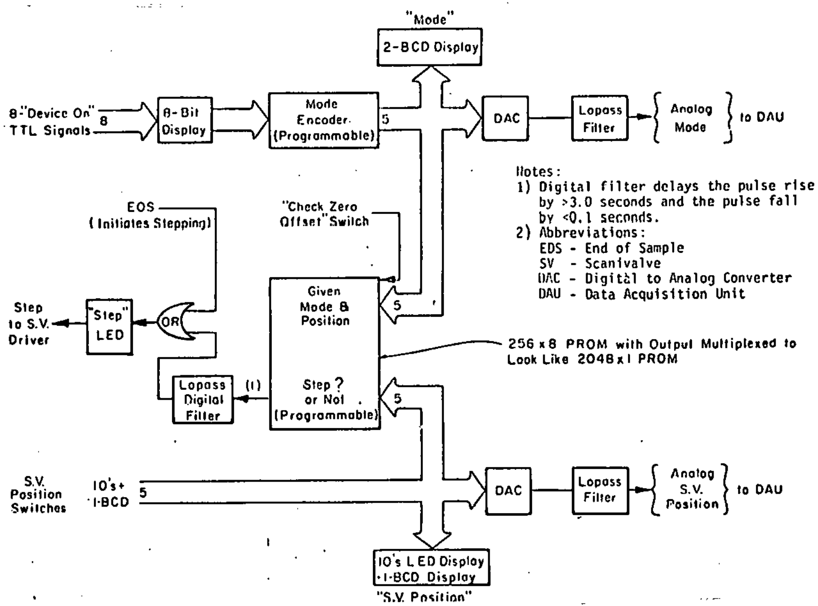

Figure 6. Air Monitor Controller and Mode Indicator

There are 24 "modes" or system states that are identifiable for basic heating and cooling functions. Each mode consists of a unique state of the blower, dampers, preheat circulation pump and evaporative cooler. The calculation of heat flows and heat balances are facilitated when all possible system states are uniquely identified in each data scan. When a system device malfunctions, the system state is identified as being "illegal" so that erroneous heat flow quantities are not included in the calculations.

Control over the selection of appropriate air flow measurement station for any system state is effected by the mode indicator. After each interval scan by the data logger, the controller advances the sampler only through the relevant monitoring stations for a given system state. This procedure maximizes the number of air flow measurement samples obtained and eliminates null (zero flow) data from the data scan.

Data Acquisition Unit

The data acquisition unit (DAU) is a Doric Scientific Model Digitrand 220 which consists of a scanner, multiplexer, analog-to-digital (A/D) converter and printer. Interfacing capability with several peripheral units are possible. Presently a Kennedy tape deck and a Wang desk-top computer are interfaced with the DAU as shown in Figure 2. The A/D converter produces 16-bit information with one microvolt resolution and has a normal sampling rate of about 10 channels per second. The interval between scans is selectable in discrete time increments and a 10-minute interval is used. A separate and different time interval between scans can be initiated by the desk-top computer with the data stored in computer memory. A one-minute interval is used and data are analyzed in "real" time. The data collection process is depicted by the block diagram of Figure 7.

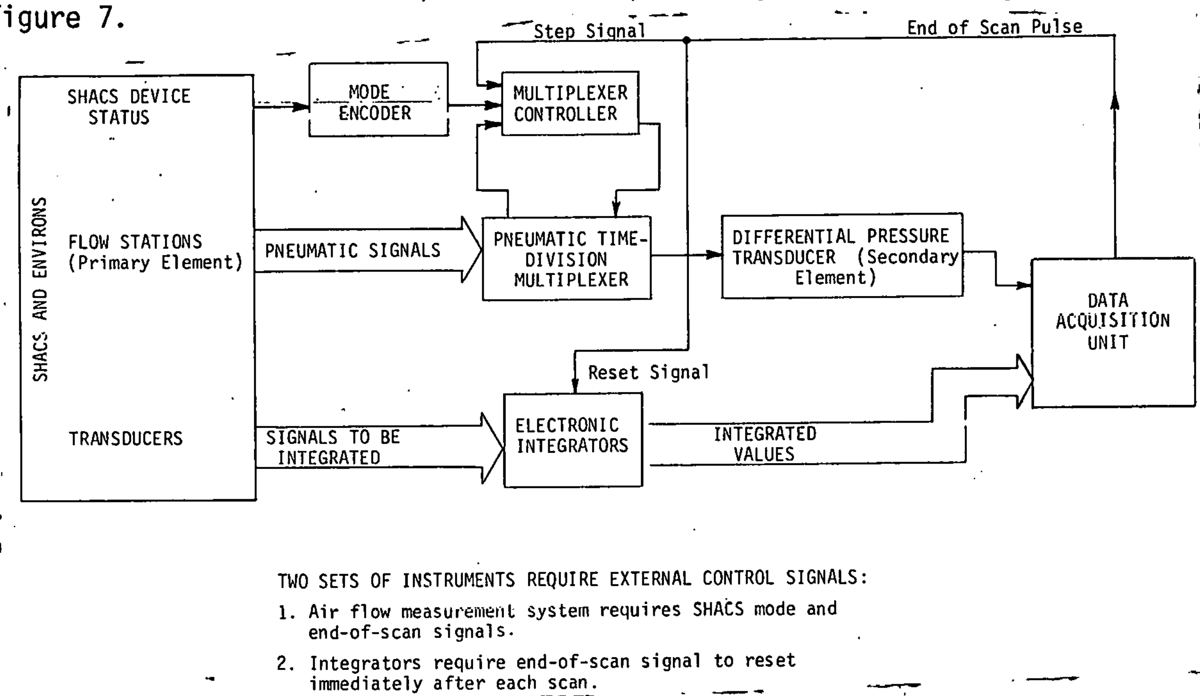

Figure 7. Block Diagram of Data Collection Process

The DAU also incorporates an alarm system which is triggered when sensor readings are not within the programmed ranges or when the system is interrupted, such as by failure in the power supply. Analog signals are multiplexed and digitized sequentially and each digitized value includes the channel number and units of measurement. In addition to sensor data, the calendar day and time of day are digitized and included in each data scan.

DATA REDUCTION AND ANALYSIS

The data acquisition and monitoring system in CSU Solar House II utilizes the minicomputer to monitor the performance of the solar system in "real" time and a 7-track magnetic tape to store data for determination of system performance at a later time. With the minicomputer system, hourly and daily heat flow rates and other parameters can be calculated in real time and instruments can be monitored as well to identify malfunctions or problems. The magnetic tape deck is used to accumulate data over long periods of time (weeks) before the tapes are processed at the computer center.

Hourly (or smaller time interval) data, analyzed in the form of heat flow rates, solar radiation or average temperatures, are also possible with the minicomputer, but the slow speed of a hard copy printer will usually lead to scans being missed during printing. Because hourly quantities are usually more meaningful when compared to other hourly values during the day, obtaining continuous scans have priority over scrutiny of hourly quantities, especially if one-minute scans are used. On the other hand, if a two-minute or greater scan interval is used, periodic real time heat flow rates in the solar heat delivery system can be printed. At Solar House II, hourly values of calculated quantities are printed out daily during a do-nothing state of the solar system and after sunset.

The quantities calculated from data on the 7-track magnetic tape are used for presentation of the system performance results because long sequences of uninterrupted data scans are available. Since the minicomputer is used as a monitoring system, there are frequent interruptions, at least daily, in the data stream, and some of the hourly summaries are incomplete. Nevertheless, the results provided from the minicomputer forms a redundancy in the analysis, and when problems arise at specific times with the 7-track tape, (such as records with parity errors) the two records can be combined to provide a continuous record of system performance.

DIFFERENTIAL TEMPERATURE DETERMINATION

Thermopile readings (Δe) are converted to temperature differences (ΔT) by polynomial representations of the relationships between emf and temperature. Temperature differences are dependent upon the air temperature as well as the emf output from the thermopile, therefore a thermocouple reading at one end of the thermopile is needed in addition to the thermopile emf. With air temperature T_1 known and Δe obtained from the thermopile, the calculation proceeds as follows:

1. Determine $e_1 = e(T_1)$, where $e(T_1)$ is a polynomial
2. Determine $e_2 = e_1 + \Delta e$, where Δe is the thermopile output
3. Determine $T_2 = T(e_2)$, where $T(e_2)$ is a polynomial
4. Determine $\Delta T = T_2 - T_1$.

The polynomial coefficients for $e(T_1)$ and $T(e_2)$ are listed in Table 3. The coefficients for $e(T)$ are listed in the NBS monograph [5] and the coefficients for $T(e)$ were determined for our present purpose. Lower order polynomials may be used, consistent with the accuracy desired. The error in determining ΔT will be approximately equal to the error in measuring Δe, but is relatively insensitive to the error (0.1 to 0.3%) in determining T_1.

AIR FLOW RATE DETERMINATION

Sampling of an air monitor in a particular mode is governed by a controller which operates the pneumatic multiplexer. With seven air monitors and a pneumatic short circuit to establish instrument zero for the pressure transducer, the eight positions in the scanivalve are stepped sequentially, with stepping initiated after each scan. At each step the mode and air monitor number are inputs to a PROM where a truth table is preprogrammed. In each of 24 modes, only certain air monitors are active, and if the air monitor number is not part of the active

Table 3. Thermocouple Linearization Polynomials

$e = \sum_{i=1}^{n} a_i T^i$				$T = \sum_{i=1}^{n} b_i e^i$		
	i	a_i: Value	Exp.		b_i: Value	Exp.
n=14	1	3874	-2	n=8	2581	-5
	2	4412	-5		5706	-10
-270 to 0°C	3	1141	-7	-50 to 0°C	6731	-14
	4	1997	-8		3492	-17
	5	9045	-10		7494	-21
	6	2277	-11		9898	-25
	7	3625	-13		7774	-29
	8	3865	-15		2793	-33
	9	2830	-17			
	10	1428	-19			
	11	4883	-22			
	12	1080	-24			
	13	1395	-27			
	14	7980	-31			
n=8	1	3874	-2	n=8	2581	-5
	2	3319	-5		7579	-10
0 to 400°C	3	2071	-7	0 to 100°C	6395	-17
	4	-2195	-9		2072	-16
	5	1103	-11		2000	-19
	6	-3093	-14		9882	-23
	7	4565	-17		2459	-26
	8	-2762	-20		2520	-30

series for that mode, the ouptut is false. On a false signal another step of the multiplexer is initiated, on a true signal the stepping halts. After a differential pressure reading is obtained in a scan, the processes is repeated.

Volume flow rate of air through the air monitor station is obtained in a standard manner, using the calibrated pitot coefficients obtained for each air flow monitor and cross-sectional areas. Calculated local flow rates are then converted to common reference air properties affecting density. The correction to density for pressure variations in the system is negligible in comparison to barometric pressure corrections. Therefore, corrections are made to standard temperature. Because the blower in the system is nearly a constant volume rate device, it is convenient to reference all the volume flow rates measured in the systems to air properties at the blower. Analysis of the sampled flow rates with and without this correction has shown that the correction reduces the standard deviations of the sampled air flow rates. Sample histograms of air flow rates obtained from the air monitors in several system modes are presented in Figure 8. The sample, x, is the volume flow rate at the blower, $\dot{V}_B$; $\bar{x}$ is the mean, N is the number of samples used in the historgram, and S_x is the standard deviation of the population. The ordinates are normalized, and the abscissa is $(x/\bar{x}-1)/S_x$. The number of "outliers", that is, data considered to be erroneous because of transients or other instrument problems, is expressed as percent of the accepted population N. Data shown are for the period 15 February through 19 April, 1977. The long term average volumetric flow rates must be converetd to mass flow rates by evaluating air density at the prevailing blower condition to calculate heat flow rates in the system.

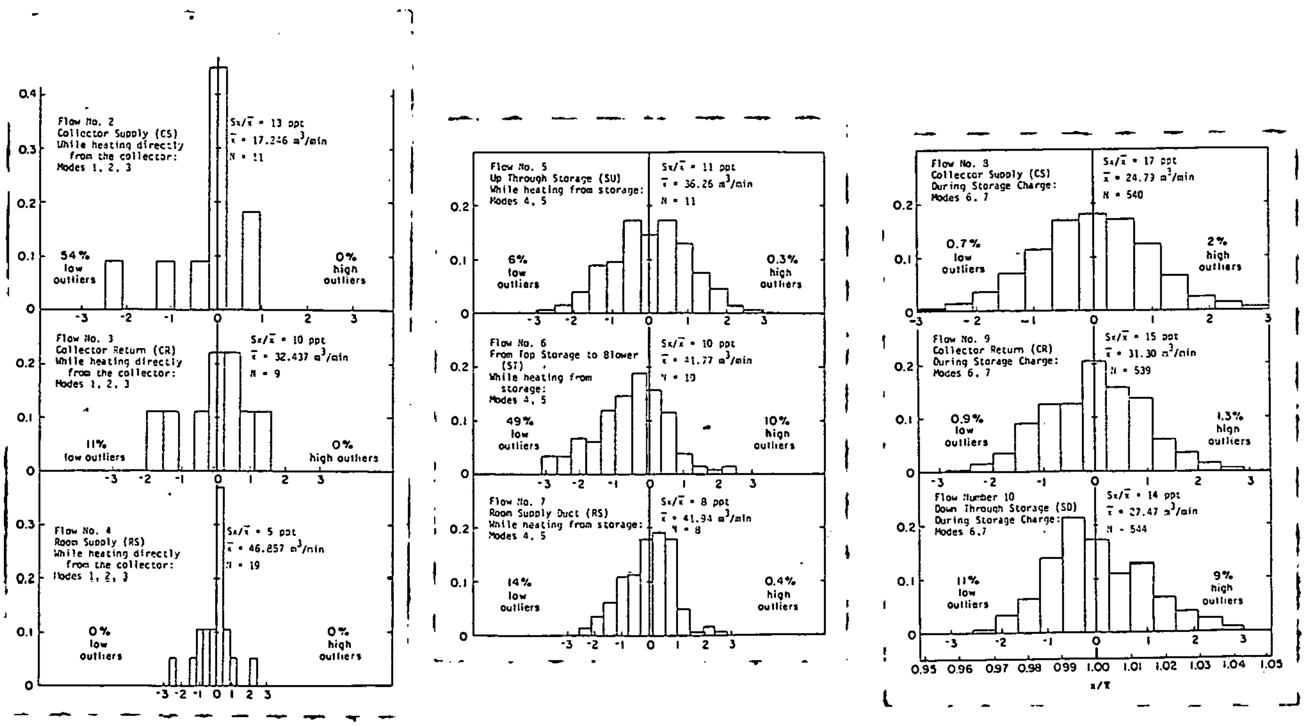

Figure 8. Normalized Distributions of Volumetric Flow Rates at Blower Air Properties.

PROBLEMS WITH HEAT FLOW CALCULATIONS

Heat flow calculations are complicated by leakages into or out of the system, leakages across dampers and heat transfer through duct walls. Every air-heating system can be expected to experience leakages at joints in the collector, ducts and across closed dampers. If there is infiltration of ambient air into one part of the system there must be exfiltration out from another portion of the system (usually into the heated space). If proper heat balances are to be made in a system performance analysis the quantity of air leakage and heat transfer through duct walls must be determined.

In CSU Solar House II, there is a significant amount of ambient air drawn into the ducting system after the air is heated by the collector, that is, the leakage is at the top manifold of the stick-built collector array. The magnitudes of the heat flows by the air leakage, relative to the total collector heat output are shown in Figure 9 for two days in January 1977. Whenever the system is in the heat collection mode, air is drawn into the circuit, and hot air is forced into the conditioned space whether or not there is demand for heat. Part of the uncontrolled heat flow to the rooms appears as an artificial increase in space heating load because of exfiltration through the heated envelope. A portion of the heat delivered is needed to maintain comfort conditions, but the balance overheats the space.

In addition to normal electrical loads in a building, which is subsequently converted to heat, a fully instrumented experimental house such as Solar House II utilizes an average of 41 MJ/day of electric energy just for the instrumentation, which is 6 percent of the heat delivered to the conditioned space over a heating season. The added heat is particularly troublesome in summer when the performance of the evaporative cooling system is only capable of cooling at a rate of about 120 MJ/day. The major contributors are the minicomputer and 7-track tape deck but the DAU and other instruments also add significant amounts of heat into the building.

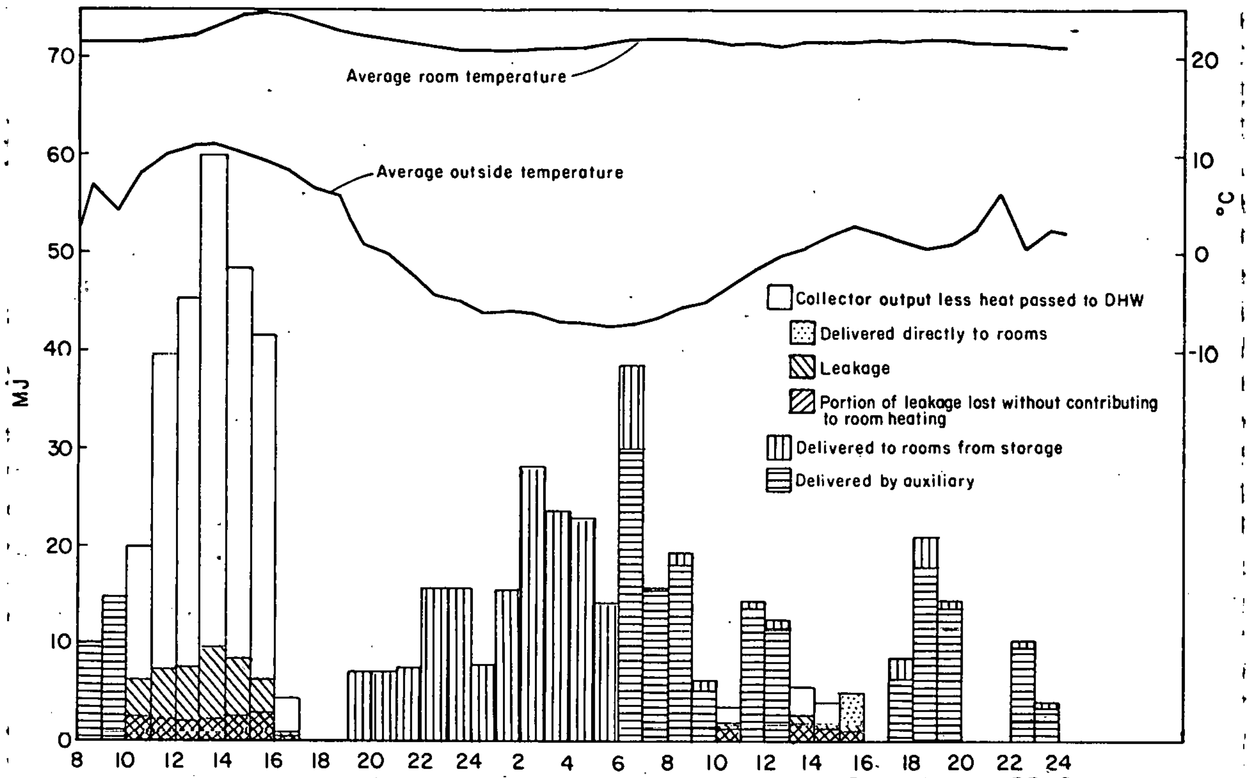

Figure 9. Selected Hourly Heat Rates for the Solar House II System.

TWO-LEVEL INFORMATION PROCESSING

The desk-top computer provides information on a daily basis which is both descriptive and diagnostic of the heating system operation. It also enables determination of proper functioning or malfunctioning of the data acquisition system that might otherwise continue unnoticed until routine analysis is made from the 7-track tape some days or weeks later. The normal logging cycle can be modified to monitor any instrument in the system. The minicomputer can be disengaged from the DAS for calibrations and specialized system experimentation can be performed and immediate results can be obtained.

The magnetic tape drive, on the other hand, is not affected by interruptions of the desk-top computer and reliabily produces a permanent, continuous record of raw data in a computer compatible format. It is the information source for the final system performance analysis.

INFORMATION PRODUCED

The following data and analysis are produced in hard copy form, both from the minicomputer and the magnetic tape. The daily records are from midnight to midnight, although during the heating season it is convenient to process data from 8 a.m., to 8 a.m., and for the cooling season from approximately 10 p.m., to 10 p.m.

(1) MODE HISTORY - A list of modes, changes in modes and their corresponding times are recorded.

(2) FLOW HISTORGRAM - A tabular record of the air flow monitor, the number of samples for each monitor, the number of samples in each interval, the mean and standard deviation are produced.

(3) DAILY ENERGY SUMMARIES - An hourly tabulation of heat flow rates through various sectors of the system, average temperatures, electric energy usage, auxiliary energy supplied and total quantities for the day are provided.

(4) COLLECTOR OPERATING SUMMARY - An hourly tabulation of total solar insolation, solar insolation while collecting, inlet air temperatures, average temperature rise, and collector efficiency parameters are provided.

The minicomputer provides in addition the following summaries:

(5) STORAGE TEMPERATURE PROFILE - A table of temperatures at six levels through storage is provided at the end of each hour of the day.

(6) CASSETTE TAPE PERMANENT RECORD - All of the calculated and processed data are stored on cassette tape. Raw data as transmitted to the minicomputer are not permanently recorded, however.

Through the computer analysis of the 7-track magnteic tape, additional information provided are:

(7) TAPE DIAGNOSTICS - A list of abnormal characteristics of the source tapes, such as missing scans, extra scans, missing channels, illegal values, etc., are provided.

(8) BINARY TAPE - A binary tape is produced which contains the directly measured quantities and calculated values derived during processing of the source tapes. Missed scans are filled in with flagged dummy records to facilitate later computer processing. Whenever specialized information is desired, the binary tapes can be referenced to reduce computer time and costs.

PROGRAMMING STYLE AND SPECIAL PROGRAMMING PROBLEMS

The data reduction program is a function of the type of computer used and style of the programmer. Several facets of the CSU Solar House II data reduction procedure described below may be of use to the reader.

The selection of a minicomputer is an extremely difficult task and many useful guides can be found in the literature. In general, the coding, programming time and auxiliary technical efforts vary roughly inversely with computer size and cost. The break even point for each operation varies and depends on a large number of variables such as the size of program, special features needed, time constraints, inventiveness in programming, and quality of the computer. Of special importance is the quality of maintenance service available. The compatibility with peripherals from other manufacturers is another important factor in computer selection. Many of these questions cannot be assessed in advance.

Time (speed) and memory constraints encountered in programming a complex problem can be overcome with special techniques. A few such techniques, though familiar to experienced programmers, deserve to be mentioned in the present context. Recursive polynomial and sum evaluation techniques have been found valuable for both time and memory conservation. So-called index threads once understood and exploited effectively, can make simple and concise that which would otherwise be difficult or nearly impossible. Overlaying is used to minimize the amount of code and special-purpose variables in memory. With the Solar House II data reduction, this involves sequential loading of three separate programs, initialization of variables, logging, and output routines, while maintaining a common block of variable memory throughout overlay operations.

Time/memory constraints are not the only problems confronting the programmer. Peculiar to continuous, real-time analysis of non-repeatable data, there is necessity to foresee many contingencies. Non-standard scan intervals, missed scans, illegal values and the like should not cause processing to stop altogether, but should be dealt with in a logical fashion including production of diagnostics for later perusal - after which processing can continue.

CONCLUSIONS

Although the determination of the performance of a solar system is basically the application of the first law of thermodynamics with simple heat flow calculations, many difficulties arise because of constraints in the type of instrumentation used, automatic data logger selected and data processing methods. The experiences gained from the work conducted at Colorado State University, some of which are described in this paper, should be of aid to others interested in monitoring the performance of solar systems. The automatic and continuous nature of data collection desired, is very frequently interrupted by weaknesses in the system. These weaknesses are inherent in the instruments as well as in the type of data collection and processing hardware selected. The real world is replete with component and power failures, and specialized circumstances become the rule rather than the exception. If the experiences of predecessors are carefully scruitinized, experimentors can minimize their difficulties in selecting and programming their data acquisition systems and data analysis routines. It is hope of the authors that some of their experiences will be useful to the reader.

ACKNOWLEDGMENTS

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RELATIONSHIP BETWEEN INSTRUMENTATION AND VALIDATION

by

Mike Potishnak*
C. Byron Winn†
and
Loren Lantz††

ABSTRACT

The Colorado State University Solar House I has been instrumented for data acquisition purposes since July of 1974. The data that have been collected and reduced have been used for the purpose of validation studies relating to solar system simulation programs such as TRNSYS and SIMSHAC. In addition to these mathematical models, more recently a real-time solar simulator has been designed and constructed in CSU Solar House I. The purpose of the real-time simulator is to provide a means by which two different collector subsystems may be compared simultaneously when being used in one solar system. Validation studies of both the real-time simulator and the mathematical simulation models have been complicated by inadequacies in the instrumentation and data recording systems. In this paper we present error analyses for the various subsystem components presently being used in the CSU Solar House I. Furthermore, quantitative examples taken from the data sets are presented that illustrate some difficulties that one encounters in attempting to use inadequate data for model validation. Finally, suggestions are made relative to improvements that should be made in instrumenting a solar house for data acquisition purposes relating to validation of simulation models.

Introduction

Earlier solar energy research experiments utilized stripchart recorders as their primary data acquisition output devices. Soon computerized data acquisition systems replaced stripchart recorders because less manual labor was required in reducing the data. A much larger data base could be processed because of the high speed capabilities of computers. Software flexibility also allows the researcher extensive capability for performing concise data reduction with this expanded data base. In order to properly evaluate the results by data reduction, errors introduced by the data acquisition system must be analyzed. The Solar House I data acquisition system is shown in Figure 1. Each component must be scrutinized for possible errors.

Thermocouples

Using copper-constantan thermocouples for temperature measurement introduces several sources of error. These thermocouples have a rated accuracy of ± 0.8°C in the temperature range of interest (-59.4 to 93.3°C). This error is mainly due to nonuniformities in the manufacturing process. Most energy calculations in the Solar House I use a temperature difference

*Graduate Student, Department of Mechanical Engineering, Colorado State University, Fort Collins, Colorado 80523

†Professor of Mechanical Engineering, Colorado State University, Fort Collins, Colorado 80523

††Systems Engineer, Solar Environmental Engineering Co., Inc., Fort Collins, Colorado 80522

between two thermocouples. For a 5°C temperature differential, an error of as much as 32 percent is possible. The standard deviation of this error is 22.6%. Since most solar energy heat transfer processes involve temperature differentials of this order of magnitude, some attempt should be made to combat this measurement error. One solution is to individually calibrate each thermocouple used in important temperature differential measurements. Replacing copper-constantan thermocouples with platinum resistance thermometers is another possible solution. Although using platinum resistance thermometers would be more expensive their rated accuracy of ± 0.05°C would introduce only a one percent possible error for a 5°C temperature differential. For temperature measurements which are not used in temperature differential calculations, copper constantan thermocouples will usually be adequate.

Experimental calibration was performed on the thermocouples used for determining the temperature differential across the cooling coil. The thermocouples are used for measuring temperatures typically between 11°C to 13°C and 5°C to 7°C to and from the cooling coil respectively. To estimate the effect of the measurement error on the determination of the cooling load, assume that the actual temperatures to and from the cooling coil are 6.4°C and 11.65°C respectively. The actual temperature differential across the cooling coil will be 5.25°C, while the measured temperature differential is

$$\Delta T = TFAC - TTAC = 12.2 - 6.7 = 5.5°C$$

The measured cooling load would then be overestimated by

$$\frac{5.5 - 5.25}{5.25} \approx 4.8\%$$

If the thermocouples were switched, the measured temperature differential would be

$$\Delta T = 11.9 - 7.1 = 4.8°C,$$

resulting in an 8.6% underestimation of the cooling load. All measured cooling loads of Solar House I have been overestimated by about 5 percent due to errors in the temperature differential measurements.

A second source of error is related to the placement of thermocouples. It is often difficult to install thermocouples at the best location for a particular temperature measurement. Errors introduced by thermocouple placement must be analyzed for each measured temperature.

A third kind of temperature measurement error is caused by the problem of differing thermal response times. Most thermostatic controllers have thermal time constants which are much longer than the time constant of a thermocouple. For example, the time constants of thermocouples used in Solar House I vary between 0.8 seconds and 15 seconds in air, while the house thermostat has a time constant of about twenty minutes. Any experiment which uses thermocouple temperature measurements to verify the correctness of thermostatic control actions must address this problem.

Turbine Flowmeters

Turbine flowmeters are used to measure liquid flows with only slightly varying flow rates. A turbine flowmeter measures flow by placing a propeller within the stream of flow. A magnetic pickup senses the propeller spin and generates a sinusoidal voltage with a frequency proportional to the flow rate. A pulse accumulator counts the number of voltage peaks which occur during the ten minute scanning interval. The number of peaks is then multiplied by a conversion factor to determine the flow during the preceding ten minute interval.

Turbine flowmeters are assigned a K-factor (cycles/gallon) by the manufacturer. The K-factor is assumed to be constant throughout all flow rates in the rated operating range of the flowmeter. A typical flowmeter with a 3 to 30 gallon per minute rated flow rate range was calibrated by a method which has a maximum error of 1/2%. An error of less than 2 percent is typical for mid-range flow rates. A standard deviation of 11.5 Hz for flow rates between 3 and 12 gallons per minute represents about a 5 percent error with a 7 gallon per minute flow rate. This amount of error is much larger than the ± .5% error rating quoted by Cox Instrument literature for the AN series flowmeters used in Solar House I. This particular flowmeter was calibrated after four months of operation. It is apparent that turbine flowmeter accuracy decreases with length of service, and frequent recalibration is required if the initial degree of accuracy is to be maintained.

Fouling problems and bearing wear have detracted from the reliability of the turbine flowmeters used in Solar House I. Frequent fouling has caused gaps in the Solar House I data base. During 1977, Solar House I experienced four instances of turbine flowmeter fouling. A total of seven turbine flowmeters are used for flow measurement at Solar House I.

Fouled turbine flowmeters often cannot be repaired and need replacement. Those flowmeters which can be repaired require extensive maintenance and time consuming recalibration. Fouling is caused by the formation of deposits in the vicinity of the turbine blades and results in the restriction of spin. Although this process may be slowed by using filtering devices such as Y-strainers, these filtering devices themselves would require routine maintenance.

Photomechanical Transducers

Solar House I uses photomechanical transducers attached to rotating utility meter needles for measuring flows with highly varying flow rates. A rotating slotted wheel passes through a photocell and the transitions from "light" to "no light" states are used to detect flow. Acceptable accuracy can be obtained from photochoppers in most cases. Dust collection on the photocell presents a minor maintenance problem. Use in a relatively high vibration environment may cause intermittent problems. Mechanical vibrations may occasionally cause erroneous "light"/"no light" transitions resulting in an erroneous flow measurement. For example, the Solar House I hot water measurements indicated grossly excessive hot water consumption about once or twice a week. Investigation revealed that the hot water meter was in physical contact with a pipe which experiences a water hammer effect whenever a certain pump is running. It was postulated that the mechanical vibrations would cause repeated "light-no light" transitions whenever the edge of a slot in the wheel would be in the vicinity of the photocell light beam and the pump was running. After the physical contact between the hot water meter and the water hammering pipe was eliminated, erroneous hot water flow measurements were eliminated.

Kilowatt-hour to Direct Current Millivolt Transducers

PX-2000 Series industrial watt transducers manufactured by F.W. Bell are used for measuring electrical energy consumption. The key component in the transducer is a Hall generator. This is a magneto-sensitive semiconductor which, when driven by an electric current and exposed to a magnetic field, generates a voltage that is proportional to the product of the current and field. The a.c. component on the d.c. output voltage does not present a problem. The output voltage is input to an integrator which will effectively see only the d.c. component(s) experienced during the scanning interval. These devices have been reliable, accurate, and maintenance-free. The transducers have a rated accuracy of .5% under normal operating conditions.

Status Indicators

Status indicators involve an energized relay which presents a non-zero d.c. millivolt level to the Doric. Limited battery life and occasional indicator relay failure have detracted from their reliability.

Replacing the current status indicator circuitry with half-wave rectifier circuits will overcome these problems. When a pump is turned on by the application of 110 volts a.c., a d.c. millivolt level between 50 and 250 millivolts is received by the Doric. When the pump is turned off, the d.c. millivolt level is about zero millivolts. These circuits are reliable, inexpensive, and require no maintenance.

Pyranometers

Eppley pyranometers have been used for measuring insolation at a 45° tilt. These devices have been reliable and require only periodic cleaning. The pyranometer must be carefully installed according to directions and the model used should be accurate at all anticipated tilt angles. Before August, 1977, Solar House I used a pyranometer that was designed for horizontal surface applications only. Errors of up to 5 percent have been caused by using this pyranometer at a 45° tilt. This pyranometer has been replaced with a model designed for tilt applications. Its specifications are: Temperature dependence ± 1%, Linearity ± .5%, and Cosine Response ± 1%.

Pulse Accumulators and Integrators

Pulse accumulators and integrators are used to totalize various kinds of inputs. A voltage level between zero and 250 millivolts is received by the Doric every ten minutes by these devices. A pulse accumulator counts the number of sinusoidal or step function peaks and outputs a proportional d.c. millivolt level. An integrator produces an output which is proportional to the magnitude of the d.c. input voltage and the amount of time which the d.c. input voltage level existed. A typical rating for a Solar House I integrator would be:

5 MV d.c. input for 10 minutes yields 250 MV d.c. output

The integrators and pulse accumulators used in Solar House I are TA 4000 Series components, manufactured by the Arizona Gear and Manufacturing Company. These components have an accuracy rating which is .5% of full scale, equivalent to 1.25 MV. For a 25 MV output, this represents a 5 percent error. Therefore, sensors, pulse accumulators, and integrators should be matched so that outputs will usually be close to full scale, minimizing the percentage of error. Pulse accumulators and integrators are generally reliable, but they must be periodically checked for changes in zero value when they are reset.

Doric Digitrend 210 Scanner

The Doric can scan up to one hundred thermocouple or d.c. millivolt inputs. Inputs are designated as being either thermocouple or d.c. millivolt inputs in groups of ten. Each decade of thermocouples will use the Doric thermocouple millivolt to degree Celsius conversion hardware. The accuracy of this conversion hardware has been checked with an ice point reference device. Calibration tests have shown that each thermocouple decade will experience significant drifting with time and introduce an absolute error often as large as 3°C. This requires frequent recalibration and zero reference checking to minimize drift errors. Thermocouples to be used in temperature differential calculations should also be installed in the same decade to eliminate drift errors. Future data acquisition systems chosen for solar research applications should eliminate or minimize this serious problem.

A fixed scan rate of ten minutes is used for reading all data points. A fixed scan rate of this duration introduces significant errors when frequent cycling occurs. For example, Solar House I heating will typically be "on" for four minutes and "off" for eight minutes. Let us assume that solar heating is being done with a constant 5°C temperature differential across the heating coil when the heating is "on". During the "off" interval both thermocouples will cool, approaching the tank room air temperature and diminishing the temperature differential experienced during the "on" time. Whenever a scan occurs during an "off" time, an erroneous temperature differential will be used in the heating load calculation (see Figure 2). The overall effect will be to underestimate the amount of solar heating. Auxiliary heating loads will not be unidirectionally biased in the same manner as solar heating. The temperature differential across the heating coil will exponentially increase with auxiliary boiler "on" time. The effect of a ten minute sampling rate on measured auxiliary heating loads is illustrated in Figure 3. Calculations of useful solar energy collected (Q_u) are also susceptible to this kind of error during periods of frequent collector cycling.

The present Solar House I data acquisition system is not capable of overcoming the scan rate problem. Future systems should be designed so that a pump turning "on" will generate an interrupt which initiates scanning of the temperature differential at a suitable scan rate. Accelerated scanning will be stopped when the pump turns "off". A data acquisition system with enough flexibility to scan in this manner will overcome this problem.

Deteriorating Effects of Electrical Noise

The presence of electrical noise can have a disastrous effect on data acquisition. Sensors should be connected to minimize the errors introduced by electrical noise in the operating environment. Noise has historically played havoc with Solar House I flow measurements due to improper grounding techniques. The cables connecting turbine flowmeters to pulse accumulators received stray voltage levels which erroneously added to the integrated flow. A measured flow has been observed to be in error by greater than 50 percent due to noise superimposed on improperly grounded cables. The Wang minicomputer interfaces also have been adversely affected by electrical noise. Interface "ready" bits occasionally have been reset by electrical noise, stopping the data acquisition process a few times a week. Information transmission between the Doric scanner and the Wang minicomputer occasionally experiences .

noise related transmission errors. Future installations should attempt to minimize the presence of electrical noise and use equipment which is highly insensitive to electrical noise.

Thermal Capacitance

The relationship between model validation and instrumentation can be illustrated in the following example. The Corning evacuated tube collectors at Solar House I were observed adding energy to a preheat tank as much as twelve hours after sundown during December 1977. Energy was added to the preheat tank two or more hours after sundown on seven occasions during December 1977. An investigation indicated that the collector controls were in fact operating correctly, and a sufficient temperature differential existed between the bottom of the preheat tank and the collector plate temperature. Since the evacuated tube collectors experience extremely low losses, energy collected during late afternoon hours is stored for many hours inside the collector. When hot water is used, cold water enters the bottom of the preheat tank, and a sufficient temperature differential exists to operate the collector. This behavior would not be predicted by a TRNSYS simulation because its collector models assume zero heat capacitance and the collector plate temperature is assumed equal to the ambient temperature with zero insolation. Thus, TRNSYS collector models have questionable validity for evacuated tube collectors adding energy to preheat tank. The net effect of this phenomena cannot be quantified at this time, however, because the controller for the preheat tank heat exchanger pump exhibited repeatability problems during December 1977.

Desirable Characteristics of a New Data Acquisition System

Two desirable characteristics of a future computer system are interrupt capability and an operating system which is multiprogrammed. Interrupts would be generated by important status changes such as the collector pump turning on. An executive program having the highest priority will interrogate the interrupts and determine the scan rate requirements for measuring the desired energy quantity. Scanning programs which read temperature differentials for energy calculations are assigned to the next priority level. For example, the collector pump turning on will initiate the scanning of the collector temperature differential at a suitable rate. When the collector pump turns off, scanning halts. Scanning of less critical values and performing logging tasks are assigned to the next lower priority levels. The remaining priority levels can be assigned to program maintenance and other less significant tasks. This kind of system will overcome the problems associated with fixed scan rates. The computer would also be accessible for performing other tasks. It would not be a dedicated device limited to slave-type operation.

ACKNOWLEDGMENTS

This work was partially supported by the United States Department of Energy under Contract No. EY-76-S-02-2577. This support is gratefully acknowledged.

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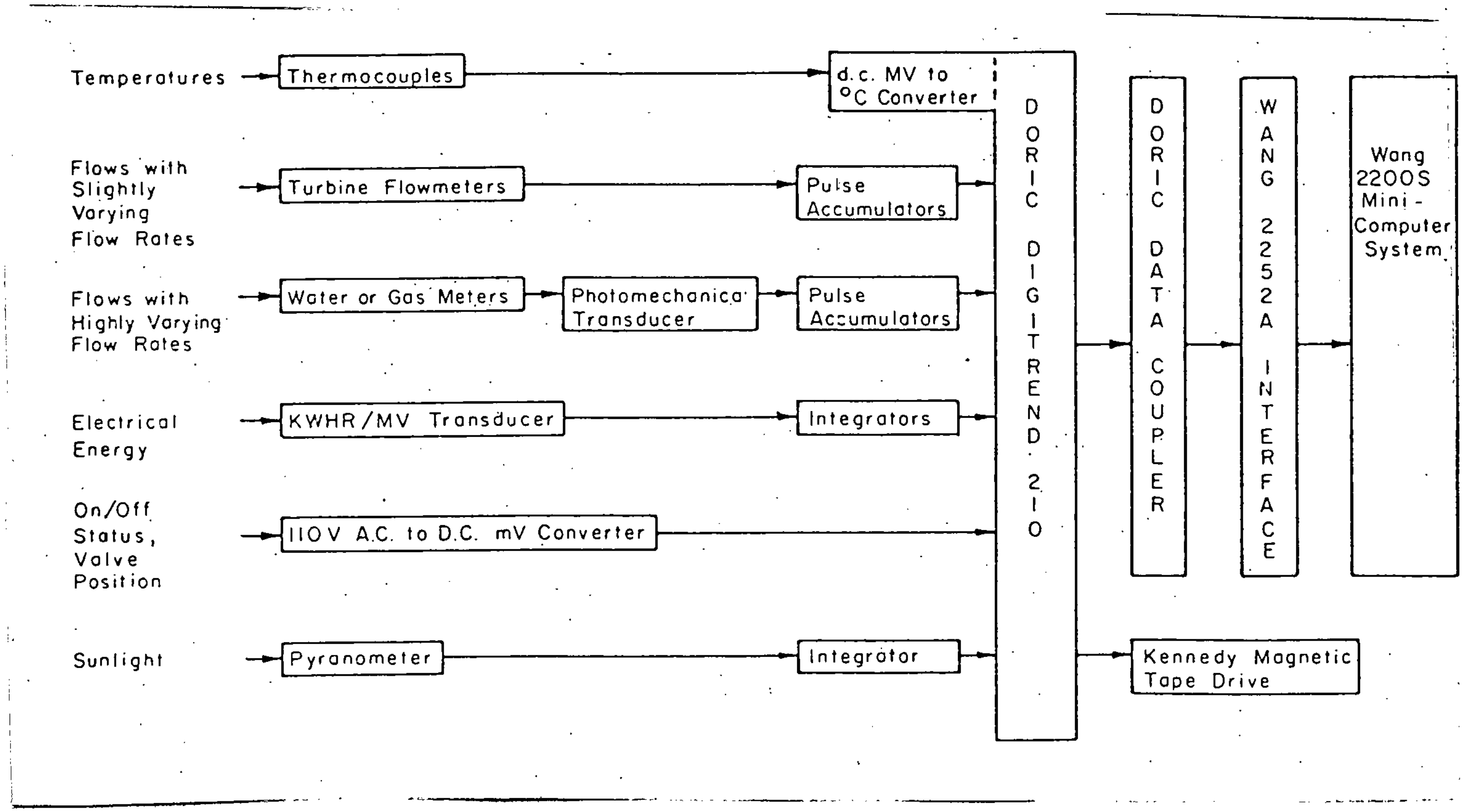

Figure 1. Solar House I Data Acquisition System

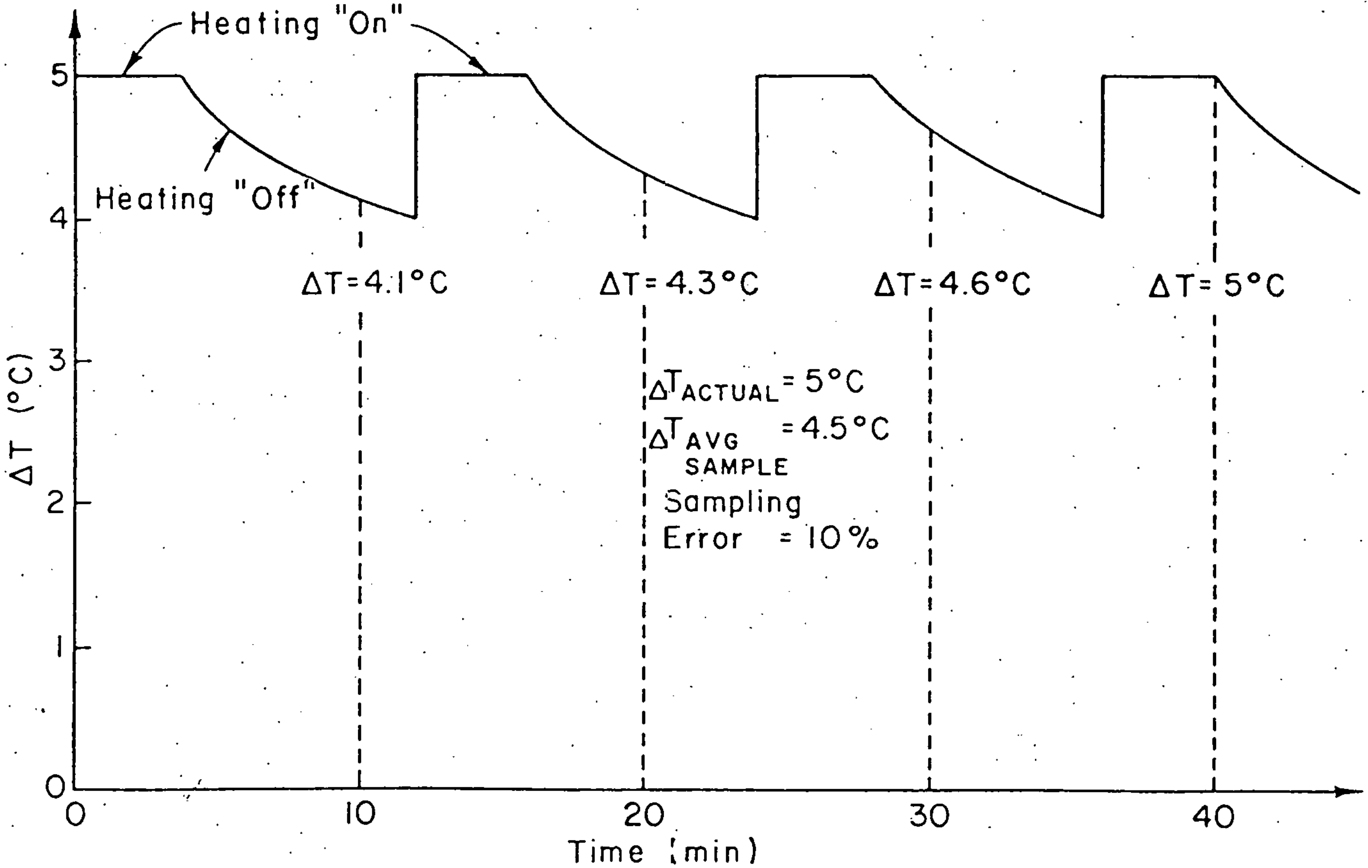

Figure 2. Measurement of Temperature Differential Across the Heating Coil when in the Solar Heating Mode.

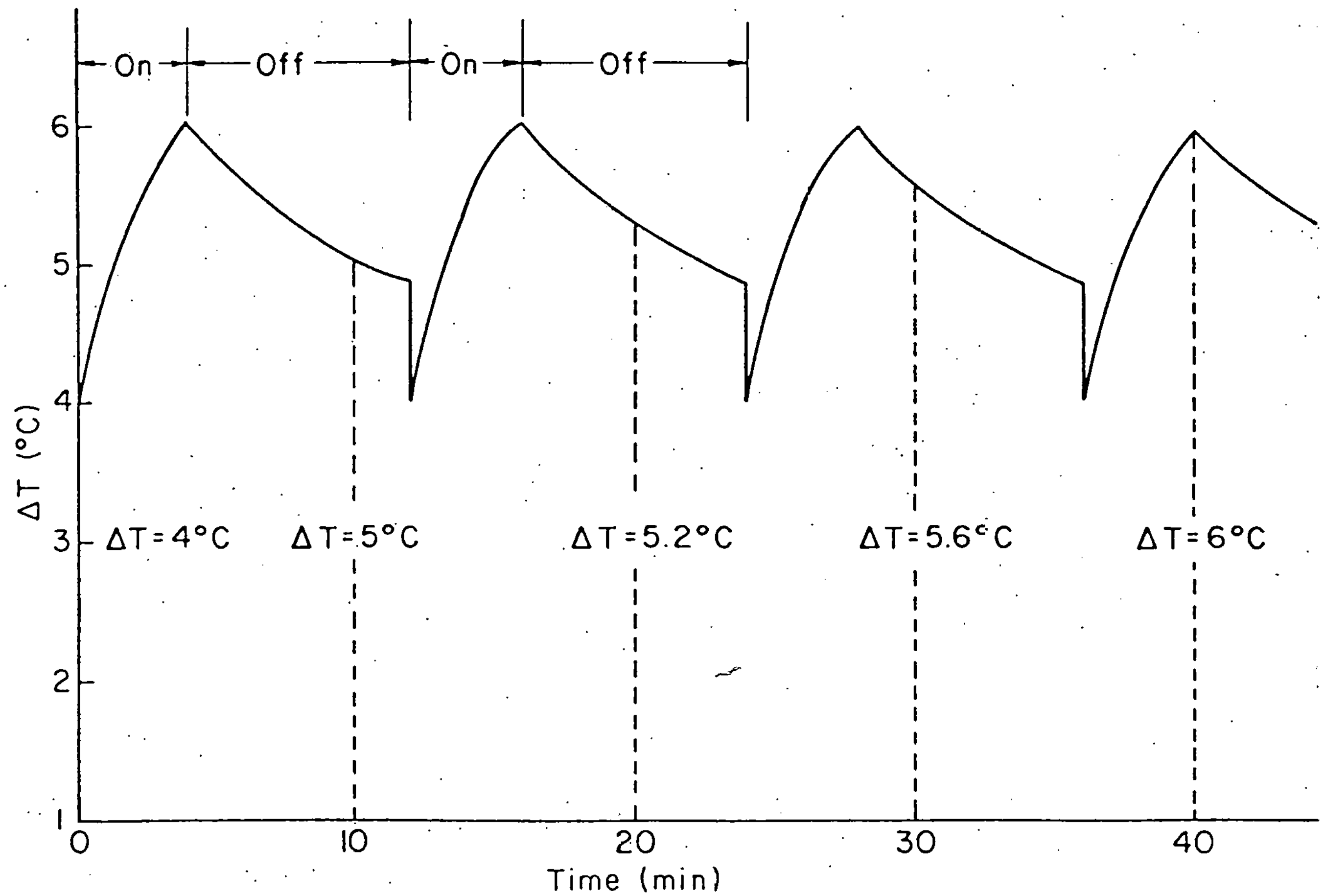

Figure 3. Measurement of Temperature Differential Across the Heating Coil when in the Auxiliary Heating Mode.

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MODERATE COST, CALCULATOR-BASED

DATA ACQUISITION FOR SOLAR HVAC SYSTEMS

J. I. Craig
Associate Professor
Aerospace Engineering

J. R. Williams
Associate Dean of
Engineering

Georgia Institute of Technology
Atlanta, GA 30332

ABSTRACT

The design and operating experiences with two instrumentation and data acquisition systems for large solar HVAC systems is presented. Many of the problems encountered with the first system and how they were resolved in the second are identified. The second system is built around an HP9825A calculator and is fully capable of unattended automatic operation along with interactive on-site display of selected data via readouts located in a solar system schematic panel. Prime objectives in the design were moderate cost and a minimum of software development along with a "friendly" operation interface. The system is operating in parallel with two IBM custom microprocessor-based systems and a comparison of these different approaches is made.

1. INTRODUCTION

As a part of a broad program of solar energy research at Georgia Tech, instrumentation and data acquisition systems for two large solar-powered heating and cooling systems have been designed. These systems have been installed in the Towns School and the Shenandoah Recreation Center, both of which employ approximately 1000 m^2 of high performance, liquid cooled, flat plate collectors driving large (100 ton) absorption chillers.

The Towns School instrumentation system was installed in late 1975 and was operated until early 1977 when the Georgia Tech data acquisition equipment was replaced with an IBM furnished "site data acquisition system" (SDAS). The system was based around a conventional 16 bit mini-computer with 8 k-words of memory and was equipped both with the means for local logging on paper tape or a teletype as well as with the capability to transmit data over a phone line. Approximately 60 channels of milli-volt level signals were handled and selected data were displayed on 6 4-digit LED readouts located in a schematic display board.

The Shenandoah Recreation Center instrumentation system was installed during the summer of 1977 and is currently operating with two IBM SDAS units and a Georgia Tech calculator based data acquisition system operating in parallel. The Georgia Tech system is based around a Hewlett Packard 9825A calculator with logging functions provided on a local miniature tape data cartridge. As with the Towns system, this system can handle approximately 60 channels of microvolt to volt level signals and in addition provides on-line data to 8 3-digit LED displays located in a schematic panel in the lobby.

In the following sections the design experiences with these two systems are described. Many of the problems encountered with the earlier system are noted and their resolution in the design of the second calculator-based system are discussed. Major emphasis is placed on the design of the calculator system and its particular advantages and flexibility for this type of application. Finally a comparison is made with the IBM furnished SDAS units since both systems have been replaced by or are operating in parallel with these units.

2. GENERAL SYSTEM REQUIREMENTS

Perhaps the greatest difficulty faced in trying to evaluate the overall energy utilization in a building data on the actual performance. The energy loss or gain mechanisms are quite complicated and it is often necessary to estimate performance based upon the behavior of a mathematical model. Performance evaluation requires that measurements be made of various thermodynamic and meteorological variables. The most critical parameters for a solar system include the following:

- Solar radiation incident on the collectors
- Heat contained in storage (hot/cold)
- Heat flow between components

Building heat gain or loss measurements would complete the definition of building energy utilization. However, because of the large surface areas involved and the number of different mechanisms in operation, precise estimation of this quantity is a most difficult task. The approach generally taken is to base estimation of the building performance on a dynamic energy balance between gains or losses and the known (measured) energy supplied.

A majority of the critical measurements involve accurately sensing heat flow in a transport medium. The parameters of interest are temperatures, differential temperatures, and mass flows of the water used as a transport medium. A thermodynamic schematic of a heating and cooling system is shown in Figure 1, which defines all major components and identifies the intercomponent heat flows. The schematic includes three switches which define major operating modes, for example:

- Heating from hot water storage
- Heating from boiler
- Cooling from absorption cooler fired from boiler or from hot water storage
- Cooling from chilled water storage

The principal variables that must be measured are also shown on the figure. Not shown are the atmospheric wind, temperature, and humidity, sensors as well as the electric power transducers (for the system pumps), which complete the measurement system.

Heat flow measurements can be made by sensing the mass flow of transport fluid between two components and the inlet-to-outlet temperature rise or fall of this fluid. Instantaneous rates are obtained as the product of these readings and the specific heat of the water; the heat quantity is determined by a numerical integration of the rate data. The computations must be corrected for storage action in those components where there is a substantial effect; for example, the difference between heat flow into and out of the storage tanks can be checked for compatibility with the gain or loss computed from the measured tank temperatures.

Platinum resistance temperature detectors (RTD's) are used for all temperature measurements and individual bridge circuits are provided for maximum flexibility. Critical differential temperature measurements such as those associated with intercomponent heat flow are made by using a direct differential bridge circuit that avoids the errors associated with differencing readings from separate bridges. Three- and four-wire sensor connections are used for maximum accuracy. Pipe-mounted sensors are installed in accordance with I.S.A. and N.B.S. recommendations.

Thermocouples, while considerably cheaper on a per sensor basis, were not used for two reasons: (1) accuracies obtainable in standard industrial/ commerical configurations are about ± 1.0°C over 0-100°C as compared to ± 0.5°C for the RTD units, and (2) signal conditioning is simpler and less costly for the resistance sensors. In the first case, while the absolute error for either type is generally acceptable when measuring single-point temperatures, it is much more critical when making the differential measurements required for calculation of heat flow between components (the accuracy may drop to around 10% when measuring a change of 10°C across a component). In the second case, the increased sensor cost for an RTD ($40 versus $20 for a comparable thermocouple unit) is offset by the requirement to use special leadwires and some type of reference point correction for the thermocouple sensors. It was found that the hardware, signal conditioning and installation costs for either type sensor averaged out about the same on a per channel basis. The increased performance and flexibility for use in direct differential measurements strongly favored use of the RTD's. It might be noted that linearized thermistor sensors, while similar in principal to RTD's generally provide accuracies comparable to thermocouples and cost about the same. In addition, a new two-terminal integrated circuit temperature sensor has recently become available (Analog Devices AD590) that is inexpensive ($2-10 each) and potentially capable of accuracies below 1°C and outputs of 100 mV/°C when used with a simple op amp conditioner. Further packaging development is needed since the unit is available only in a TO-52 transistor case at this time.

Operating experience to date after about 90 sensor-years service has been generally good with only two sensor failures - one due to element open circuit and one due to moisture contamination.

Mass flows or volumetric flow measurements can be made using several different types of sensors which typically can range in cost from several hundred to several thousands of dollars. For medium temperature liquid type solar systems the following types are usually appropriate:

- Head loss (orifice, venturi, nozzle, with d/p cell)
- Drag (turbine, impact)
- Vortex shedding
- Magnetic

While many other types have been made their designs are often not compatible with the size or cost requirements in a solar system. Impact type drag flowmeters (RAMAPO) and vortex shedding (Fischer & Porter) meters are used in the two systems. In the sizes used (2-4" dia.), the relative merits are:

TYPE	ADVANTAGE	DISADVANTAGE
Impact	Cost ($700) Accuracy (½% F.S.)	Square law response Limited dynamic range (10:1) Fragile
Vortex	Linear output Ruggedness Dynamic range (20:1) Accuracy (1% rdg)	Cost ($1500)

Overall, the two types compare favorably, with the advantage of cost to the impact units and the dynamic range/accuracy to the vortex units. In terms of operating experience to date, there have been no problems of any kind with the vortex units in over 2 years of operation. The impact units have been operating for about 3/4 year with two failures, one due to malfunction of the strain gage bridge used to sense drag and one due to damage to the impact target from debris in the flow.

The remaining sensors - meterological, solar radiation, electric power - are of a conventional nature and will not be discussed here. These outputs range from about 10 mV to 5Vdc, full scale.

3. EARLY SYSTEM DESIGN - TOWNS SCHOOL

General

The Towns School data acquisition subsystem was designed in 1975 and was based around a small minicomputer (HP2100A) with 8 k-words of 16 bit memory. Figure 2 shows the arrangements in schematic form. The Teletype is used to enter program directives locally as well as to provide detailed reports of system operation. For public display of operating parameters, six digital display units are also provided. Under program control up to 24 parameters of interest are displayed and periodically updated. For example, this might include certain temperatures and flow rates, solar heat conversion rate, percent solar augmentation, or building cooling load.

The 60 channel reed relay scanner (Vidar Autodata 616) and digital voltmeter (Fluke 8800A) operate under direct computer control. This configuration provides the capability to dynamically and selectively adjust sampling rates on individual channels to suit the measurement requirements. The basic sampling cycle is 10 min. This has proven to be extremely important for accurate measurement of radiation and intercomponent heat flows where a rate quantity must be integrated over a longer measurement interval. In these cases sampling cycles of 15-30 sec. were found to provide satisfactory results (e.g., component heat balances within a few percent). The system will handle up to 100 (60 installed) three-wire, guarded channels dc/ac voltage at up to 100 V with as low as 10μV resolution.

The RTD's are operated from simple passive wheatstone bridge circuits adjusted for a nominal 1mV/°F. The sensors (bridges) are continually powered to minimize transient thermal self-heating problems sometimes encountered when excitation is used only during measurement. The millivolt signals are handled directly by the system. Vortex flowmeters are used throughout and when powered by 24 Vdc, provide a 4-20mA output which is converted to a 40-200mV signal by means of a dropping resistor at the scanner. All other sensors provide from 10mV to 5Vdc signals which are handled directly by the scanner. The general philosophy has been to provide no active conditioning (amplification - which is susceptable to drift, etc.) and instead to rely on the performance of the small auto-ranging digital voltmeter.

The connection to the campus computer is made via a standard bit serial terminal interface connected to a Bell 103 series Modem on a private line. In this way the communication interface appears identical to a conventional terminal (Teletype, for example) and programming is correspondingly simplified. The relatively slow 300 baud service was selected for economy and reliability.

A crystal controlled time base (clock) is included as a computer interface circuit. The circuit provides periodic interrupts that are used by the program to maintain a software clock. This is used to time all measurements.

Finally, the software performs all scaling to calibration curves entered in the system so that data are recorded in engineering units. Provision is made to easily change the program mode of operation via switch inputs and error or quick-look data can be listed on the Teletype.

Costs

The system hardware costs - not including sensors - are given below. The computer cost has been corrected to a current (1978) value for comparable performance.

Computer (16 bit, 8 k-words) and interface boards	$7000
Paper tape reader	2600
Teletype terminal	1700
Voltmeter	1100
Scanner	2600
Modem	600
Display board	1400
Rack mounting	400
TOTAL	$17,400

Experience

The experience after system installation, over one year of operation, and analysis of data has yielded the following conclusions.

1. Software development involved considerable expense not shown above. In addition to the FORTRAN data acquisition programs, a memory-based operating system had to be developed. It is estimated that outright purchase of such a system would add about $1500 to the hardware cost.
2. The ability to selectively vary the channel sampling rates provided accurate rate measurements (radiation, heat flow) while allowing logging of all data at more convenient intervals of 10-15 minutes. It was not possible to carry out heat balance checks in the data unless the rate measurements were made at about 15-30 sec. intervals.
3. The ability to output data to the terminal or the display board (in engineering units) proved extremely useful for setting up or adjusting the solar system.
4. Under conditions of power failure, the software clock time was lost so that resynchronization of the data acquisition was needed. A hardware clock with battery backup would be more flexible.
5. The inability to accomodate local mass storage of data required frequent transfer of data over the phone line. If the central computer was shut down, the site system had to punch the 10 min. data on paper tape via the Teletypewriter. Assimilating this all into a single data base proved troublesome.
6. In order to obtain solar system heat balances to within a few percent, small corrections had to be made in the differential temperature measurements to account for leadwire resistance effects. Once established this was easily done in the software.
7. It was found to be somewhat difficult to determine which mode the system was in solely from the transducer outputs. As a result, switches were added to sense key control valve positions and relay this to the data system as an input voltage signal.

4. LOW-COST SYSTEM - SHENANDOAH

General

The Georgia Tech data acquisition system at Shenandoah is based around an HP9825A calculator rather than a minicomputer. The system is shown schematically in Figure 3. The analog "front end" of the system (signal conditioning, scanner, voltmeter) is identical to that used at Towns School except that a slightly more powerful voltmeter (1μV resolution, 20 chan./sec) is used. Impact type flowmeters which employ a strain gage bridge for sensing drag are used, and since this circuit closely resembles the bridge used for the RTD's, it has been possible to utilize the same type signal conditioning for each. As with the Towns School system, conventional electric power, meteorological, and radiometeric transducers are also used. A large system display board is provided and the data acquisition system furnishes 8 3-digit readouts of key operating parameters for engineering public use. In the Towns design the viewer could manually select one of 24 measurements to display, but for simplicity in the present design this was reduced to 8 fixed parameters, with little loss in utility.

Principal features of the calculator system are:

1. Fully automatic and unattended operation. The only operation intervention required is weekly change of the tape data cartridge.
2. Automatic power failure recovery with a battery backup for the system clock. On power-up the data acquisition program is reloaded from tape and data acquisition resumes.
3. Up to 12 days storage of data when logged at 15 min. intervals using the built-in tape data cartridge.
4. Interactive display of data and system function using the calculator live keyboard and display. In addition, 8 data values are displayed on LED readouts located in a system display panel.

The basic measurement is dc voltage at resolutions to 1μV and rates to 20 chan/sec. Sixty 3-wire channels are handled with capability for 100, and as with the Towns system variable scan rates can be programmed. Simple bridge circuits are used for flow and RTD measurements, and all offset correction and linearization are done in the calculator. The "live keyboard" feature of the 9825A provides a friendly interactive means for dynamically examining the data without affecting the acquisition functions.

Cost

The basic hardware cost, not including the sensors and cabling, are as follows:

Calculator (HP9825A, 8 k-words, interfaces)	$7500
Voltmeter (HP3455)	2900
Acurex (616)	2400
Clock (HP59309)	1100
Display board	1100
Rack mounting	200
TOTAL	$15,200

It is apparent that while originally (1975 dollars) the minicomputer system was considerably more costly, the two approaches are currently more nearly equal in hardware costs.

Experience

The single major advantage of the calculator system is the extreme ease of software development for relatively simple tasks like the present. In contrast to the minicomputer system, no operating system needed to be written and only applications programs were required. Furthermore, the built-in calculator functions allow simple on-site alteration of programs when required and minimize the time spent debugging since all aids are readily available. Programs can be distributed on tape in either source form or in object code, the latter so that no alterations can be made to the software locally. When realistically accounted for, the software cost differential increases the relative advantage of the calculator system to about $3,700 or 22%. In all respects the calculator is fully able to equal the minicomputer performance. While perhaps not of major importance, it was found that interface design work - particularly for the display board - was quite easy, and in fact, was completed by non-electronics level personnel.

As can be seen above, all of the major problems with the early system were resolved in the calculator system. The only difference in capability involves the omission of a telephone data link and this was done primarily as a cost savings. Georgia Tech personnel routinely visit the building for inspections and simply replace filled data cartridges. If required, an RS-232C serial interface can be added to the calculator and with a suitable telephone modem will provide auto-answering and dumping of data to a remote facility. In marked contrast to the minicomputer system, there have been a minimum of start-up problems. Because of the compact size and interactive calculator functions, it has been relatively simple to troubleshoot problems in the field.

Finally, the present system could be further reduced in cost in future versions in several ways. First, a smaller calculator (HP9815A) could be used with no loss in performance but with some loss of programming flexibility. Basically the 9825A provides excess capability, even in its minimum configuration. Secondly, a smaller voltmeter could be used with only minor loss of sampling speed. Together, these modifications would reduce the cost by about $4,500 and would yield a system hardware cost of under $12,000 in single unit quantities.

5. COMPARISON TO IBM SYSTEMS

The calculator-based system is presently connected in parallel with two IBM-furnished microprocessor based system. Both are relatively compact and require a minimum of special connections or sensor wiring. However, while up to 100 channels of voltage, current, resistance, or thermocouple inputs can be accommodated by the calculator system, a single microprocessor system can only handle 48 channels and two complete systems (including separate phone lines) are required at Shenandoah. Both can handle the acquisition tasks routinely although the calculator system can be much more readily programmed with its built-in keyboard and can easily furnish data for display purposes. While the calculator programming language is easy to learn, programs can be routinely distributed on small tape data cartridges. A cost comparison is difficult to make since prices for the IBM hardware are not available. However, the present calculator system, including software and all required hardware, can be assembled from commercial instruments for under $15,000 and with a somewhat less powerful but still adequate calculator for under $12,000 in single quantities. While these values are probably

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comparable to a single microprocessor system, two of the latter are required. In this case the mass production economies of the calculator system outweight much of the microprocessor appeal. This is further emphasized when service is considered since maintenance for the calculator is readily available on a contract basis nationwide.

ACKNOWLEDGEMENT

The systems described here were designed and constructed under grants from the Department of Energy. Their support for the work is gratefully acknowledged.

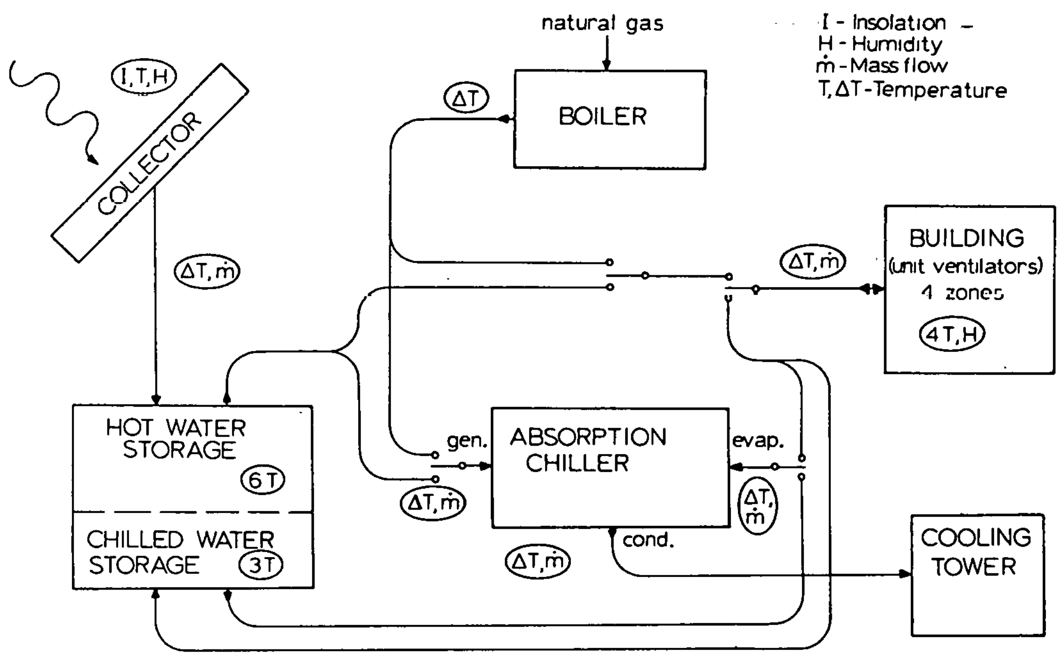

Figure I. Thermodynamic Schematic Showing Performance Measurements.

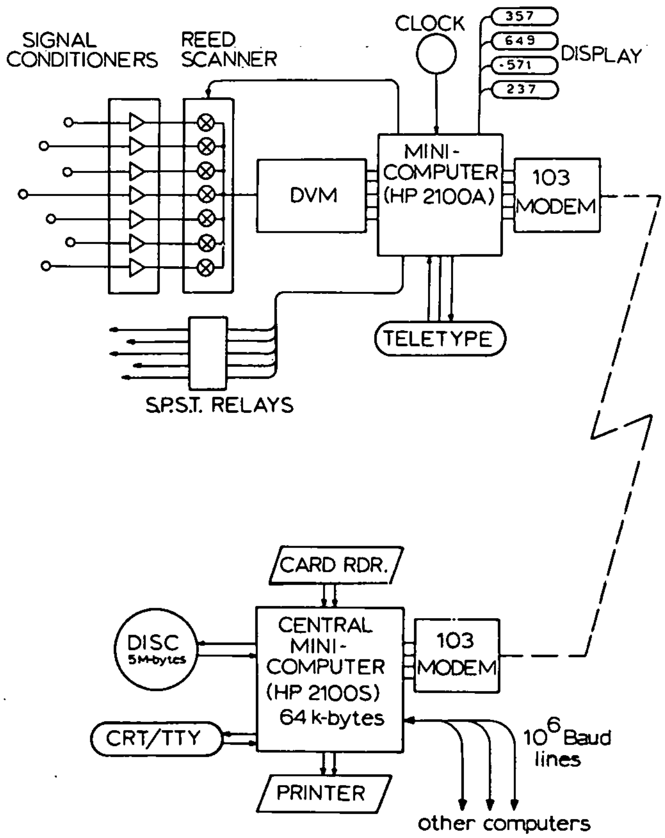

Figure 2. Towns School Data Acquisition System Schematic.

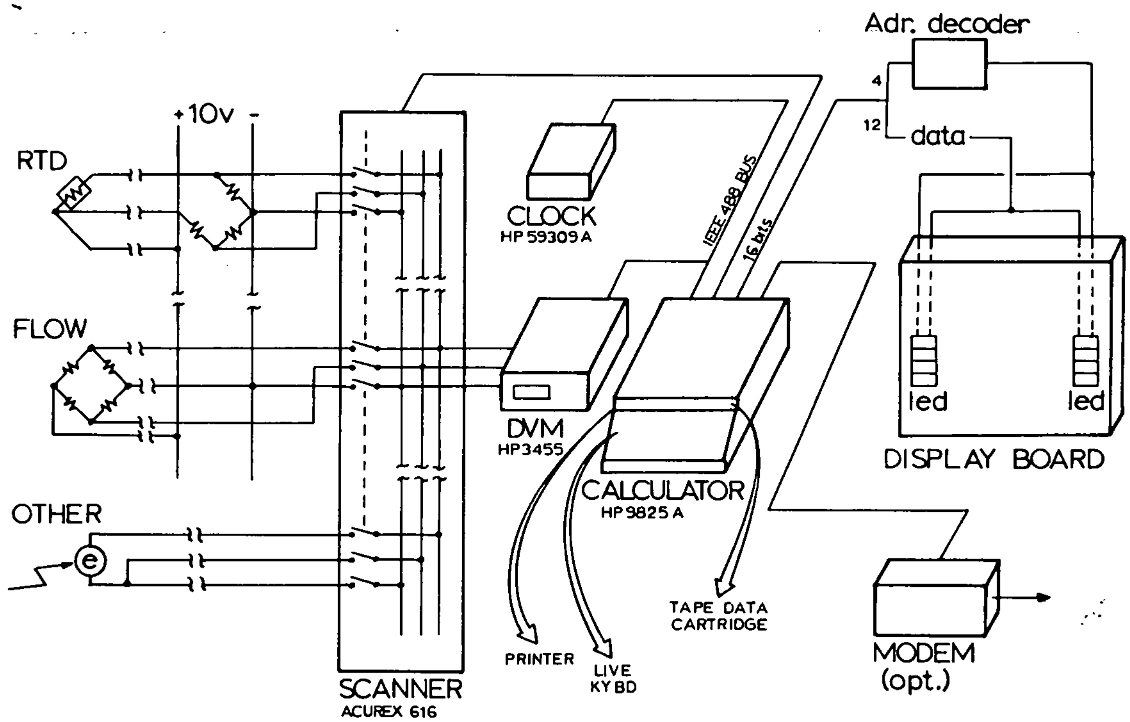

Figure 3. Calculator-Based Data Acquisition System at the Shenandoah Solar Recreation Center.

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ABSTRACT

Use of an Automated, Centrally-Controlled Data Acquisition System for Monitoring Multiple Remote Sites

by

M. W. Wildin, Albert Fong and James Nakos*
Department of Mechanical Engineering
The University of New Mexico
Albuquerque, New Mexico 87131

A variety of approaches may be taken to obtain data from multiple remote sites continuously. One type of approach is to place locally-controlled automated data sampling and recording equipment at each remote site and to periodically visit the site or establish telephone communication with it, to retrieve the stored data. An alternate approach is to place sampling and digitizing equipment at each remote site and to command it from an automated central station via a telephone connection, to sample, digitize and transmit the data. The data is stored, displayed and reduced at the central station. Both of these approaches has unique advantages, disadvantages and costs.

This paper describes the factors considered in reaching a decision to select a system representing the second approach, using a central station and dial-up telephone connections to three remote sites in Albuquerque, New Mexico. The favorable and unfavorable features of both approaches are identified, and their implications for continuity and reliability of data, and for costs and manpower requirements, are discussed. Reasons for selection of the second approach over the first are stated, and the system purchased to implement this approach is briefly described. Instrumentation and data acquisition, checking and validation are discussed. Subsequent experience in the installation and operation of this system is summarized. This experience illustrates both the strengths and weaknesses of the approach selected.

*James Nakos is currently associated with Sandia Laboratories, Albuquerque, New Mexico 87115.

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by

M. W. Wildin, Albert Fong, and James Nakos[1]
Department of Mechanical Engineering
The University of New Mexico
Albuquerque, New Mexico 87131

INTRODUCTION

The selection of a data acquisition system for monitoring performance of equipment at multiple remote sites is not a simple matter. It is necessary to balance considerations of adequacy, continuity, and reliability of the data obtained against the cost, time, and manpower required to obtain, reduce, and analyze the data. In the case of occupied buildings, there is also the constraint that the normal activities of the occupants not be disrupted excessively. Selection of a system depends upon the objectives to be achieved, the methods used to achieve the objectives, and the constraints within which one must operate, including available funds and manpower.

It was our objective to monitor and analyze the performance of three heat pump space conditioning systems installed in widely-separated single-family residences located in Albuquerque, New Mexico. One of the systems was a solar-boosted water-to-air heat pump and the other two were conventional air-to-air heat pumps. It was decided early in the planning stage that only the minimum number of data channels necessary to analyze and interpret the performance of the heat pump systems and to monitor the behavior of the collector and storage elements of the solar-boosted system would be observed, and only the items of data and results essential to these purposes would be recorded. This decision was based on consideration of data handling time and storage capacity requirements and of system capital and operating costs. However, this decision was tempered by the need we perceived, based on previous experience, to observe redundant data to help insure acquisition of reliable data. Thus redundant temperature sensors were used, so that drift or failure of critical temperature sensors could be readily detected.

To enhance the reliability of the data obtained, our philosophy of data acquisition dictated that in addition to redundancy, provision be made for simultaneous measurement of related variables, to permit validating the data by computation and comparison of related instantaneous energy flow rates and by comparison with manufacturer's data. Provision to output some intermediate results, in addition to final results, was also considered desirable, to aid in assessment of the validity of the large quantities of data obtained from continuous monitoring. Experience indicated that if provision is not made to output some easily interpreted results on a regular basis, the risk of "drowning" in a "sea" of unassessed data is heightened.

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[1] James Nakos is currently associated with Sandia Laboratories, Albuquerque, New Mexico 87115.

The remainder of this paper describes the types, advantages and disadvantages of data acquisition systems we considered, the selection we made, the measurements performed, the operating and data handling strategies employed, and our operating experience to date.

DATA ACQUISITION SYSTEM SELECTION AND USE

Because of the large amounts of data to be handled continuously, only automated data acquisition systems were considered. Three types of systems were analyzed. One type involves automatic sampling and recording of data at each site. Each channel of data may be recorded on a separate channel, or the inputs may be automatically scanned, digitized and recorded sequentially on a single channel. The data are retrieved by visiting the site and retrieving a storage medium, or by establishing telephone contact with it and commanding that the data be recalled from storage and transmitted. An advantage of this system is its on-site control, so that data losses normally occur only when a power failure occurs at the site. This tends to enhance the continuity of the data. However, the data can be examined only when they are retrieved, and this normally occurs at periods ranging from once a day to once a month. An unacceptable drift or failure of a sensor or a malfunction of an item of equipment would not normally be detected until after the data are retrieved and examined, which could be one or more days after the event. More important than the delay itself is the fact that in diagnosing problems with the data acquisition or heating and cooling systems, the utility of the data decreases rapidly with time. If the data cannot be examined within a relatively short period, its utility for diagnostic purposes is low. And the importance of rapid diagnosis and correction of a problem in a system that should operate continuously cannot be overemphasized.

A second type of system considered uses a controller at a central site to establish telephone communication regularly and automatically with each remote site and to command equipment at the site to scan the input channels and to digitize and transmit data. This system has the advantage of permitting immediate access to data from each site at a single, central location at frequent intervals. This facilitates diagnosis of problems and permits frequent inspection of data sampled at regular intervals, which helps increase the utility of the data and assists in deducing and monitoring the operating pattern of the system, thus enhancing acquisition of valid data. This type of system is more susceptible to breaks in the data, since operation of the entire system depends on the central controller. When the controller fails or is shut down for service, the entire system is inoperative. Many systems of this type provide for automatic restart in the event of a power failure, which helps minimize data losses; but the problem of data losses during failure, servicing or reprogramming of the central controller cannot be avoided unless a duplicate controller is used.

A third type of system is, in reality, a combination of the previous two types. It utilizes locally-controlled sampling and storage to help minimize data losses, but it permits intervention by a controller at a central site. In the event of intervention, data are sampled, digitized and transmitted to the central site, as well as recorded locally. Also, data may be called from storage and transmitted to the central site. This type of system represents "the best of both worlds," in that both maximum continuity of recorded data and immediate access to the data are possible. But it is likely to be the most expensive system.

The systems given serious consideration in our selection process were of the first two types. The third type was not given serious consideration after its cost had been estimated, since it appeared to be beyond our means. One of the on-site recording systems we considered employs four-channel cassette tape recorder units manufactured by Westinghouse Electric. Each unit records a time base on one channel and thus permits recording of data on the other three channels. Normally, one recording channel is used for each input channel. It is possible to place several channels of data on one recorder channel, but non-commercial recording and translating equipment must be used to accomplish this (1). The data are recorded on magnetic tape in the form of pulses, the pulse rate corresponding to the level of an analog signal or to the rate of generation of square wave pulses from an instrument such as a watt-hour meter. Thus, devices must be used to convert analog signals to pulse rates and to produce pulses related to the rotation of a meter. Specialized, automated equipment must be used to translate the recorded data into digital form for handling, reduction and output in a more easily-interpreted form. Although the tape cassettes have capacity for more than a month of data, they may be retrieved and translated as often as one desires. It is common among electric utilities, who are heavy users of this type of recorder, to exchange the tapes once a month, at which time the meters are visually read and the readings recorded manually by a meter-reader. Many utility companies own the translation equipment, and this was the case with Public Service Company of New Mexico, which offered to provide us with translation service for our project.

Although we had initially planned to use this type of system, identification of some disadvantages of this system and difficulty in obtaining detailed information on it caused us to re-examine our thinking. The advantages of this type of system in providing continuous data were recognized, particularly if one purchases a battery carry-over option offered by the manufacturer. However, it is necessary to visit a site to ascertain the status of the heating and cooling and recording equipment, which we consider a major disadvantage. When at the site, it would be relatively difficult to diagnose problems, since data are output locally in terms of pulse counts for each channel. And a comprehensive output of data could be obtained only after the data were from four to eight weeks old, at best. These disadvantages together with doubts about the utility of this type of recording equipment for future uses we could foresee, led us to consider other types of systems.

An alternative on-site type of recording system was also considered. It was essentially a data logger, which samples and digitizes data at regular, periodic intervals. The digitized data are usually printed on a "grocery tape" and may be output via an RS 232 interface to a magnetic tape recorder or a paper tape punch. This type of system greatly facilitates diagnostic work by providing regular periodic printed output of data or instantaneous sampling and output of data upon command of the operator. However, the equipment would have to be duplicated at each of our sites, since they were much too far apart to hard-wire more than one site to a single data logger. Also, separate recording equipment would have been necessary at each site. And the data tapes would have to be retrieved by site visits or by using sufficiently sophisticated and expensive recorders to permit automated retrieval of the data via the telephone system. This type of system was rejected because the capital cost associated with duplicating the equipment at each of the three sites appeared to be at least as high as that of a centrally-controlled system and its use appeared to be much less convenient.

Two different makes of centrally-controlled systems were considered. Both offered the advantage of immediate access at a single convenient location to data recorded at regular intervals from each remote site, plus the capability to sample and record data from a given remote site as frequently as desired through minor changes in programming, or "software" of the central controller. Due to the minicomputer nature of the controllers, both systems also offered great flexibility in controlling acquisition of data and great power and latitude in data reduction, calculation of results and output of data and results.

Both systems offered the capability to contact and communicate with data acquisition equipment at a number of remote sites through interfaces with the telephone system. Use of the telephone system offers flexibility in locating the sites to be monitored, but it introduces an independent element into the system and it makes it more complex and expensive. We concluded that in our case the advantages of using the telephone system would probably far out weigh the disadvantages. Both makes of data acquisition systems suffered from the inherent disadvantage of centrally-controlled systems identified previously; namely, the entire system is inoperative when the central controller is disabled. For about the same initial cost, one system offered a data acquisition capability that appeared more immediately useful, but it had less capability for interfacing with other computational equipment. It also offered less potential for future expansion of its computational and display capability. This system was selected, despite its disadvantages, due to our immediate need for data acquisition capability, the potential for relative ease in future use by students and the lack of a clear need for much larger computation and display capability. Also, it was decided that in any event the University's central computer system would be used to manipulate and display our data and results, to reduce initial costs; so this system could be used to supplement our computational capability if that became desirable.

The central controller of the system selected is a Hewlett-Packard 9825A "Computing Calculator" or minicomputer with 15,036 bytes of core storage and 250,000 bytes of storage per tape cassette (2). Other items of equipment in the system at the central station are various read-only memories and interfaces attached to the minicomputer, a digital clock, a common carrier interface and telephone equipment, including a modem, a data set and an autodialer. (See Figure 1.) At each site is a unit termed a multiprogrammer, two interfaces between this unit and the telephone system, a modem and data set. Also at each site is a shop-built item of equipment, including a power supply for the temperature sensors and some signal conditioners. The multiprogrammer receives, scans and digitizes inputs in preparation for their transmission to the central controller.

The minicomputer initiates calls via the autodailer to each of the remote sites at a predetermined interval and it also traps errors in the calling routine. If adequate communication is not established, the call is abandoned and a new call initiated. When communication is established, the minicomputer commands the multiprogrammer to scan the inputs to it in any desired order, to digitize the data and to transmit them to the central station. In the command and data transmission processes, a check is performed on each item of information by means of a process termed handshaking, which echoes back to the sender the signal received by the receiver. The minicomputer places the data in core storage along with the time the call was initiated and initiates a call to the next site in the polling sequence. After all the sites have been polled, intermediate results in the form of data in engineering units and instantaneous and integrated energy flow rates are calculated and stored in core. Then the minicomputer continues to sample the digital clock to determine when the next polling sequence begins. Initially, a five minute interval was used between polls; but this was increased to six minutes due to frequent inability to complete the sequence within five minutes because of the necessity to reinitiate calls several times. This time interval could be reduced by eliminating the handshaking procedure. After every third polling sequence, further operations are performed on the data to calculate average room and outdoor temperature, total electrical energy use and total thermal energy flow. These results are stored in core, along with the instantaneous energy flow rates, to provide a picture of the operating pattern of the equipment and of indoor and outdoor conditions. At the end of every 12 polls the results and data are transferred to magnetic tape storage. Complete files are formed at the end of 60 or 72 minutes of data collection. The tape cassettes are capable of storing 360 hours of continuous data, although usually data is transferred to alternate storage at shorter intervals.

For normal operation, the only information output on the grocery tape printer of the minicomputer is the date and time in hours, minutes, and seconds at which a polling sequence was initiated, the sites called, the integrated thermal energy flow to the house at the site since the last previous call and the elapsed time since that call. However, when desired, one can also output the data received from each channel on each call to any or all of the sites by calling out a special code by pressing a few keys on the minicomputer keyboard. This type of intervention can be performed without interrupting normal operation or data collection. This feature of the machine and the programming has been found to be of great assistance in checking out the system and in diagnosing problems. A more complete and easily-interpreted display of data and results can be obtained by transferring the data through an RS-232C interface to a Texas Instruments Silent 700 terminal with dual tape cassette storage. This operation requires interruption of data collection. It is subsequently transferred to disk or magnetic tape storage at the central UNM computer facility, where it can be output on paper or it can be plotted by means of a Hewlett-Packard plotter at the location of the minicomputer, under control of an operator, by means of the TI terminal.

INSTRUMENTATION USED AND DATA OBTAINED

At the solar-boosted heat pump installation, data were obtained on electrical energy use by four subsystems: 1) the heat pump compressor, 2) the blower, 3) the pumps (2 each) which circulated water from storage to the heat pump or the hydronic heating coil located downstream from the heat pump discharge and 4) the auxiliary boiler (for heating) or the evaporative cooler (for cooling). (See Figure 2.) Water system temperatures were measured at mid-height in the storage tank, at the collector return to storage, in the system supply line upstream of the auxiliary boiler, at the inlet of the heat pump or hydronic coil and in the return line from the heat pump or hydronic coil. Indoor air temperature was measured downstream of the return air register and outdoor dry bulb temperature was measured close to the evaporative cooling tower inlet. Both of the air temperature measurements were made with duplicate sensors, to help insure valid data, although these measurements were used for monitoring rather than for energy flow rate calculations. It would have been desirable to measure the average air temperature at the inlet and outlet of the heat pump, to permit direct calculation of energy flow rate to the air stream, but this was found to be impossible, due to the configuration of the supply ducts. Hence, heat flow rate to or from the house was calculated from heat flow rate from or to the water stream, combined appropriately with the electrical power to the compressor and blower. Solar radiation incident on the collectors was measured at one location in the plane of the collectors. It was necessary to amplify the signal to a level appropriate for input to the data acquisition system. All the above measurements and the power supply voltage for the thermistors were sampled and recorded automatically. In addition, water flow rates from the tank and through the collectors and the heat pump or hydronic coil were measured manually and periodically, using Annubar flow meters.

At the conventional air-to-air heat pump sites, the electrical energy used by the following components was measured and recorded: 1) heat pump compressor, sump heater, controls and outdoor fan, for heating operation, 2) compressor, controls and fan for cooling operation, 3) indoor fan and 4) supplementary resistance heaters. (See Figure 3.) Average indoor air supply and return temperatures were measured at the outlet and inlet, respectively, of the heat pump using air samplers. These measurements were made using duplicate sensors, as was the outdoor dry bulb temperature, to provide redundant measurements of these important quantities to help insure acquisition of valid data. An effort was made to measure indoor return air dew point, but this was abandoned, due to continual problems with contamination of the sensing element. The thermistor power supply voltage was also measured at each of these sites.

Since data are sampled periodically at intervals of several minutes and all readings are instantaneous values, it is necessary to integrate between successive samples to evaluate total thermal energy flow during the intervals between samples. For the solar-boosted heat pump installation, this was done by applying the trapezoidal rule to the temperature difference across the hydronic heating coil or the water-to-refrigerant coil in the water-to-air heat pump. Such an integration technique was considered sufficiently accurate, since the heat pump and hydronic coil tended to operate continuously for relatively long periods. On the other hand, the air-to-air heat pumps cycle on and off frequently, so it was necessary to account for the transient nature of the heat flow from the heat pump after start-up. This was accomplished by fitting an exponential curve to the instantaneous heat flow rates calculated at two successive samples. However, when these heat flow rates differ by no more than ten percent, the trapezoidal rule is used.

CHECKING AND VALIDATION OF DATA

Use is made of redundant temperature sensors, or sensors whose readings are redundant under certain operating conditions, to perform continual checks on most of the temperature data. These checks are particularly helpful, because they can be performed frequently and conveniently at the central station.

Another check which could be performed easily at the central station was to compare experimental values for instantaneous heat flow rate to or from the heat pumps and electrical power use by them, with the manufacturer's data for the same air or water temperatures. We also compared visual observations of rotations of the watt-hour meter disks with data obtained by means of the automated data acquisition system. These observations were motivated by a need to resolve a problem encountered early with invalid electrical energy measurements. The problem was traced to noise in the square wave signals, and it was eliminated by using pulse shaper circuits.

OPERATING EXPERIENCE

Our experience in operating the system for over seven months illustrates both the advantages and disadvantages of the data acquisition system we selected. The system provides useful, easily-interpreted output at a single, convenient location. By pressing a few keys, all the data obtained from current polls of the three sites can be observed on the grocery tape output. Since the nearest site is about six miles and a minimum of 20 minutes' driving time from our laboratory, the savings in time and energy are significant. But the most important feature is that the convenient availability of data causes greater and more frequent attention to it. This enhances the value of the data and helps to insure acquisition of valid data. When trouble-shooting visits to a site are necessary, the data set at the site facilitates voice communication. This permits quick feed-back on the effects of steps taken to correct problems.

Although the system works very well when it is functioning properly, serious problems with unscheduled shut-down of the computing calculator have occurred. We were able to avert most of these problems through software changes. However, occasional problems in obtaining an acceptable telephone connection induced us to increase the interval between successive rounds of polling from 5 to 6 minutes. Also, we encountered a problem which "locked up" the communication lines between the items of equipment at the central station, which condition could be cleared only by manual re-start of the minicomputer. This problem occurred randomly in time, so it required constant surveillance of the central station. As a result, very little valid data were collected during the cooling season and the early portion of the heating season. After several weeks of intensive work on the problem and when we were about ready to take major steps which were expected to eliminate it, its frequency of occurrence dropped off sharply. Hence the effort to diagnose its cause was dropped, temporarily, since about two months later the frequency increased again. By trading out items of equipment at the central station, the problem was eventually traced to a faulty common carrier interface unit. Solution of this problem required sustained, intensive effort on the part of project personnel, supported by representatives of the data acquisition system manufacturer and the telephone company.

CONCLUSION

The selection of an automated data acquisition system for monitoring multiple remote sites requires consideration of at least the factors of utility and validity of the data obtained, cost and personnel requirements. A system which permits easy observation of data at a single central location by personnel knowledgeable about the system being monitored, enhances the probability of acquiring valid data. The initial and operating cost of such a system may be higher than on-site data acquisition equipment. But this is not necessarily the case, since equipment with comparable capability at each site may be at least as expensive initially; and it requires much more frequent visits to the remote sites. The most important factors differentiating between the two types of systems are the ease with which recent data may be observed and the continuity of the data obtained. Experience gained with a centrally-controlled system illustrates its advantages and disadvantages. When the system operates properly it produces data which are easy to observe and check. But when the central system does not operate properly, little useful data may be obtained.

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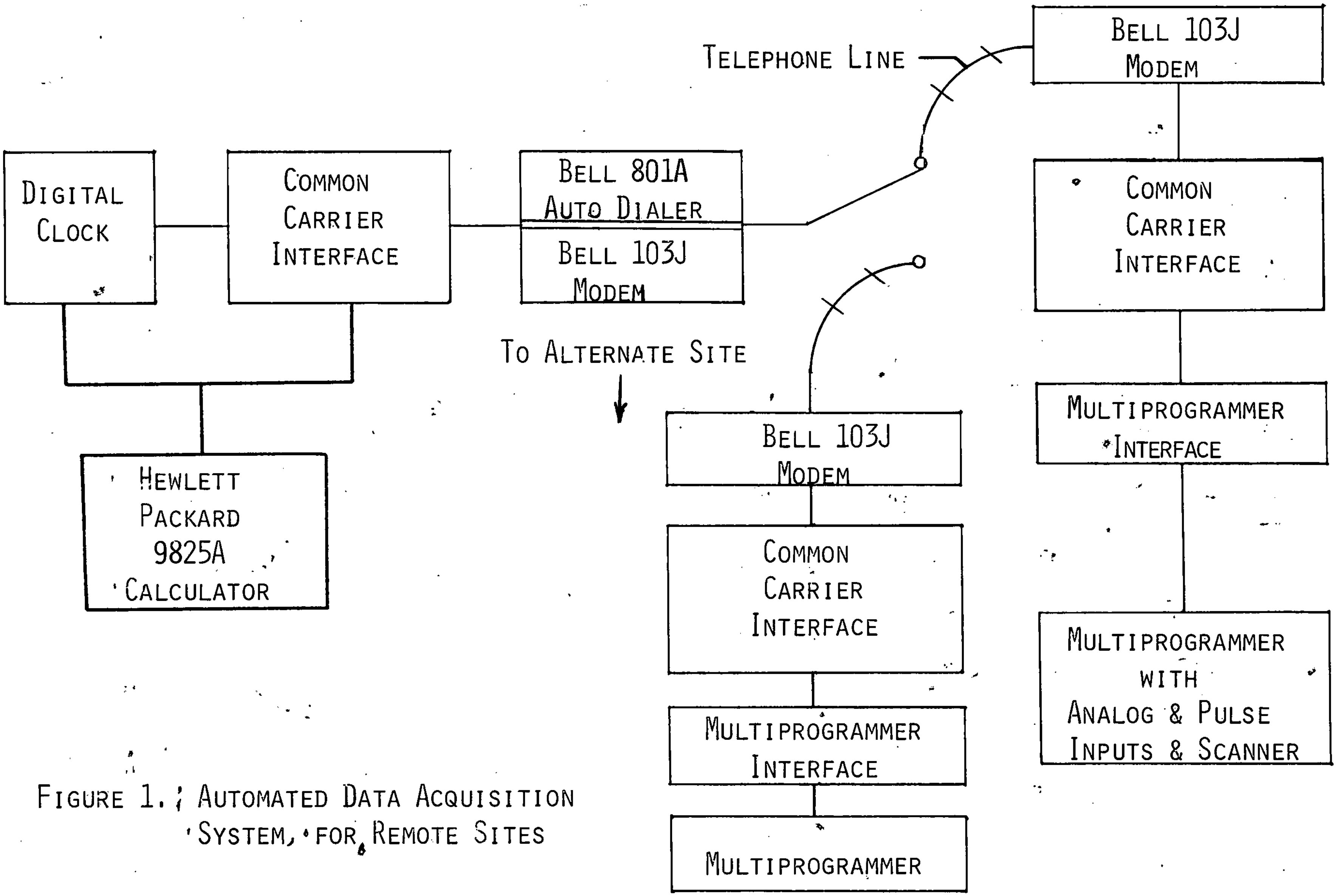

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Figure 1. Automated Data Acquisition System for Remote Sites

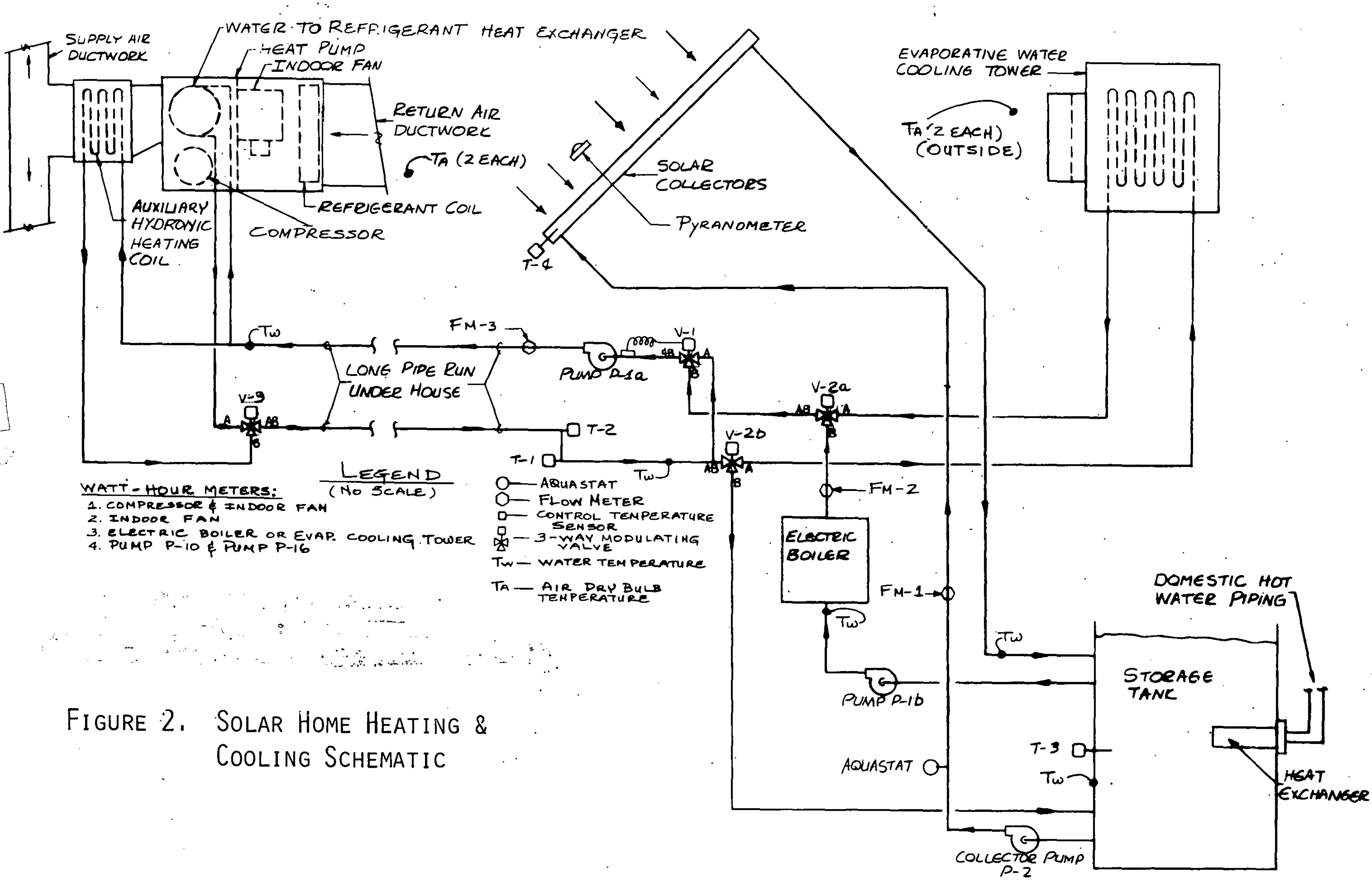

FIGURE 2. SOLAR HOME HEATING & COOLING SCHEMATIC

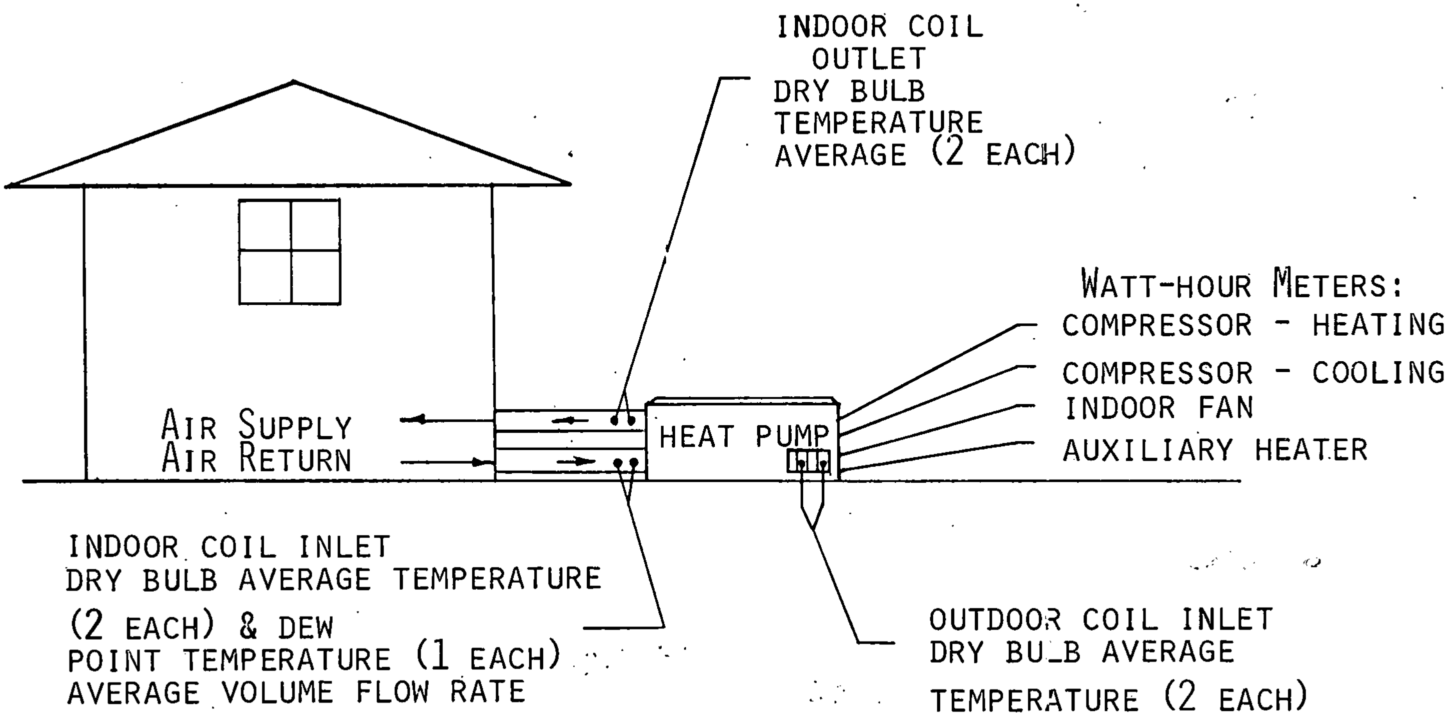

FIGURE 3. DATA ITEMS FOR CONVENTIONAL HEAT PUMP INSTALLATION

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THE ADVANTAGES OF A REAL TIME DATA ACQUISITION, MONITORING, AND ANALYSIS SYSTEM FOR A RESTAURANT EQUIPPED FOR ENERGY CONSERVATION, HEAT RECLAMATION, AND SOLAR ENERGY

by

Donald L. McClenahan
Senior Research Associate
Project Manager
Atmospheric Sciences Research Center
The University at Albany
Albany, New York 12222

Abstract

A Data Acquisition System (DAS) to monitor, analyze and record data at an ERDA funded energy conservation and heat reclamation system incorporated into the design of a national chain restaurant is described. The several advantages and flexibility of an on-line real time DAS is described.

During the Winter of 1975 and Spring of 1976, a Jolly Tiger Restaurant of the Sambo's Restaurants, Inc., of Santa Barbara, California, was constructed in Colonie, New York, near the Capitol, Albany. This restaurant incorporated a number of energy conservation and heat reclamation features engineered by Elster's, Inc., of Hollywood, California.

A data acquisition, monitoring and analysis system was designed by the staff of the Atmospheric Sciences Research Center (ASRC) of the State University of New York at Albany and the Science and Technology Staff of the New York State Assembly. Funding for both the energy conservation system hardware and for the DAS was provided by the United States Energy Research and Development Administration (ERDA), now the Department of Energy, under Contract No. E(04-3)-1177 to the prime contractor, Sambo's, Inc., and No. E(04-1)-1304 to ASRC.

During the design phases, personnel of Sambo's, Elster's, ASRC and the New York State Assembly Scientific staff consulted to determine the number, kind and location of sensors to be installed, in order to make a thorough analysis and later a return on investment (ROI) of the eight energy conservation and heat reclamation subsystems. The engineering firm of William S. Fleming Associates of Manlius, New York, who will be responsible for the economic and ROI analysis, assisted.

Early in the design phase, a decision had to be made regarding the DAS. Two options were considered. One would be to monitor and store all data from a data logger on magnetic tape, to be reduced and analyzed later on the UNIVAC 1110 computer at the University at Albany. Second would be to monitor all data points, reduce, analyze, print out and store data on site on a real time basis.

It was determined that in order to make a thorough analysis of the system approximately 220 data points, scanned each two minutes, would be required. Further it would be advantageous to have the flexibility and convenience of modifying software on site. Having the ability to see the effect immediately of changes in the operating modes of the energy conservation equipment would be a real advantage.

The cost of the two alternatives was approximately the same. The first option would have had some additional computer time sharing costs. On this basis, the choice was made to develop the project around a real time Data Acquisition System.

Many systems, and components which might be interfaced to provide a DAS, were evaluated. The decision was made to install the Hewlett-Packard 3050 System. The selection was made on the basis of cost, flexibility, optional equipment interfacing capability and the computing-controlling feature of the HP 9825A. The cost of this DAS was below $200 per channel, a very reasonable price for such a flexible and powerful system.

With over a year of operating experience, and with minimum maintenance of the HP system and other advantages not foreseen at the start of the project, in hindsight, the right decision was made.

The ability to develop simple software routines to allow equipment maintenance personnel to make spot analysis of the several subsystems is a time-saving capability. Checks of the several operating modes of the equipment, printing out temperatures and flow rates, can be made quickly between routine scans without interrupting normal data acquisition. This was one advantage not anticipated during the design stages.

The energy conservation and heat reclamation subsystems to be monitored are listed:

1. AC1 - Coffee Shop Heat Pump - Air Conditioner
2. AC2 - Dining Room Heat Pump - Air Conditioner
3. AC3 - Food Preparation Heat Pump - Air Conditioner
4. EARS - Exhaust Air Recovery System
5. R1 - Refrigeration Rack
6. DW - Dishwasher Heat Recovery System
7. LS - Electrical Lighting System
8. SC - Solar Collectors (to be installed in 1978 with funds from the New York State Energy Research and Development Authority)

The requirements of the Data Acquisition System are as follows:

1. to determine the energy consumed by the several subsystems
2. to determine the energy conserved or reclaimed by these subsystems
3. to determine the operating costs of each component of the energy conservation and heat reclamation system
4. to identify and isolate the energy saved or reclaimed by each component
5. to maintain a record of all data needed to perform the system analysis, which can easily be assessed for future analysis which may be required later.

While there are eight subsystems in the restaurant's overall energy system, multiple modes of operation and interaction of subsystems will require over 40 different areas to be studied and analyzed.

Operation of the DAS. Refer to Figure 1. The boxes on the left side of the block diagram indicate the several physical parameters which are monitored. Data sensor output signals are conditioned before entering the Hewlett-Packard DAS. The HP 3050 system collects two basic types of data:

1. measurement of a physical parameter (TF, KW, ME, TW, TA, AF and DP)
2. detecting and recording an event (E, EV on-off status of equipment and F, liquid flow)

The HP 9825A Computing Controller controls the acquisition of data by:

a. initiating data scans
b. retrieving data
c. converting the electrical sensor signals to engineering units
d. performing certain data reduction and systems analysis routines
e. sending output to the HP 9871 Printer
f. storing the reduced data on cassette tapes in the HP 9877A Cassette Tape Drive for future analysis

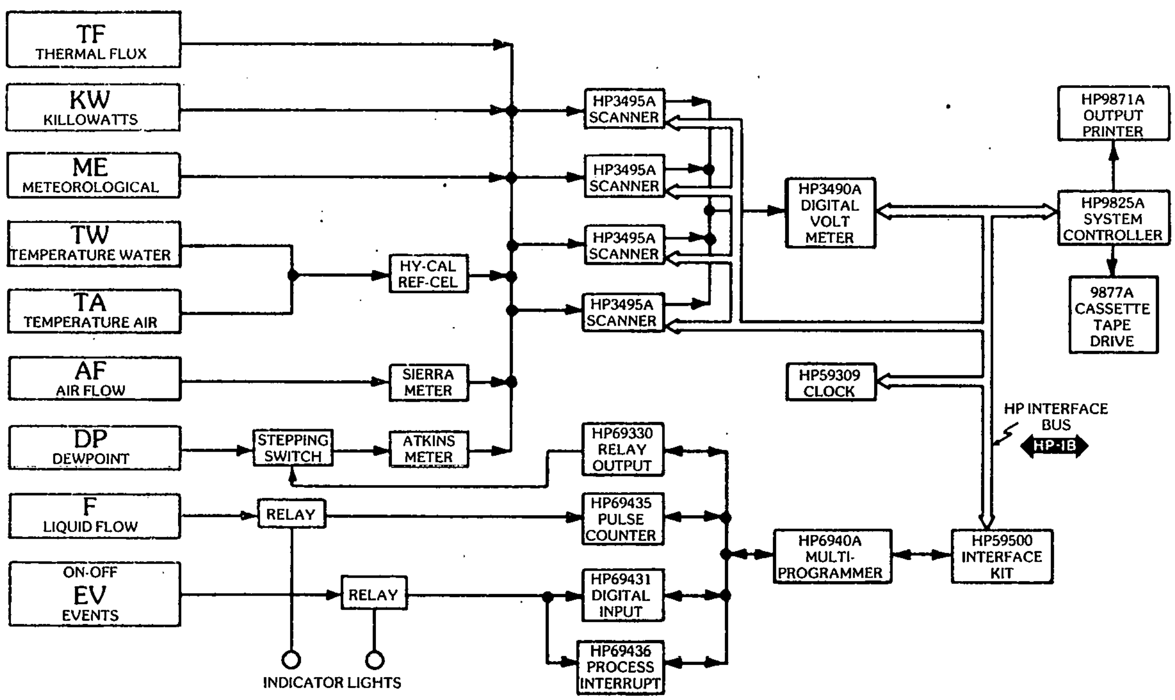

Figure 1. HP 3050 Data Acquisition System

The HP 9825A Computing Controller is interconnected to the rest of the DAS through the HP Interface Bus (HP-IB). This allows two-way communication between the HP 9825A System Controller and the HP 3490 Digital Multimeter, HP 3495 Low Thermal Scanner, HP 59309 Clock and the HP 6940 Multiprogrammer.

The HP-DAS includes the following optional components and channels monitored:

HP Components	No. of Channels	Physical Parameter
HP 3495A Low Thermal Assembly (16 cards with 10 channels each)	160	TF-Thermal Flux, KW-Kilowatts, ME-Meteorogical, TW-Water Temperature, TA-Air Temperature, AF-Air Flow, DP-Dewpoint Temperature
HP 69435A Pulse Counters	7	F-Liquid Flow
HP 69431A Digital Output	60	E-Events (on-off)
HP 69436A Process Interrupts	12	EV-Selected Events
HP 69330A Relay Output	12	RO-External Control

The HP Low Thermal Assembly relays switch the analog measuring circuits to the Digital Multimeter during the two minute scans. Sixteen cards of 10 channels each are addressed. For example:

Card	Channel	Sensor	Location
1	1	TF-1	Southeast - slab end
	2	TF-2	Southeast - below slab
	3	TF-3	Southwest - slab end
	4	TF-4	Southwest - below slab
	...	...	.....
	9	TF-9	Southwest - concrete block wall
	10	TF-10	Southeast - wooden stud wall
4	1	TA-1	Coffee Shop - near door
	2	TA-2	Coffee Shop - north corner
	3	TA-3	Food Preparation Area
	...	...	.....
	10	TA-10	DAS Room
8	1	TW-11	R-1 out
	2	TW-11a	Ice Machine No. 1 out
	...	...	.....
13	1	KW-11	Heat Pump No. 2 (HP-2)
	2	KW-12	Exhaust Fan No. 2 (EF-2)
	...	...	.....
14	1	ME-1	Wind Speed
	...	...	.....
	7	DP-1 to 11	All Dewpoint Temperatures
	...	...	.....

The HP Pulse Counter Card is connected through the HP Multiprogrammer to the Interface Bus (HP-IB). This component totalizes the one pulse per gallon electrical signals from the seven liquid flow meters. Seven cards with one pulse train totalizing capacity are listed:

Card	Sensor	Type	Location
1	F1	Brooks	Heat Exchanger 1 to Tank 1
2	F2	Brooks	Tank 1 to AC's and R1
3	F3	Brooks	Tank 2 to AC's
4	F4	Brooks	Preheat Loop
5	F5	Brooks	Heat Pumps 1 and 2
6	F6	Brooks	Supplemental Heating Return
7	F7	Invalco	Dishwasher Hot Water

The HP Digital Input Cards are also connected through the HP Multiprogrammer to the HP-IB. This is used to indicate the on-off status of compressors, pumps, blowers, valves and other electrical equipment. This data is used by the computing-controller to determine the mode of operation of a subsystem and to select the appropriate software subroutine for analysis. There are five cards with 12 channels each devoted to this purpose, for example:

Card	Channel	Sensor	Location
1	1	EV-1	AC-1 spoiler
	2	EV-2	Pump No. 1 (P-1)
	...	...	...
	11	EV-11	AC-2 Compressor 1
	12	EV-12	AC-2 Compressor 2

The HP Process Interrupts also connected to the HP-IB through the Multiprogrammer contains a single card of 12 channels. This component has the capability to momentarily interrupt the computing controller at any time during or between scans to record the status of equipment which operates sporadically for short intervals of time which might be missed during a regular 2 minute scan. Any event sensor can be used as an interrupt: examples are:

Card	Channel	Sensor	Location
1	1	EV-49	Hot Water Heater
	2	EV-51	Dishwasher Effluent Pump
	...	...	...
	6	EV-25a	Walk-in Freezer Fan
	...	...	...

The HP Relay Output connected in the same manner to the HP-IB contains one card of 12 channels each with a SPST switch which can be closed by the computing controller to control outside events. These 12 channels are devoted to stepping switches in the Atkins Dewpoint Indicator. Eleven channels can be used for dewpoint measurements, and the twelfth channel provides an "off-scale" electrical signal to indicate the end of the sequence to the computer-controller.

There are nine types of sensors used in this system as follows:

1. TF-Thermoflux sensors provide a mV signal proportional to the heat flux through them. These are supplied by Hy-Cal Engineering.

2. KW-Kilowatt transducers monitor the electrical power consumption of AC units, Refrigeration Rack, Heat Pumps, etc. Seventeen KW transducers are assembled in various configurations, i.e., 3ϕ, 3 wire; 3ϕ , 4 wire; or 1ϕ, 2 wire, etc. These are made up from 42 Bell PX 2000 Series Watt Transducers and 35 General Electric Type JCH-0 Current Transformers. Each KW unit provides an mV output signal proportional to the Kilowatt consumption of the electrical device being monitored.

3. ME-Meteorological Data are provided by a Kahlsico instrument for wind speed and direction. Solar radiation is monitored by a Kipp and Zonen Pyranometer.

4. and 5. TA and TW-Air and Water Temperatures. Type T (copper-constantan) thermocouples were used. Air temperature sensors were made on site by ASRC staff. Single junctions were used except in air handling ducts where multiple junctions, wired in parallel in a grid fashion across the air stream, were installed to obtain average temperatures. Water thermocouples were supplied by Hy-Cal Engineering. These are 1/8 inch diameter stainless steel probes which can be inserted into piping through "Pete's Plugs." These are self-sealing fittings which permit insertion and withdrawal without leakage at normal water pressures. All thermocouples are referenced to 32°F (0°C) by a Hy-Cal Engineering (Ice Point) "Ref-Cel."

6. AF-Air Flow rates in the air handling system are assumed to be constant for analysis purposes, based on periodic checks and measurements made during air balance determinations. A Sierra Instrument, Model 440 Air Velocity Meter with a 0 to 1 volt DC output, calibrated to air flow velocity, permits temporary mounting in an air duct. The output can be fed to the DAS for logging purposes.

7. DP-Dewpoint Temperatures. An Atkins Technical Dewpoint Instrument was modified by ASRC personnel to multiplex 11 DP probes into the DAS using a 12 channel stepping switch activated by the calculator-controller. As noted above, the twelfth channel gives a 70 mV "off scale" signal which indicates the end of the switching sequence. Dewpoint measurements are used to determine the changes in total energy, sensible and latent heat, in the heating and air conditioning system. A computer software subroutine makes these calculations.

8. F-Liquid Flow is measured by two devices: 1. Turbine vane flow meters with both visual readout and electrical, one pulse per gallon, signals which are totalized by the HP 69435 Pulse Counter Cards and sent through the HP Multiprogrammer to the system controller. These flow meters were supplied by Brooks and Invalco. 2. Bell and Gossett "Circuit setters" are used to control flow through some individual coils, heat exchangers and pumps. These flow meters are adjustable and are calibrated. These constant flow rates are rechecked from time to time and are used in certain software calculations.

9. E and EV-Events. This group of 60 events and 12 selected sensors are crucial to the evaluation of all other data. For example, in the case of the AC Heat Pump/Air Conditioners, the on/off status of seven electrical components of these units is used by the HP Computer-Controller to determine in which of some 16 operating modes the AC unit is operating. With this information, the Calculator selects the proper subroutine and appropriate data to make the necessary analyses. The on/off status is determined by the position of a DPDT relay with its coil wired in parallel with the electrical component being monitored. One pole of the relay is wired to

the HP Digital Input Card which sends a "1 or 0" logic signal to the HP Calculator-Controller. The other pole of the DPDT relay is wired to an indicator light on the instrument panel, which shows the operating status of the equipment.

Selected events for critical equipment, which may operate for short duration between or during scans, are wired to the HP Process Interrupt Card. These events interrupt, momentarily, any routine operation to record and store that information.

Several of the energy conservation and heat reclamation systems listed above are shown in block diagrams on Figures 2 through 7. The Heat Flow Diagram of Figure 2 depicts how all of the various subsystems use or reclaim heat energy.

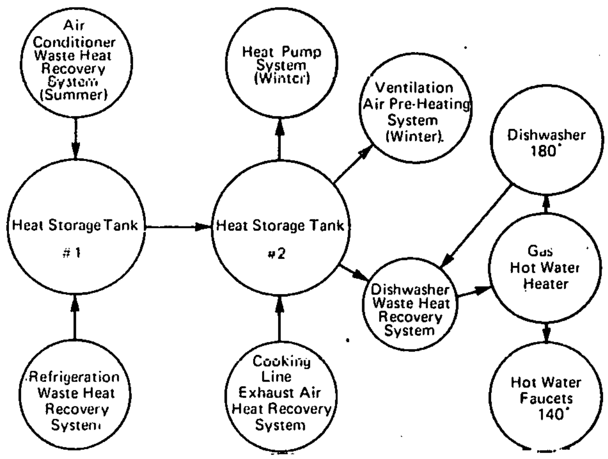

Figure 2. Heat Flow Diagram

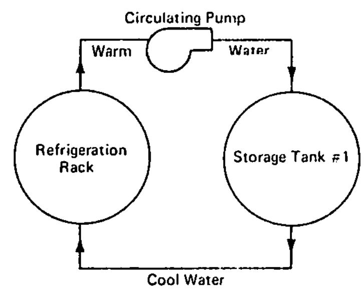

Figure 4. Refrigeration Rack Heat Recovery System

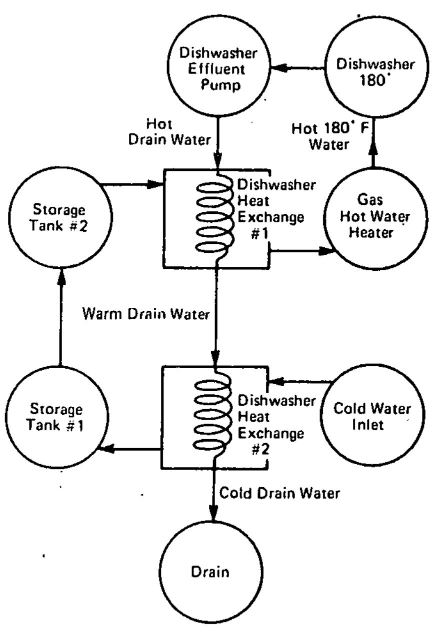

Figure 3. Dishwasher Heat Recovery System

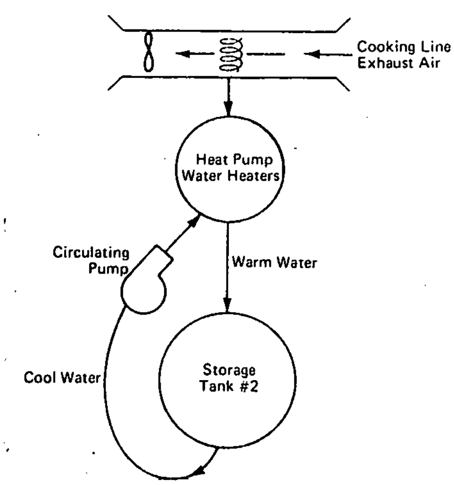

Figure 5. Exhaust Air Recovery System

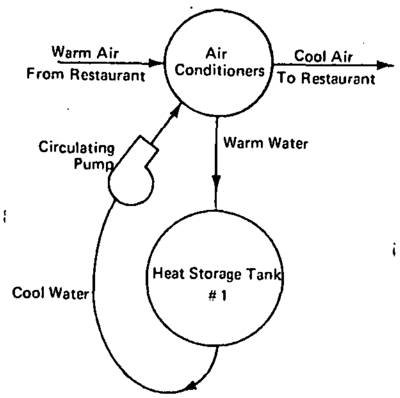

Figure 6. Air Conditioning Heat Recovery System (Summer)

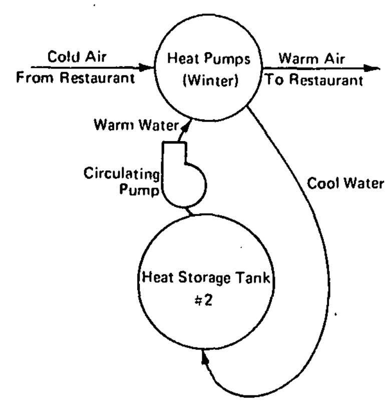

Figure 7. Heat Pump System (Winter)

In addition, solar collectors will supply heat to Tank No. 2. The Dishwasher Waste Heat Recovery System (DW) of Figure 3 supplies heat to both Tank Nos. 1 and 2, from the hot water effluent, exchanged in Heat Exchange Nos. 1 and 2. In most restaurants, this heat is lost when the hot drain water is discharged.

Refrigeration compressors are equipped with water cooled condensors. The cooling water is pumped out of Tank No. 1 and then back as warm water. This heat is recovered from the walk-in coolers, freezers, ice making machines and refrigerators. See Figure 4.

The Exhaust Air Recovery System (EARS), shown in Figure 5, reclaims heat from the cooking line exhaust duct. The evaporator coils of two heat pumps are mounted in the exhaust duct, the condensing coils are water cooled, taking water from Tank 2 and returning it as warm water in a manner similar to the Refrigeration Rack Waste Heat Recovery System above. An additional energy conservation feature of EARS is the make-up air system which prevents the conditioned air of the coffee shop from being exhausted through the cooking line area.

The AC Heat Pump/Air Conditioners are shown on Figures 6 and 7. In summer, the water cooled condensing coils of the AC compressors are cooled with Tank No. 1 water and return warm water to the same tank. This heat is used to boost the temperature of water going to the Hot Water Heater for the dishwasher. In winter, the AC Heat Pumps use heat from Tank No. 2 through their evaporator coils. Heat reclaimed from Refrigeration, EARS, and from Solar Collectors is thus used to heat the restaurant.

In all the systems described above, data sensors TA, TW, TF and F are installed in fluid lines and air handling ducts in order to make analysis of energy used or recovered. KW Transducers monitor electrical power usage. E and EV denote the operating mode or duration of operation.

The development of the computer software and reporting routine was developed by the ASRC team. Two software categories were necessary. The first was to write programs to run the Data Acquisition System, that is, to assure that the data from sensors is acquired, conditioned, converted to engineering units and stored in memory. The second was to develop analytical programs to reduce this data, evaluate system performance and printout and store the output. The Department of Energy contract requires a monthly status report. The latter category of software development is used in this report, which gives a running account of energy used, energy reclaimed and cost. Actual power and LP gas bills, customer count and receipts are also used in preparation of the monthly reports. The final report will include economic analysis and ROI. Preliminary results indicate that savings in energy use of 30% or more can be expected with the types of energy conservation and reclamation equipment installed in this restaurant. The Department of Energy will disseminate these results to the nation after the final report is prepared.

In summary, this on-line, real-time Data Acquisition System:

(1) permitted interfacing of a number of different types of sensors,

(2) allowed frequent scanning of all sensors, every two minutes, holding this data in memory, averaging data for one hour and printing out and storing this "crunched" data for later reduction,

(3) permitted critical events to be recorded and stored in memory during or between routine scans,

(4) gave a continuous printout of equipment status which could signal trouble or possible malfunctions so prompt corrective action could be taken,

(5) made it easy to develop simple software routines for quick printout of temperatures and liquid flow for the use of maintenance personnel during routine service checks of the equipment, saving them considerable time, and

(6) was reasonably priced for such a flexible, convenient, but powerful system.

The author wishes to acknowledge the aid and assistance of those who contributed to the planning and execution of this project. Special thanks to Edward Price of the New York State Assembly Scientific Staff; to James Healey, Harry Misuriello and Joel Scott of ASRC; to Dennis Landsberg of William S. Fleming Associates; to Dave Simmonds of Hewlett-Packard's Albany Field Office; and to the many others, students, technicans and secretaries who contributed so much to the success of this project.

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A MODERATE-COST DATA GATHERING SYSTEM

Russell K. Johnson
Copper Development Association Inc.
405 Lexington Avenue, New York, New York 10017

Abstract

A moderate-cost (about $10,000) data gathering system, built around a Tektronix 31/53 programmable calculator, is described. The calculator does all data reduction, and prints hourly and daily summaries of heat flows and significant temperatures. Accuracies in heat flow measurements of about ±10% can be obtained.

When the Decade 80 Solar House was completed in 1975, CDA recognized the need to document the value of its solar heating and cooling system. Also, since the system was one of the first residential solar heating and cooling installations, a cycle of debugging and modification was foreseen. A versatile method was sought to measure the systems performance. First, the data system must have the capability of giving detailed real-time data on site, as a necessary aid in tuning up or modifying any component of the solar energy system. Second, it must yield a measurement of the total system heat balance showing what fraction of the energy required to heat and cool the house is actually saved through the use of solar energy.

A full mini-computer system was ruled out on the basis of the lower cost, operating simplicity, and equal versatility of the programmable calculator approach. A system built around a Tektronix 31/53 programmable calculator was chosen.

Data have now been collected at the CDA Decade 80 Solar House for over two years with this instrumentation system. The cost of the basic system hardware was about $10,000.

The main elements of the data system were supplied to CDA by the New Products Center of Raytheon Company, who used the same approach in their solar testing program. Raytheon designed and constructed the stepping relay assembly (the only component not supplied by Tektronix) and made the original sensor selection. The system was installed in the Decade 80 Solar House and programmed by CDA.

The Calculator. The heart of the data system is the Tektronix 31 programmable calculator. This machine is programmed in its own keystroke language, much like an HP-67 or a TI-59 pocket calculator. Unlike a pocket calculator the Tek 31 can interface with the outside world. The basic calculator comes with 512 program steps and 64 registers. In our system we required the maximum available memory/register combination, 5120 program steps and 640 registers. The calculator has a capacity (with optional additional memory) of up to 8192 program steps, or up to 1000 data registers in various combinations. Our machine includes an optional paper-tape alphanumeric printer, a magnetic tape storage and an auto-start feature, which reloads the program back into the machine after a line-power failure.

The system used by CDA is built from Tektronix components; a similar system could be built up around another calculator, of course.

There are several advantages to using a desktop calculator system like the Tektronix. First, almost all components are available from the same manufacturer. For companies that do not have a large body of in-house computer expertise this is important. The computer manufacturer has taken care of all compatibility and interfacing complexities, allowing the user to design his system in building-block fashion. This is advantageous for maintenance as well; one service contract is all that is necessary to keep the system healthy.

Ease of programming is a second advantage to the desktop calculator. Since programs are written in a keystroke language rather than in BASIC or FORTRAN no assembler need be run, and the programming language can be learned easily. Special subroutines need not be written or purchased for math functions like logs, exponentials, powers and roots, etc., since each is available at a single keystroke. The machine also has the full computer capabilities of decision making and branching on the basis of the decision, looping, and nesting of subroutines.

A disadvantage to using this machine for unattended data-taking is its volatile memory. Each time power is lost the semiconductor memory in which the program and data are stored is erased. In an area with frequent thunderstorms, this can happen as often as several times a day, for a fraction of a second to several minutes.

This problem is partly solved by the use of an Auto Start Termination Pack. This device commands the computer to go immediately to the magnetic tape on power-up. The entire program is reloaded into memory, and the program resumes the scanning operation.

The computer continues its operation after a power failure, but all data in its memory registers are lost. Therefore our program, as an insurance measure, prints a summary of the day's data so far after each hourly printout. The total day's data then can be reconstructed manually after a power failure.

The calculator system used by CDA is called the Tek 31/53 Calculator Instrumentation System, since the package includes the Tek 153 Instrumentation Interface, ready to plug in to the Tek 31 calculator. The Tek 153 unit is a mainframe which has the necessary interface module and cabling, and can accept two other Tek instruments of the user's choice, such as Digital Multimeters or Counters. In our case both slots are used for Tek DM501 Digital

Multimeters.

Since all data are printed on paper tape, the thermal printer option is included in the package. It can print both letters and numbers but not on the same line.

A useful feature of the Tek 153 Interface is its output pulse capability. A program-initiated pulse from the Tek 153 is used to drive a stepping relay, connecting one sensor after another to the digital meters. (A second output pulse is available but unused.)

If the user wishes, other instruments may be added to the system by daisy-chaining one Tek 153 Interface to another, up to 10 units.

The system configuration is shown in Figure 1.

Digital Multimeters. Two digital multimeters are used in this system, rather than one programmable-function meter. Though this may seem wasteful, it demonstrates an advantage of the packaged system: it proved less expensive to use two Tek DM501 meters ($370 each) than to interface to a more expensive programmable multimeter.

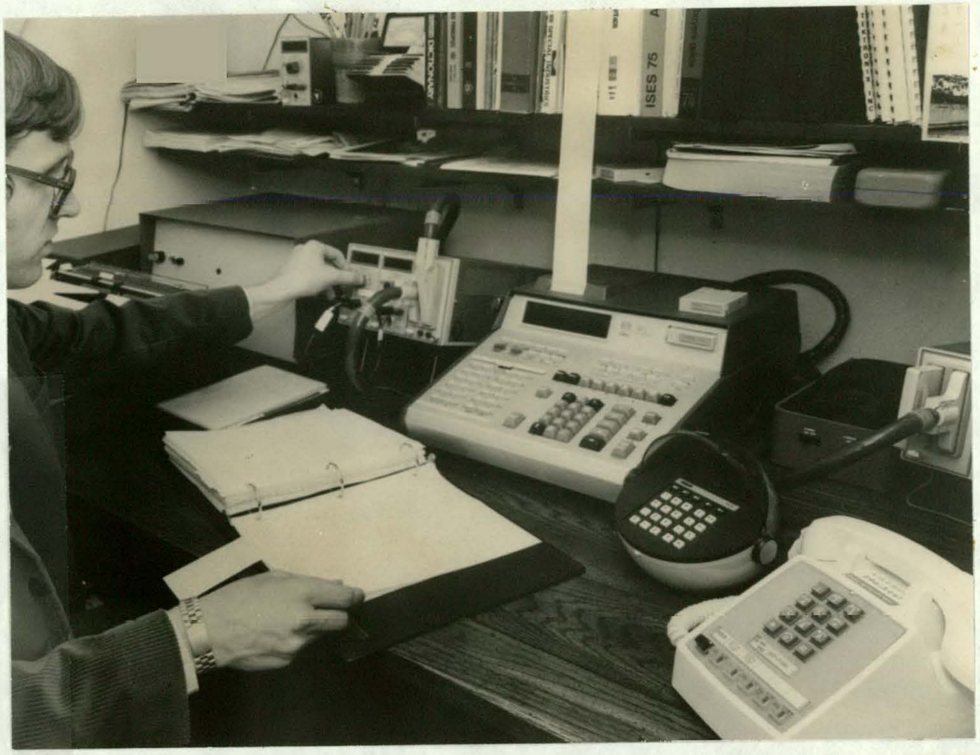
The DM501 is a 4 1/2 digit instrument that measures AC and DC voltage and current, resistance and temperature. It is useable only with the mainframe/power module (TM500 series or, Tek 153 Interface).

The temperature function uses a surface-sensing probe, accurate to ±1.5 C. Since the probe is not useful in the present system, the DM501 was ordered without the probe at a savings of $105.

Voltages are measured on the 2V DC scale, to 0.1 mV resolution; resistances are measured on the 20 Kohm scale, to 1 ohm resolution. One DM501 is connected only to thermistors, measuring their resistance, while the other DM501 measures only voltages from the pyranometer and other sources.

Stepping Relay. The stepping relay assembly is the only part of the system not supplied by Tektronix; it was built from scratch. The relay is the device which connects each sensor in turn to the proper digital meter.

The relay's common contacts are connected to the DM501 inputs; the outer contacts are connected to each of the sensors throughout the system. The relay is stepped from one sensor to the next by pulsing its coil with an output pulse from the Tek 153 Interface. Each step simultaneously connects a thermistor to one pair of relay contacts and a voltage source to another pair of contacts. Since the output pulse is only 5 V, logic level, and the relay coil requires 24 V at higher current, the pulse must be processed. It is sent into a 555 one-shot timer circuit where it is lengthened, and then it is amplified so it can drive the stepper coil.



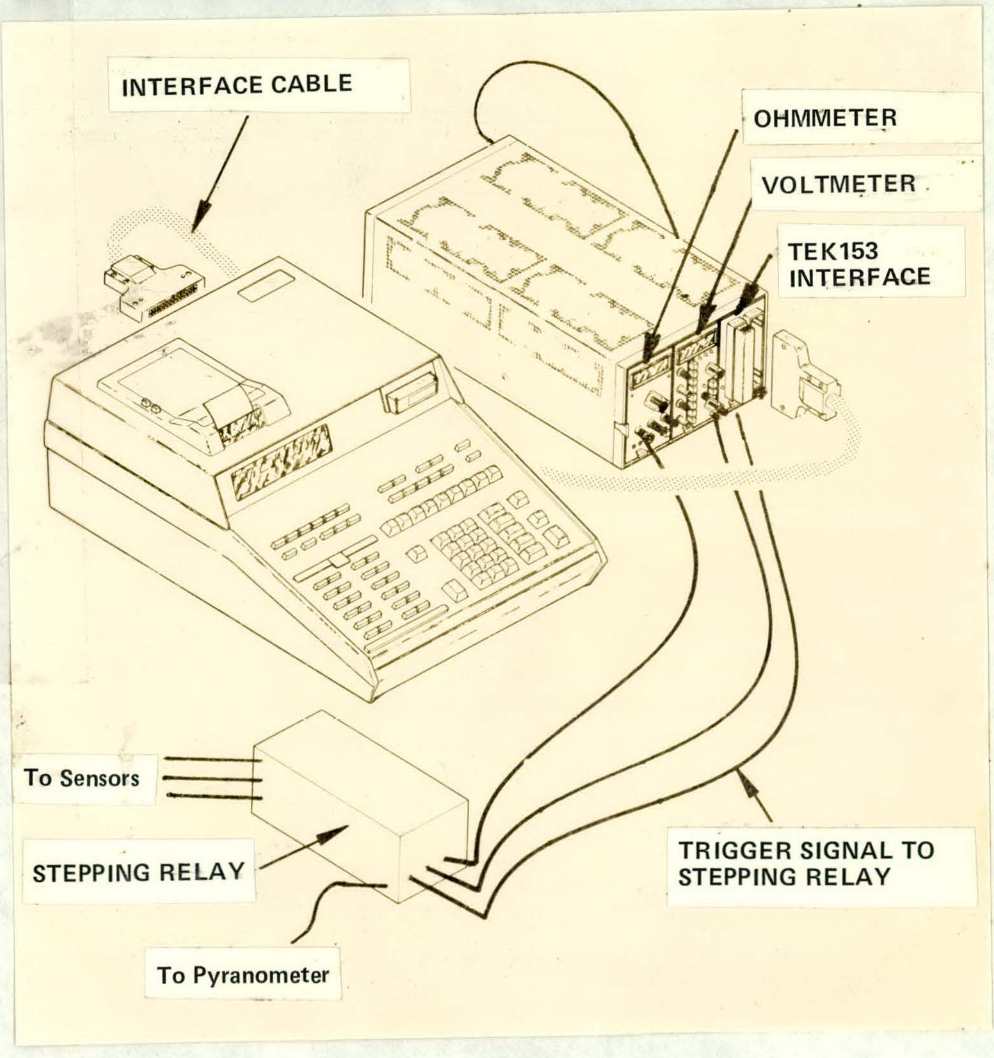


Figure 1. The Decade 80 Solar House Data Gathering System Built around the Tektronix 31 Programmable Calculator.

The stepping relay itself is a C. P. Clare 52 position, 4 level unit with a 24 V DC coil. The relay contacts are gold plated for minimum contact resistance over the units lifetime.

Sensor Selection. Pyranometer: The pyranometer used in this system is an Eppley 8-48; its output signal is about 10 millivolts under maximum insolation. Measured on the DVM's 2 V DC scale, resolution is ±0.1 mV, or about 1% of reading at best. An Eppley model PSP, though more expensive, would be more accurate, as it is a Class I pyranometer. The unit's signal is carried to the data system via a shielded cable, grounded only at the data system end. Thermistors: Temperatures are measured throughout the system with Yellow Springs Instrument Co. (YSI) Precision Interchangeable Thermistors, Series 400, composite 44033. Each probe is inserted into the water or air flow-stream. No surface contact sensors are used.

The manufacturer claims 0.1 C accuracy and interchangeability for the Series 400 between -40 and +100 C, and ±0.2 C between +100 and +150 C.

This accuracy is important. Consider a measurement across a collector operating at about 210 F, with a 10 degree gain. A tolerance of 0.2 C on each sensor yields a tolerance of 0.4 C, or 0.7 F for the differential measurement. This is a 7% error. If the flow measurement had a 3% possible error, the calulation of Btu flow from the collector would then have a possible error of 10%. A measurement at a lower collector temperature would have better accuracy, about 6% to 7% possible error on a 10 degree differential.

The resistance of each thermistor is converted to temperature by the calculator according to an equation specified by the thermistor manufacturer:

$$\frac{1}{T} = A + B\ (\log_e R) + C\ (\log_e R)^3.$$

R is the measured resistance and A, B and C are constants determined by the characteristics of the particular thermistor composite chosen. Interpolation data generate by this equation are said to be accurate to ±0.01 C or better.

There are several advantages to using themistors, rather than thermocouples or platinum RTD's. The normal working resistance range of these thermistors is between about 150 ohms and 7 Kohms, while an RTD would have a range of about 100 to 150 ohms over the same temperature span. Readability is thus much better, and lead resistance due to long wires is less significant. (In our system lead resitance is typically about 7 ohms over 100 to 150 ft of lead; the actual value is subtracted from each reading.) Errors introduced by changes in the lead wire resistance due to temperature fluctuations are not significant, as they might be with an RTD.

No cold junction reference or compensation is needed, as it would be with a thermocouple. Shielded leads, special alloy connectors, and a highly sensitive microvoltmeter are not needed. Thermistor probes need not be individually calibrated.

Long lead wires may be a practical necessity in some installations. Digital equipment becomes erratic or inoperative in an environment about about 100 F. The data system can not be placed in a mechanical room along with a storage tank or absorption chiller, where the ambient temperature might be 120°F on a hot day. Flow sensors: Flows are measured using Ellison Instrument "Annubar" flow sensors. These devices measure differential pressure, and cause very little pressure loss in the flow stream, typically less than 1 in. water head. The sensors require a significant straight flow path 7 to 24 tube diameters upstream and 3 to 4 diameters downstream of the device.

It is possible to attach differential pressure transducers to these flow sensors, thereby allowing the computer to automatically read differential pressure and convert to flow at each data scan. It was found however that adquate differential pressure transducers (that could read 4 to 7 in. water differential at a common mode pressure of 25 to 100 psi) were expensive. Therefore a compromise was made. Flows are measured manually, reading them on an Ellison "Eagle Eye" differential pressure meter. These measured flow values are typed into registers in the computer. The data system simply senses pump operation, and assumes the flow to be either zero or the pre-measured constant value. Pump and valve sensors: There are ten pumps and three-way valves whose status must be checked with each computer scan. This is done quite easily by taking advantage of unused relay contacts in the energy system's control circuitry. A voltage from the stepping relay power supply is applied to a contact of each pump or valve-operating relay. When the relay closes and the device operates, the digital voltmeter reads a voltage at the relay contact. The computer thus recognizes that the particular device is "on".

Another pump sensing technique used successfully employs an optical coupler. The pump or valve's operating voltage (115 or 230 V) is applied to the neon lamp in a Clairex Photomod[R] photocell-lamp module. The photocell's resistance change can be sensed by the data system.

System Hardware Cost. The cost of each component of the basic system is as follows:

Tektronix 31/53 Calculator, w/basic memory		$ 3,995
Maximum memory option		1,500
Thermal printer option		800
Auto Start Termination Pack		120
Tek 153 Interface		995
Tek DM501 Digital Multimeters ($370 each)		740
Stepping relay subsystem		540
Relay, with gold contacts	$140	
Power supply	100	
Chassis & misc. hardware	100 estimated	
Relay driver circuit	200 "	
Cable & Connectors		300
Flow sensors 7 @ $65 each		683
1 meter @ 228		
Temperature sensors 25 @ $38 each		950
Pyranometer, Eppley model 8-48		590
		$10,448

Optional Features. The user may wish to add other options to his system, such as disc storage of his data, remote printout capability, a real-time clock, or an uninterruptable power supply.

Disc storage is available from Tektronix for this system for $3995, plus $300 for the necessary interfacing circuit. The disc would allow the user to store hourly or daily data for later computer analysis.

The present system prints all data on paper tape. Analysis is then done manually from daily summary data.

The CDA data system has an additional capability: immediate data can be printed on a remote teletype, in an easily readable format simply by telephoning into the Tektronix computer. A phone coupler automatically answers the phone and connects the computer. This option requires the Tek 154 RS-232-C Interface, at $995, plus a Data Access coupler, and a phone line from the local telephone company.

A real-time clock would be a valuable addition to the system, since the computer program keeps time only by "knowing" how long each scan of the sensors and each printout should take. This timekeeping technique is normally accurate to 1 to 5 minutes per day, unless there is an unusual amount of system activity requiring extra data printing, during a period of trouble-shooting or system development. The optional clock would allow the system to run for longer periods without a manual correction of the program's time code.

The real-time clock would require the Tek 152 BCD interface at $1150, plus a digital clock circuit of the user's design.

An uninterruptable power supply would prevent the loss of data due to line-power failures. This device continuously charges a set of batteries, then draws power from the batteries and converts it back to 115 V AC. This power operates the data system. In the event of a power failure, the batteries continue to operate the system, keeping its memory intact. A UPS would cost about $1500 to $2500 including batteries.

The Program. In order to demonstrate the versatility of this computer data system, the basic parts of the data collection and analysis program will be described below.

Most data collection is done with the goal of achieving a daily heat balance, showing heat into and out of each component, and the proportion of auxiliary power used to provide the necessary heating, cooling and hot water. Other data are taken to monitor the performance of various subsystems.

The program has the form of a master routine and many subroutines. The master routine calls on each subroutine in turn to perform a specific task, and directs the printing of necessary data and significant events. Each subroutine is labelled by a single keystroke-name; there are as many labels available as there are keys on the keyboard (over 140, including upper case). Subroutines can easily be nested into each other.

The master program first sets the stepping relay to its starting position and then verifies that it is actually there. It then prints the current time and date on the printout, and commences its data scan.

First the voltmeter is read, then the ohmmeter. Each measurement is repeated until it is sufficiently stable. The measurement of the thermistor's resistance is converted to temperature via the formula mentioned above, and that value replaces the resistance reading in its proper storage location. The stepping relay is then incremented and themeasurements repeated, in a loop, until all data points have been measured.

The master program next verifies that the final position of the stepping relay was reached. If not, the data from that scan are dumped and the scan is repeated.

The master program then calls up a series of data conversion and reduction subroutines. The pyranometer output is converted to Btuh/square foot. Voltages at each pump and valve relay sensing point are converted to 1 or 0, representing "on" or "off".

If any pump or valve changes its status, that fact is noted on the printout. One can tell from a glance at the printout tape how the entire system is operating, and which components are currently functioning. This is a great diagnostic aid.

The next subroutine calculates the amount of heat, in Btu's that has been collected, stored, delivered to the heating or air conditioning system and cooling tower, and delivered to the domestic hot water subsystem and the living space since the last data scan. These values are integrated into hourly-total and daily-total registers for later printout.

Each measured temperature is summed into another register to give hourly average temperatures at the end of each hour. (Some averages are useful, others not it is easier to use a looped routine to average all values than it is to average selected values.) Some temperatures are checked to see if they are the daily maximum or minimum, and if so the data and the time of the scan are stored for printout at the end of the day.

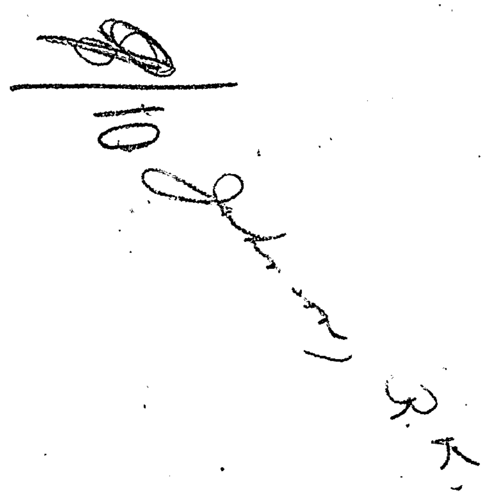
The master program then enters a section where data of immediate interest are analysed. The instantaneous collector efficiency is printed (if the collector is operating). The output of each Arkla air conditioning machine might be printed (in tons) if that is of current interest. Temperatures across various other components may be printed, as the operator wishes: duct fan coils, air conditioner generator or condenser circuit differential temperatures, or any other information of a current, but perhaps temporary, interest.

There is also a subroutine to verify that temperature and insolation data are believable, i.e. that no sensor is shorted or disconnected.

The entire scan of 51 data points and reduction of the data takes just under two minutes. It is important to make as many data scans per hour as possible. Since the heat flow calculations approximate an integration, several measurements of a heat-delivery cycle should be made. If, for example, the domestic hot water heating cycle takes four minutes, it could be missed completely by a data system that makes a scan every five minutes.

The master program finally goes to a timekeeping routine where the "current" time value is incremented by the amount of time required to complete the data scan. The program notes whether it has reached the end of an hour or the end of a day. At the end of each hour, average temperatures of significance are printed, operating times of each device are printed, and Btu flows are printed. Each day at midnight a summary of the day's energy flows and operating times are printed for permanent storage in a notebook, for monthly and seasonal reports, as shown in Figure 2.

Conclusion. The Tektronix Calculator Instrumentation System can be a versatile solar energy system analysis tool



◆◆◆MIDNIGHT◆◆◆	
20224	February 2, 24:00
DAILY TOTAL BTUS	
COLLECTED	
785000	
INTO STORAGE	
782000	
OUT OF STORAGE	
344000	
MST	Mean storage temperature
136.34	
DHW	Heat to domestic hot water, from storage
6700	(Most heat today was from auxiliary)
ADDED BY WH-1	(From the gas-fired boiler, to heat the house)
4000	
TO BOTH ARKLAS	
334000	
E ARKLA	
TO GEN/HTR	Heat delivered from storage or boiler to fan coil
37300	or Arkla generator
TO/FROM AIR	
58600	
W ARKLA	
TO GEN/HTR	
242700	
TO/FROM AIR	
340400	
NET H/C	Net heating or cooling
399000	Heating
0	Cooling
% SOLAR	
98.9	
PUMPS ON, HRS	Operating time, in hours
P-1 6.33	Collector
P-2 6.18	Collector HX to storage
P-3 5.78	Main circulator
P-4/5 1.67	Domestic hot water
V-5 E .87	East fan coil bypass/operating valve
V-6 W 4.80	West fan coil
V-2	
DFS 23.97	Time in the "drawing from storage" position
RECIRC 0	"Recirculating" position
PROP .03	"Proportioning" position
WH-1 .03	Auxiliary boiler
WH-2 13.70	Hot water heater electric element enabled
TOTAL INSOL.,	
BTU/SQ FT/DAY	
1982	
BTU, /P-2 ON	Total insolation during collection period
1492	
COLL. EFFIC, %	
TOTAL DAY	Collector efficiency integrated over entire day
21.17	
WITH P-2 ON	Efficiency integrated over collection period
27.35	
MAX/MIN OUTDOORS	Dry-bulb temperature
67.82	Degrees F, maximum
15.26	Time of maximum
43.85	Minimum temperature
6.24	Time of minimum
DD	Degree-days
10.57	Referenced to 65°F
AVG	
54.43	Average outdoor DB temperature

Figure 2. Midnight Summary Printout for the Decade 80 Solar House Data System, with Explanatory Annotations.

P/10 Johnson, R. K.

A MICROPROCESSOR BASED SOLAR MONITORING SYSTEM

Dr. William P. Moran, Mr. Gene E. Kouba
Associate Professor of Physics, Research Associate
Solar Energy Research Laboratory
University of Tulsa
Tulsa, Oklahoma 74104

ABSTRACT

A monitoring and analysis system has been developed around the Heath H-8 microprocessor (Intel 8080 A), the Datel Sinetrac 800, 32 channel 12 bit A/D multiplexer and the Intel 8253 programmable interval timer (PIT). Simple linearized thermistors measure temperatures to $\pm 0.1^{\circ}C$. Flow rates, totals, and time are measured by 18 PIT's.

INTRODUCTION

This paper reports the design and performance of an energy monitoring system for determining the energy budget of a building, evaluating the solar contribution to the budget, separately monitoring each component and conducting experiments with operational parameters or active control. The constraints on the hardware were cost, flexibility of operation, completeness of the measurements, minimum signal conditioning with standard instrumentation, minimum construction and maintenance, long term unattended operation, compatibility of the precision and accuracy with the system operation.

THE SOLAR HOME

The house to be monitored for a period of one to two years is equipped with the solar system described in Table 1. The energy conservation features and thermal parameters of the house are listed in Table 2. The house will be monitored in three phases: unoccupied demonstration and experiment; simulated occupancy; occupied by a family.

Table 1. Solar Home Parameters

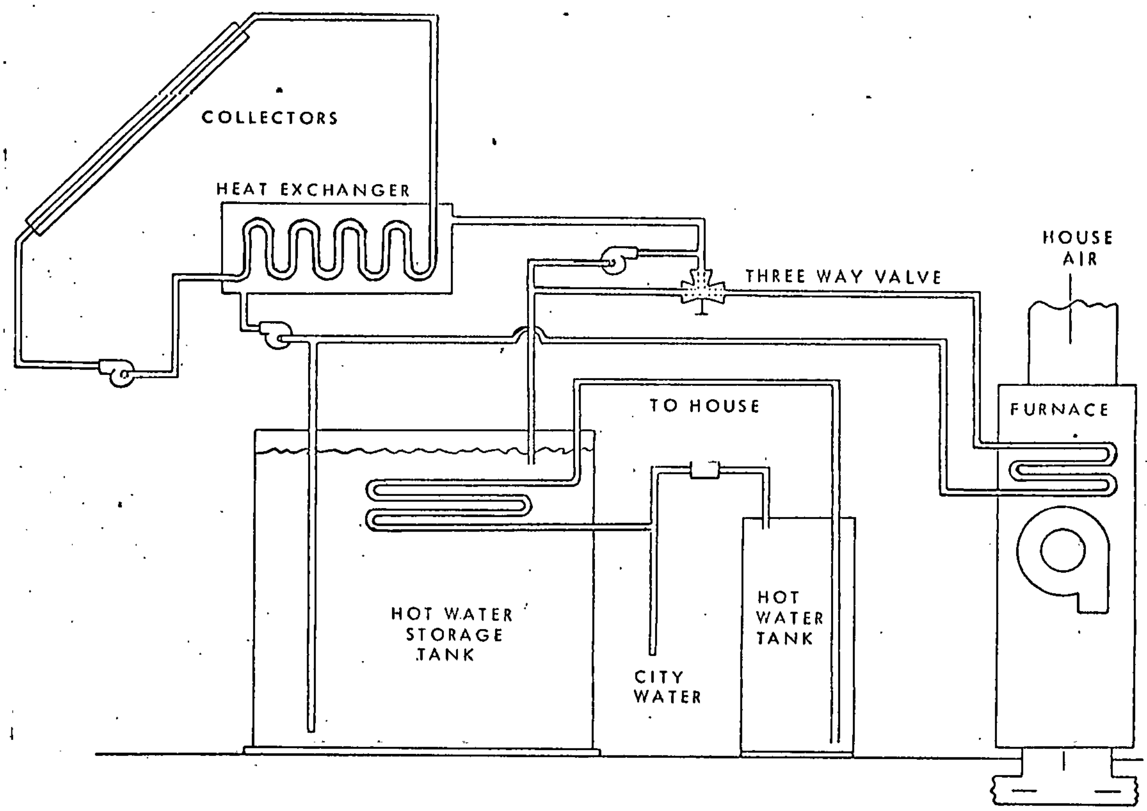
Size	1750 f^2	Auxiliary heat	gas
Collectors	369.6 f^2 net	Design goal	75% space heat and hot water
Storage	1400 gal		

Moran 1/7

Table 2. Heat Load Data

R values		Heat Loss	
Walls (N,E,S)	14	Winter $\Delta T = 65^{\circ}F$	36,600 Btuh
West	19	Heat Gain	
Ceiling	26	Summer $\Delta T = 25^{\circ}F$	
Floors	7	(Structure)	23,000 Btuh

Figure 1. The Solar System



VARIABLES TO BE MONITORED

Table 3 lists the variables to be monitored directly by the computer. Others such as humidity, precipitation, atmospheric pressure, equipment status, and activity level in the house will be logged by the operator or house occupants. Several of these variables will be monitored only infrequently since they are not subject to much change except during experimentation or seasonal changes. Table 4 lists some of the experiments to be conducted.

Moran 2/7

Table 3. Variables to be Monitored

Temperatures	Flows	Others
Collector I/O	Collectors	Insolation
Furnace Hydronic Coil I/O	Hydronic Coil	Wind Direction
Heat Exchanger I/O	Domestic Hot Water	Status
Line Losses by Difference	Flue (mass)	
Domestic Hot Water	Furnace (mass)	
Supply, Storage, Delivery	Gas	
Furnace I/O/Flue	Electric Power	
Storage Tank (4 levels)	Wind Speed	
Ambient	Duct Outlets	
Interior (6 movable probes)		

Table 4. Experiments

Heat load analysis
Stratification in storage
Heat exchanger operation
Heat rejection (summer)
Thermostat and control efficiency
Wind-efficiency correlation
Response times
Line losses
Storage tank and room losses
Variable storage capacity

THE MONITORING SYSTEM

The monitoring system consists of: instruments and their interfaces for signal conditioning shown in Table 5, the analog to digital converter, the programmable digital counter-timer, the computer, and input-output devices. It is important to maximize use of available university computer power and economize on the small computer I/O. The use of paper tape is the most rudimentary method of communicating between computers. It is easily upgraded through high speed tape reader to magnetic tape conversion. Paper tape consumption is greatly reduced through the power of the Extended Basic on the microprocessor. Solar monitoring is ideal for off-line data transfer during the non-solar hours. Thus there is little danger of building back logs of untransferred data even at the slow paper tape rates. Even with disk storage for the microprocessor, monitoring programs of months to years duration will require transfer of the data to larger computers eventually. Very attractive economies are being found however in several fields when low cost mini or micro computers are operated for hours or days on lengthy calculations to save expensive CPU time on big computers.

Table 5. Monitoring System Components

Standard Instruments Pyranometer, Eppley 848 Wind speed and direction, Texas Electronics Mass flow meter, Data Metrics Turbine flow meters, Halliburton	**Computer** Heath H-8 8080 A 1 K ROM 24 K RAM Console 12 line 80 character Cassette Punch-Reader 2 Free parallel ports 4 Free interrupts
Tailored Instruments Thermistor temperature sensors, Yellow Springs Inst.	
Acquisition Datel 32 ch, 12 bit, A/D converter Intel 8253, programmable interval timers	**Processing** Extended Basic HASL Assembly language and Basic utility routines PAM Monitor, utility routines
Interfaces Heath Console Cassette Paper Tape Tailored Interrupts PIT to 8080 A bus Datel to 8080 A bus Digital or Analog command bus Flow meters to PIT	**Output** Console Paper Tape to TTY **Final Processing** Mass storage and processing Xerox Sigma 6

The availability of multi-channel analog to digital converters with microprocessor control greatly simplifies the acquisition of analog data. We have interfaced the Datel Sinetrac 800 32 channel A/D to the Heath H-8 (Intel 8080 A) microprocessor. This permits use of simple linearized thermistor sensors for temperature measurement to a resolution (least significant bit) of 0.1°C without analog signal conditioning. The only required signal conditioning is the amplification of the pyranometer output (x 150) all the other analog instruments are compatible with the voltage and resolution range of the A/D (0-5 V, 12 bit). Measurement requirements are listed in Table 6.

The Datel unit is very versatile in that its operation is completely controlled by the computer through its status register and channel address registers. The speed of data acquisition is so high that there is little benefit in operating in anything but the full 32 channel program control mode. This conserves interrupts. All 32 channels can be digitized and transferred to memory in about 10 ms. The speed of the acquisition permits multiple samples to be taken over a span of a second and averaged to reduce 60 Hz interference before the data is processed by the main program. Program control of the Datel unit can be done with commands in Extended Basic itself or in a machine language subroutine. The latter is itself very simple and conserves significantly on time compared to Basic. Interfacing of the Datel unit involves 40 lines of the 50 line Heath H-8 bus. No processor clock is needed and the acknowledge lines to the Intel MDS-80 or SBC busses are not used. The Datel unit's on-board sequencing timer is disabled in favor of an interrupt generated

Table 6. Measurement Requirements

Analog Signals				
Class	Range	Precision	Conditioning	Post Conditioning
Pyranometer	0-15 mv	1%, 100 μv	x 150 low drift noise filter	Signal averaging in computer
Temperature	1-2 v	0.1°C, 1 mv	Noise filter	Signal averaging in computer Linearity corr.
Power supplies	0-3 v	1 mv	Noise filter	Signal averaging in computer
Wind direction	0-5 v	10 mv	Noise filter	-
Mode	0-5 v	0.25 v	-	-
Mass flow	1-2 v	1%	Noise filter	-

Digital Signals			
Source	Range	Precision	Conditioning
Interrupt	0.1 and 1 Hz	power line	Pulse = 15 μs
Turbine flow meter	100-500 Hz	0.5%	Noise discrimination, TTL compatible, divide to 100 to 200 pulses per gallon
Electric meter	0.1 Hz	1%	Debounce
Gas input	1 Hz clock	-	Debounce gate
Wind speed	0-300 Hz	1%	TTL compatible
Time in mode	-	-	Logic and/or functions

1/10 Hz clock provided directly to the H-8. Only two of the Heath bus lines need to be inverted to match the Datel logic. These are IOR and IOW. The bus expansion to a three slot expander does not require bus termination. The input of the Datel channels has 100 Meg ohm impedance and 100 pf capacitance. These values allow simple low pass filtering of the analog input signals (50 k ohms, 10 μf). This provides at least 30 db reduction of the 60 Hz interference. Operation of the thermistor temperature sensors is monitored by using A/D channels to measure the voltage powering the linearized thermistor circuit. Thus the output of the temperature probes is always normalized to the instantaneous power supply voltage. Careful ground referencing is necessary to prevent offsets in the millivolt range.

Digital data is acquired through the use of the Intel 8253 Programmable Interval Timer. This device contains three programmable 16 bit down counters. By reading these counters periodically both flow rates and integrated flows are easily measured. The counters provide for control through the pulse rate, the gate time, and the events which occur when zero count is reached. Very high or very low frequencies can be totalized or differentiated without tying up computer processing time. We have chosen turbine flow meters for the collectors, hydronic coil, and domestic hot water. Their signals must be amplified and made TTL compatible. A simple amplifier with some high frequency roll-off drives an operational amplifier comparator with an adjustable threshold. This provides a large symmetrical square wave which is immune to noise at either saturated end point. This signal is interfaced to TTL scalers through a diode, resistor network. The flow meters are scaled to 90-200 pulses/gallon to increase the capacity of the 16 bit counters. Wind speed is monitored by a photochopper anemometer which produces a quasi sine wave that is converted to TTL pulses in a Schmidt trigger. Electric power consumption in the solar system (pumps, control unit and furnace blower while on solar) is monitored by a demand meter which produces a pulse for each $.166 \times 10^{-3}$ kw-hr. These pulses are mercury switch openings and must be debounced before scaling. Variables such as natural gas consumption or time of operation of any component are monitored by generating a gate signal from pump or valve for the PIT and counting a standard frequency.

The computer has three types of inputs which are useful for providing control of data acquisition or in defining the mode of operation of the solar system. These are the two spare 8 bit parallel input ports, any spare analog channel, and the PIT's. In particular it is very easy to logically combine signals to produce a mode signal to gate the PIT to measure the time in mode without searching raw data or altering data processing paths. One analog channel can easily create command words by applying a fixed voltage to that channel in increments. Analog signals in the future will be integrated by the use of a precision voltage to frequency converter (Burr-Brown VFC 32, 12 bit resolution) feeding one of the 18 PIT's. The long characteristic times of solar related variables make this an ideal way to integrate them in digital form. The high sensitivity of the VFC 32 allows direct integration of even thermocouple signals. This method is ideal for integrating the pyranometer signal.

PERFORMANCE AND COST

The claims made for this system in the introduction will be examined in detail. The design yielded a true system in the sense that there are no difficult or unusual interfacing problems. The computer system is guaranteed compatible since it is all from one manufacturer. The A/D converter is especially designed for the Intel 8080 A microprocessor. The Heath bus organization is very close to the Intel bus. The Intel 8253 PIT is directly compatible with the Intel system in the Heath H-8. The clock speed of the 8080 A reduces problems with bus expansion. The interfacing itself is simplified by the availability of matching parts and components from Heath. Expansion of the computer capability is insured by the ongoing development at Heath, e.g., the recently announced floppy disk. Finally, the instrument operations are fully compatible with the convenient Basic language in which there is a set of utility routines available for machine language programs. If necessary the great wealth of background on 8080 A hardware and software supports more exotic projects. The measurement system is complete in the sense that any signal which can be converted to a voltage, a gate signal, or a frequency can be measured. In particular we are anticipating that ease of measuring real or elapsed time for any event or variable will greatly simplify data analysis and the design of short term specialized experiments without disturbing the general system operation. The ease of expanding the number of either analog or digital channels encourages complete measurement. The variables to be measured are realistically matched to the precision and accuracy of the data acquisition system with a bare minimum of analog or digital signal conditioning. Most of the equipment has been assembled with student help and has proven highly reliable. All custom made circuits are assembled by wire wrap techniques using either universal circuit boards or Vector board with Circuit-Stik pads and power busses. The cost of the system has proven to be very low. The computer and peripherals came to approximately $2,400. The analog system for temperature including all probes, power supplies, and the 32 channel A/D came to less than $40 per channel. The digital system costs about $15 per channel.

The quantitative performance of the system is excellent. For critical measurements such as inlet-outlet temperature differences the accuracy of each A/D channel is verified and corrections are applied to the voltage to temperature conversion function to remove most of the linearity error and any thermistor error. Line noise effects are much less than 1 mv rms when both passive analog filtering and digital filtering are employed. The turbine flow meters have a first order correction to the pulses per gallon conversion amounting to 1/4% for the 1" meters and 1/2% for the 3/8" meter (hot water). Stability of the power supplies is better than 0.5 mv over periods of weeks and over temperature changes of 10-15°C in the equipment room. Computer reliability is good although care must be exercised to eliminate static electric discharges from the carpeted floor.

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A MICROPROCESSOR COMPATIBLE TEMPERATURE MEASURING SYSTEM

Gene E. Kouba
Research Associate
Solar Energy Research Laboratory
The University of Tulsa
Tulsa, Oklahoma 74104

ABSTRACT

A low-cost microprocessor compatible temperature measuring system has been developed to provide accurate linearized temperature data over a wide range of temperatures. Details of design and construction are presented along with possible variations.

INTRODUCTION

The need to accurately measure temperatures over a wide temperature range in monitoring the performance of a solar energy system is evident. It is important that decisions be made concerning what is to be done with the various temperature data. For instance, it may be desirable to store discreet temperature samplings or to store average temperatures for some time increment or to use the temperature data to obtain other more complex information such as heat transfer rates or total heat transfer.

Microprocessor technology offers the flexibility and capability of data acquisition, storage, manipulation and reduction along with decision making capabilities. Therefore, it is desirable to have a temperature measuring system that is microprocessor compatible. Naturally, accuracy and stability over a wide useable temperature range are prime considerations in selecting a temperature measuring system. In addition, the temperature sensor should be relatively inexpensive, interchangeable and easy to calibrate. Other aspects to consider are the ease of signal conditioning, noise susceptibility and ease of noise filtering.

THE TEMPERATURE MEASURING SYSTEM

As part of an effort to develop a low-cost data acquisition and data reduction system for the University of Tulsa's Solar Home Energy Evaluation Project, several possible alternatives for a microprocessor compatible temperature measuring system were examined. Among the temperature sensing devices considered were thermocouples, thermistors, RTD's and linearized thermistor circuits (LTC) each with certain advantages and disadvantages. The LTC seemed to offer the best combination of advantages for the intended purpose. A linearized thermistor circuit consists of a thermistor composite and a resistor composite providing a linear response with temperature change. The thermistor composite consists of two thermistors packaged in a single sensor. The resistor composite is two metal film precision resistors (0.1%) which govern the temperature range over which the LTC produces a linear response. The device can be wired for single-ended temperature measurements providing either resistance or voltage varying linearly with temperature. Also two such devices can be wired together such that the voltage output is proportional to the differential temperatures. Figure 1 shows the circuit for linear voltage vs temperature for the LTC.

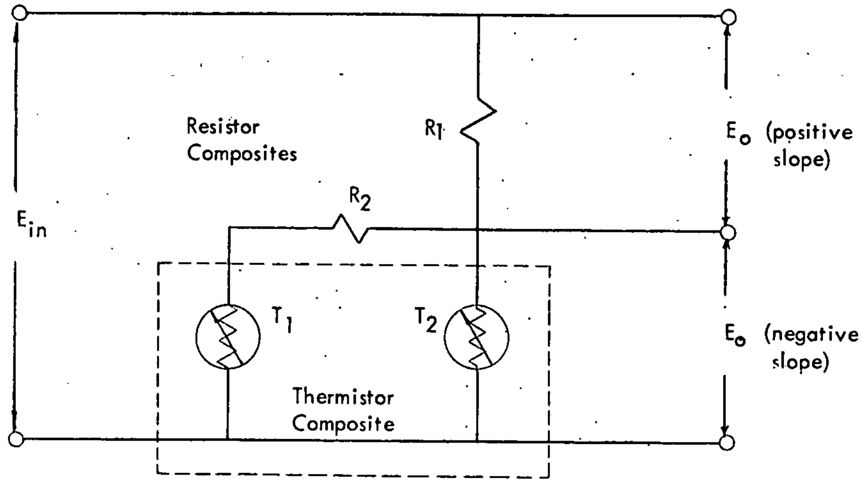

Figure 1. LINEARIZED THERMISTOR CIRCUIT
LINEAR VOLTAGE vs. TEMPERATURE

A linear response over many different temperature ranges can be obtained by selecting the appropriate resistor composites for a given range. The deviation from a linear response will in general increase with the width of the temperature range. Three ranges were considered appropriate for most solar system monitoring, -30 to 50°C, 0 to 100°C and 95° to 150°C. These were all possible with one thermistor composite and three sets of resistor composites with linearity deviations of .16, .22 and .07 respectively.

CIRCUIT DESIGN

The circuit and hardware for the temperature measuring system were designed and constructed to utilize the multimode capabilities of the LTC. Figure 2 shows the circuit design.

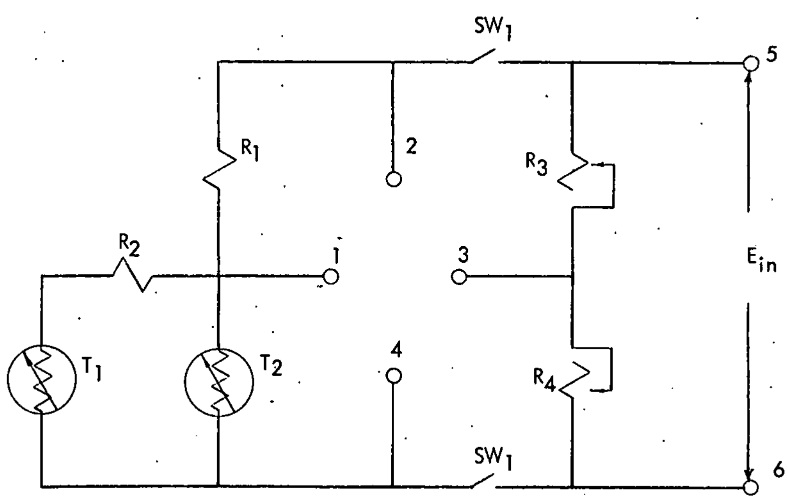

Figure 2. SCHEMATIC OF MULTI-MODE-LINEARIZED THERMISTOR CIRCUIT

With a supply voltage E_{in}, and the switch SW_1 closed, the voltage between points 1 and 3 varies linearly with temperature. Variable resistors R_3 and R_4 allow the intercept of the voltage versus temperature to be adjusted. R_3 and R_4 are preset with SW_1 open. For inputting to a microprocessor, R_3 and R_4 may be omitted. Voltage output between points 1 and 2 varies linearly with temperature and has a positive slope while the voltage output between points 1 and 4 has a negative slope. When no power supply is available, a linear resistance vs temperature is available by jumping points 2 and 4 together. The resistance between points 1 and 4 varies linearly with temperature. For measuring differential temperatures, two LTC's may be jumped together at their number 2 and at their number 4 points. With SW_1 closed and a supply voltage E_{in} the differential voltage between the number 1 points of the two circuits is proportional to the differential temperature.

The circuit of Figure 2, except for the thermistor composite T_1 and T_2, was housed in a small metal box with 6 external jacks connected to points 1 through 6 respectively. Inside the box the resistors R_1 and R_2 of the resistor composite have been installed in sockets for quick and easy change of resistors and temperature range. Attached to the outside of the box is the temperature probe which consists of the thermistor composite potted with silicone heat transfer grease in a sealed brass tube. Composite used is the Yellow Springs Instrument 44018. The brass probe assembly protects the thermistor composite while providing adequate heat transfer. The time constant for the assembly is 3 seconds in gently stirred water and 1 second for the bare thermistor composite bead. The probes may be inserted into fluid streams or into thermal wells to allow the entire probe and box assembly to be interchanged without disturbing the fluid stream. When the brass probe is potted in a thermal well with silicone heat transfer grease, the time constant is approximately 5 seconds. For this assembly no significant self-heating was evident at 40°C with an input voltage up to 2.25 volts.

Figure 3 is a sketch of the circuit for the adjustable voltage regulator used to provide the steady input voltage to the LTC's. One voltage regulator is used to power as many as 6 LTC's. The regulated voltage was found to remain stable to better than 1 mv even in fluctuating temperatures of approximately 10°C.

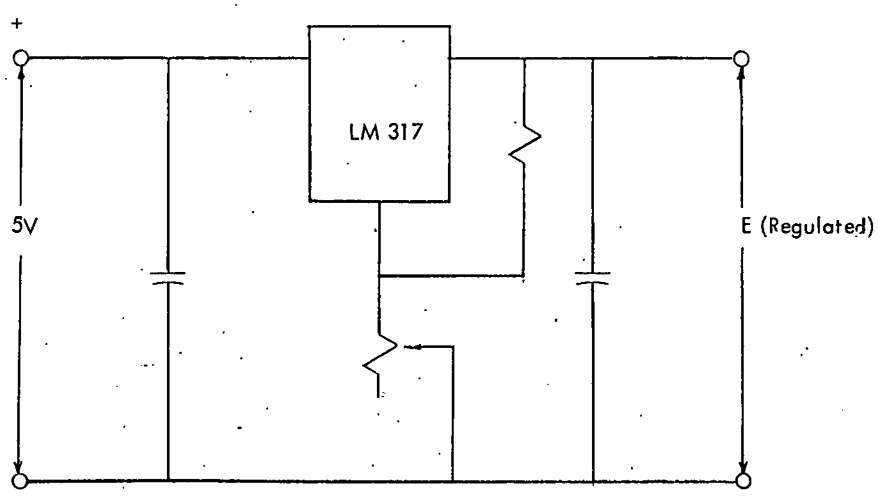

Figure 3. SCHEMATIC OF VOLTAGE REGULATOR CIRCUIT

CALIBRATION

Thirty thermistor composites in brass probes were calibrated in an insulated, temperature regulated water bath to determine their interchangeability and accuracy. The standard deviation of the thirty probes at six different temperatures ranging from 20 to 86°C was 0.06°C or less. This indicates their high degree of interchangeability. The temperature readings from the thermistor composites agreed with a 0.1°C mercury in glass laboratory thermometer to better than 0.1°C, including stem correction, verfying their accuracy. Preliminary tests of the linearized thermistor circuit in the voltage (E_{out} 1&3) versus single-ended temperature mode at 80°C produced readings approximately 0.15°C higher than the lab thermometer's readings with stem correction. This agrees with Yellow Springs Instruments specified linearity deviation at 80°C.

MICROPROCESSOR COMPATIBLE

In order to be microprocessor compatible, the analog voltage signal from the temperature probe circuit must be digitized. The particular analog to digital converter used is the Datel Sinetrac 800, 32 channel, 12 bit A/D multiplexer which provides a digital signal to the Heath H-8 microprocessor, (Intel 8080-A). The Datel A/D was selected for voltages from 0 to 5 volts. For 12 bits this is a resolution of 5000 mv per 2^{12} bits or 1.22 mv per bit. The voltage input (E_{in}) to the LTC should be selected to provide a signal (E_{out}) back to the A/D with a reasonable resolution match with the A/D. But if E_{in} is too large self-heating of the thermistor probe can cause an error in the temperature reading. For the linearized thermistor circuits used, a value of $E_{in} = 2.2$ volts yields a resolution of 0.10°C/bit from the Datel while producing an insignificant self-heat error in the thermistor composite.

To eliminate errors due to line voltage drift, the input voltage to the temperature probe boxes as well as the output voltages are monitored by the microprocessor. Both of these voltages are measured using the four point method. This eliminates errors due to voltage losses in the lines.

SYSTEM ADVANTAGES

The microprocessor compatible temperature measuring system utilizing a linearized thermistor circuit offers several advantages. Physically the system is rugged. Probe assemblies are easily and reliably interchanged and relatively inexpensive to build. The materials cost is approximately $20 per completed probe assembly of which the thermistor composites and the resistor composite cost about $12 and the rest of the hardware costs about $8. Adding to this the cost of the Datel A/D converter and installation produces a total cost of about $40 per temperature measuring channel. Electrical connections are simple with long cable runs posing no serious problems. Large signals are possible which can be easily digitized to 0.1°C resolution or higher if desired. Output impedance is low, reducing noise susceptibility and the signal can be easily filtered since the input impedance of the Datel A/D is high (100 megohms). Several modes of operations allow in place cross checking capabilities. All probes have been calibrated in a temperature regulated, insulated water bath to verify their accuracy and interchangeability. Also the time constant of the complete probe assembly including the thermal well was found to be about 5 seconds. The self-heat errors of the thermistor composite was found to be insignificant for input voltages, E_{in} less than or equal to 2.25 volts. Thermistor composites and certain resistor composites are available from Yellow Springs Instruments and can be purchased together under the trademark "Thermilinear Component". YSI also offers special calibration services when extreme accuracy is demanded.

Many design possibilities exist that might make this temperature measuring system more suitable for particular applications. For single mode operation in combination with a microprocessor, much of the hardware may be omitted simplifying the unit and lowering the cost. In some applications, switching the resistor composites in and out of the circuit to achieve different temperature ranges might be advantageous rather than replacing individual resistors. Possibilities for increasing the accuracy of the system include microprocessor compensation of LTC linearity deviation, reducing the linearity deviation by limiting the temperature range with appropriate resistor composites and individual calibration of LTC's.

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A Microprocessor Monitoring System for a Solar Energy Installation*

Harold E. Taylor
Associate Professor of Astrophysics

Faculty of Natural Sciences and Mathematics

Stockton State College
Pomona, N.J. 08240

ABSTRACT

An inexpensive Motorola 6800 microcomputer is used to continuously and automatically monitor the performance of four solar collectors and two heat storage units at Stockton State College's Energy House. The system currently monitors fourteen different temperatures and the insolation. Solid state temperature sensors, an inexpensive A to D Converter, a single multiplexing chip and a digital clock are the essential additions to the computer itself. Overall System cost is about $1000.

INTRODUCTION

A Solar Energy project was begun at Stockton State College in 1974 and has grown over four years to a significant Teaching/Demonstration and research facility. As five different types of solar collectors were placed into operation, the task of monitoring and comparing their performance coupled with the advent of the microcomputer led to the development of an automatic, flexible data acquisition system. This is a report on results from the first stages of this project.

The microcomputer based system was chosen because it offered a relatively inexpensive way to provide flexible, round the clock monitoring of the solar equipment. Other

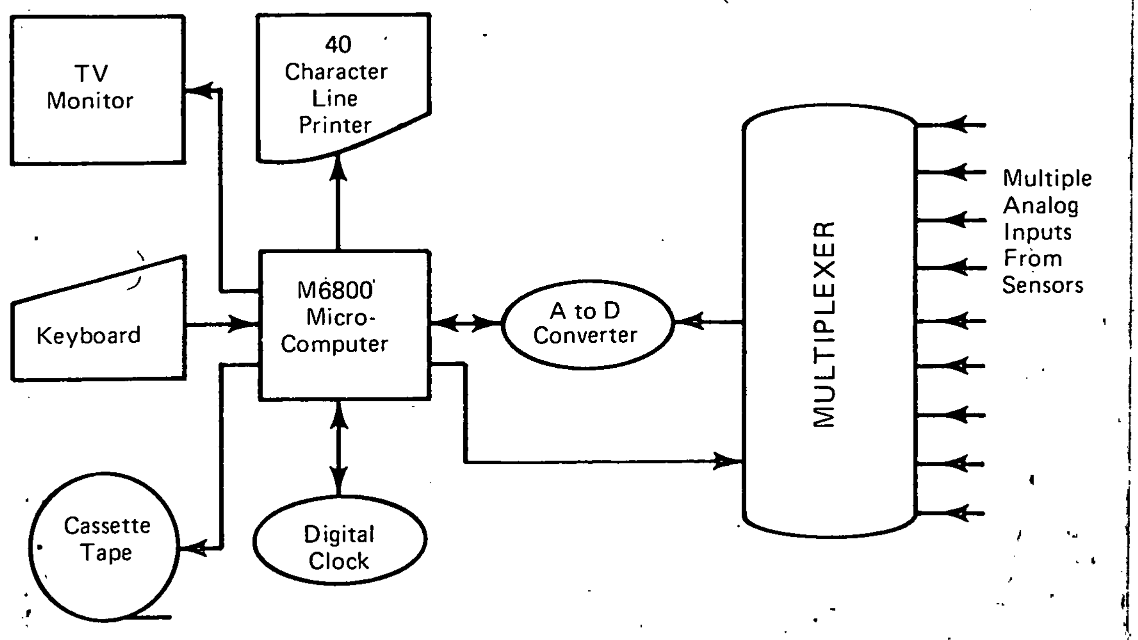
*This project supported in part by a grant from the Research and Professional Development Committee of Stockton State College.

similar work with microprocessors has been reported by several workers[1-5]. In this first stage the computer monitors insolation and temperature. The flexibility offered by a programmable computer, allows easy and inexpensive expansion of the system to include other measurements as the need arises. In addition, real time processing of the data is possible, the system could be interrogated remotely via telephone lines and could even be controlled via remote terminals. Finally the computer offers the possibility of a programmable control for the solar equipment and of the monitoring instruments. The wide ranging abilities of such a system require a good programmer who understands not only the computer system, but also the solar equipment. Experience at Stockton has shown that upperclass undergraduate physics majors frequently have the necessary background, and that graduates of Stockton's Applied Physics program interested in either computers or solar energy are prepared to do the necessary programming.

Although the computer system can be used to monitor any solar installation, a brief description of Stockton's[6] is is included here for completeness. It consists of two independent systems, one using water and the other using air the heat transfer fluid.

The system is a small scale version of what might be used to heat the building and to provide service hot water. Temperature sensors attached to the computer system are included at the input and output of each collector, the two heat storage devices, in the outside air and in the room air.

The computer monitoring system is shown in figure 1.



MICROPROCESSOR MONITORING SYSTEM

Figure 1

Taylor
2 of 9

Its heart is the M6800 computer, consisting of; central processor, random access memory, read only memory and peripheral interfaces. Connected to the interfaces are the TV typewriter, two cassette tape recorders, a digital alarm clock/calendar, a forty character per line printer, and the analog to Digital (A to D) converter with a sixteen channel analog multiplexer. The sensors providing analog voltages carrying fourteen temperatures and the insolation data are attached to multiplexer lines with the common output line feeding the selected voltage into the A to D Converter. The sixteenth multiplexer line is reserved for the output of a flow meter. Two additional interfaces are a crystal controlled interval timer and a scientific calculator.

With this general introduction to the Stockton setup, the reader can begin to understand the potential of the system. It has direct access to the essential parameters which describe the performance of the collectors along with the necessary signals to establish a regular data recording routine. All that is needed are the programs (software) to specify the intervals between measurements, to read and calibrate the sensors, to compute interesting quantities such as heat output, collector efficiency, relative performance of air and water systems etc.

MONITORING SYSTEM DETAILS

The monitoring system is conveniently described in four different segments: 1. The computer itself; 2. The interface to multiple analog sensors; 3. The permanant outputs; and 4. The programs or software. Each of these segments of the overall monitoring system will be described fully below. Reference to figure 1 may help in following the text. The system is intended to provide a flexible, automatic system for obtaining, recording and analyzing data on the performance of the solar equipment.

The Computer

The computer is centered around the Motorola M6800 microprocessor chip. This is connected to, up to 65,536 (65K) memory locations via sixteen address lines, 8 data lines and a few additional lines for timing, data flow, control, interrupt inputs etc. Programs to allow the user to communicate with the machine, that is; enter and change programs in memory, execute a program, trace or debug a program etc. are stored in read only memory (ROM). The communication between the operator and the machine is done via a TV typewriter terminal. This is an electronic typewriter with a TV monitor instead of paper. The computer itself, as well as the typewriter keyboard displays information on the screen. The TV terminal communicates with the microprocessor via an interface which makes the terminal look like a memory location to the computer. Writing a value in this location displays a character on the screen. Reading a value from this location obtains a character from the keyboard.

The computers memory consists of both random access read and write memory (RAM) and the ROM mentioned above. The RAM is necessary for the storage of data taken and the storage of programs. It is volatile, meaning that it forgets when the power is turned off. Thus programs stored in RAM must be stored on magnetic tape and reloaded each time the machine is turned on. For programs that have been tested and are used routinely, it is very convenient to store them in ROM. The most versatile ROMS are Erasable-Programmable-Read-Only-Memory (EPROMs) since these can be erased and reprogrammed quite simply. Programs stored in ROM are immediately available as soon as the system is turned on. What's more they can't be altered by programming errors or by power surges. Programs for monitoring Stockton's solar equipment are stored in ROM.

Additional important devices which are connected to the microprocessor through interfaces include a combination digital clock/calendar, a timer and a scientific calculator. The clock/calendar[7] is important because it allows the computer to obtain the correct date and time at will. For recording solar data having the time and date automatically available at all times is essential. The clock also has alarm features which may be used to remind the computer that it is time for certain special functions such as printing out a summary of the day's operations, taking data, reminding an operator of a need for attention etc. Since the alarm is set under computer control, the machine can store many different alarm times and functions.

The timer is useful for both measuring an unknown interval between two events and for marking a regular time interval. At present the most useful function of the timer has been to measure the interval between successive measurements and to interrupt the computer to tell it that it is time to take new measurements. Taking advantage of this feature allows the computer to be used for other purposes most of the time, and yet still record the regular measurements at the proper times.

The calculator is included to allow easy computation. Once the data recorded is converted to calculator format, any calculations that can be done by an ordinary scientific calculator can be carried out by the computer. This allows real time analysis of the data being obtained.

The above description of the computer hardware should evoke numerous ideas about the far ranging capabilities of such a machine. Programs have been written to allow the use of higher level languages like BASIC or even APL on the system. This can simplify programming, although attention must be given to the interfacing of the BASIC programs with machine language programs necessary to read the sensors. The hardware for reading sensors measuring temperature, insolation and fluid flow are described in the next section.

Interfacing Analog Sensors

Since the computer is a digital device, the analog signals from the temperature, insolation and flow sensors must be converted into digital format. This is carried out by an analog to digital converter chip. An inexpensive and satisfactory device has been found to be the National Semiconductor MM4357. With the connection of power lines, a reference voltage, a clock signal, three control lines and the 8 output lines, this chip converts input voltages between the reference voltage inputs into a digital value between 0 and 255. For the temperature sensors and the insolation monitor, the necessary reference voltage must be maintained using regulators for stable operation. In the current set up levels of 2.00 to 4.55 volts have been chosen so that 1 count corresponds to a 10 millivolt signal. This seems adequate for most purposes though a 10 or even 12 bit converter could extend the possible input voltage range without sacrificing resolution.

The time required to make a measurement with the A to D converter is about 2.5 milliseconds. Faster conversions are possible if necessary too. In solar energy systems, most parameters change over minutes or even tens of minutes, so successive measurements, taken milliseconds apart are perfectly adequate. Thus, it is economical to use an analog multiplexer to sequentially switch the A to D converter among the various sensors desired. For this we used the CD4067 device. This chip decodes the binary number represented by the signals on four input lines and turns on one of 16 different input lines to a common output. Thus, by outputing a binary value from 0 through 15, the computer can select any of the 16 sensors connected to the multiplexer. The chip also has an inhibit line which turns off all its inputs allowing expansion to more than 16 inputs by adding additional multiplexer chips. No problems have been encountered with the multiplexer.

The sensor used to measure temperature is the National Semiconductor LM3911 temperature controller. These units measure the temperature with an uncalibrated accuracy of ±10°C and a typical linearity of 0.5% over a temperature range of -25°C to + 85°C. With a simple single temperature calibration an accuracy of ± 1°C is obtained over the entire 110°C range covered. This seems to be adequate for most purposes. Extended temperature range and increased accuracy is obtained with the more expensive temperature transducer, the LX4500. ($4.50 each) The LM3911 sells for about $1.00 each in small lots.

Power for all fourteen 3911's is obtained from a single

6.8 Volt zener regulated supply so that no components in addition to the controller chips itself are required at the spot where the temperature is to be measured. The circuit is shown in figure 2. They are fed with 3 conductor,

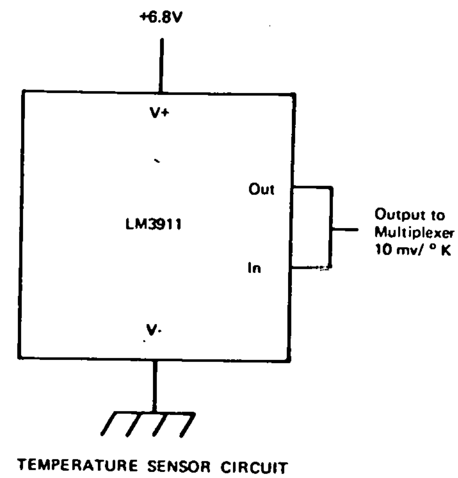


Figure 2

shielded cable to reduce noice pickup since some of the leads are over 50 feet long. The sensor response time to a temperature change ranges from 3 or 4 minutes in still air to less than 10 seconds in a high heat transfer medium.

The insolation monitor is an operationa amplifier connected as a current to voltage converter measuring the short circuit current output of a silicon solar cell. The circuit is shown in figure 3. An integrating circuit would be

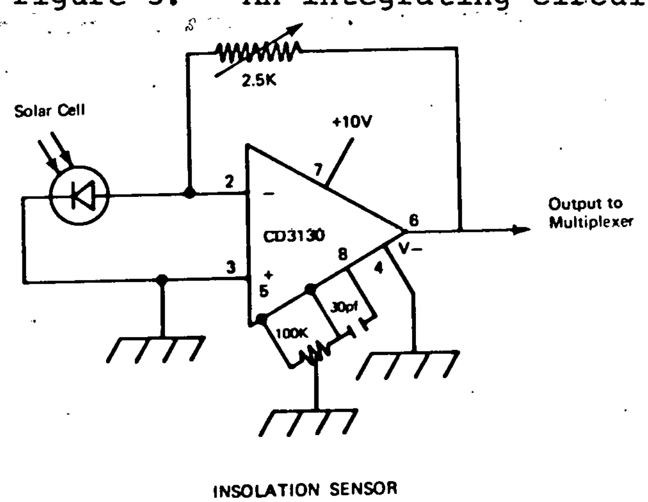


Figure 3

preferred, but as yet, no fully satisfactory one has been found. Additional tests are being conducted.

Data on the flow meters is not yet available because of a malfunction in the associated electronics. The device being installed is manufactured by Flo-Scan instruments. Future reports will describe results after it is tested.

Besides the analog inputs, simple one bit digital inputs indicating the state (ON/OFF) of the circulator and blowers are available to the computer. These are used to determine turn ON/OFF times and time of operation.

The Permanent Outputs

A choice of two forms of permanent output is available on the Stockton system. One, a 40 character per line printer, for human readable output and the other a cassette tape recorder for storing the data in computer readable format. Both are operated under the control of programs described in the next section. Both were also built from inexpensive kits purchased from Southwest Technical Products Corp. in San Antonio, Texas. They have performed as intended with little trouble.

The Software

The programs written thus far have been to read and record the data at regular intervals. The primary program monitors the clock and reads the sensors each minute, displaying the results together with the time and data on the TV screen. Every 10 minutes, averages are recorded on the printer for a permanent record. This program runs routinely when the computer is not being used for other purposes. It has been reliable and trouble free.

The program uses numerous subroutines, the most important of which are: read the date, read the time, read the A to D converter, display the sensors, convert A to D output to degrees C, convert binary temperatures to BCD temperatures, check pump/blower status, etc. The programs have been written in 6800 assembly language and will not be presented in detail in this paper. Readers who desire more information should contact the author.

CONCLUSIONS

This initial report is intended to describe the system being developed at Stockton College, and several general conclusions may be mentioned. Firstly, the important ingredients of such a microprocessor based system seem to be a computer with some permanent output devices, a clock/calendar and an array of sensors to measure the relevant parameters. Measurements can be made at regular intervals from as short as a few milliseconds (for a single sensor) to as long as desired--24 hours or even longer. Analysis of the resulting data is simplified through such devices as a calculator interface since the microprocessor itself does not even have multiply and divide instructions and thus would have difficulty doing solar calculations which invariably require trig functions at least. The computer would become usable for other purposes if its interrupt features were utilized to initiate the solar data taking sequences, thus freeing the computer between these times. Work is currently in progress on this important improvement.

No sensors for measuring air flow have been obtained although these would improve the monitoring of the air collectors. Also connections to the annamometer to obtain readings of wind speed and direction would be simple and useful.

It appears from the work done already, however, that a microprocessor based monitoring system can be built inexpensively and run reliable. It's flexibility through programming make it particularly attractive for experimental type setups where plans frequently change as new insights are obtained.

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DESIGN OF THE DATA ACQUISITION SYSTEM AT SOLAR ONE

James H. Higgins
University of Delaware
Institute of Energy Conversion
One Pike Creek Center
Wilmington, Delaware 19808

The data monitoring equipment at the University of Delaware's energy research laboratory, Solar One, is examined with regard to its capabilities and limitations. Specific problem areas are identified and recommendations are made with regard to scheduling of similar data monitoring tasks. Innovative techniques are described, emphasizing multiplexing and mass data storage.

I. Introduction

The full-scale energy research laboratory of the University of Delaware's Institute of Energy Conversion, Solar One, was instrumented under an ERDA grant during the 1975-1977 period. The purpose of this program was to collect and store daily energy data from approximately 300 sensor points to allow determination of the performance of the facilities solar system. The installed data monitoring system is neither completely "scratch" built nor off the shelf, but contains examples of both approaches. This particular mix of methodology was not selected outright as the optimum approach, but the result of adaptations of previous approaches modified to meet greater demands. The original design of the monitoring system at Solar One for internal use consisted of a limited number of thermocouple and millivolt inputs; sufficient for component analysis. The subsequent acceptance of the first ERDA data acquisition grant, however, increased demands on the original design tenfold. The existing design was modified and construction begun. The data gathering portion of the system was fully operational one year later. Work continued past this date on the computer interface and software development. Several new and useful techniques were developed to channel and store the 1.2 million data characters generated by the system daily. It was this bulk of data that presented what was easily the single largest problem encountered in the program.

The lessons learned have application in both the "scratch" built and off-the-shelf type approaches to data monitoring.

II. System Description

A. Inputs

Solar One (Figure 1) was fully instrumented to determine in detail such parameters as heat load, solar system efficiency, passive heat gain and limited photovoltaic analysis. The data acquisition system (Figure 2) contains inputs for pressure, wind speed and direction, relative humidity, temperature, radiation, precipitation and voltages. The solar system of Solar One employs three eutectic salt storages, a solar assisted heat pump, photovoltaic arrays and electrical storage facilities. As a result, the analysis of these systems require large numbers of temperature, pressure and electrical measurements. At the core of the system is an Esterline Angus D2020 20-channel data logger. This unit contains a 20-channel multiplexer, A to D converter, internal clock, visual 4-digit display and 21-column printer. It was extensively modified by additional multiplexing and magnetic

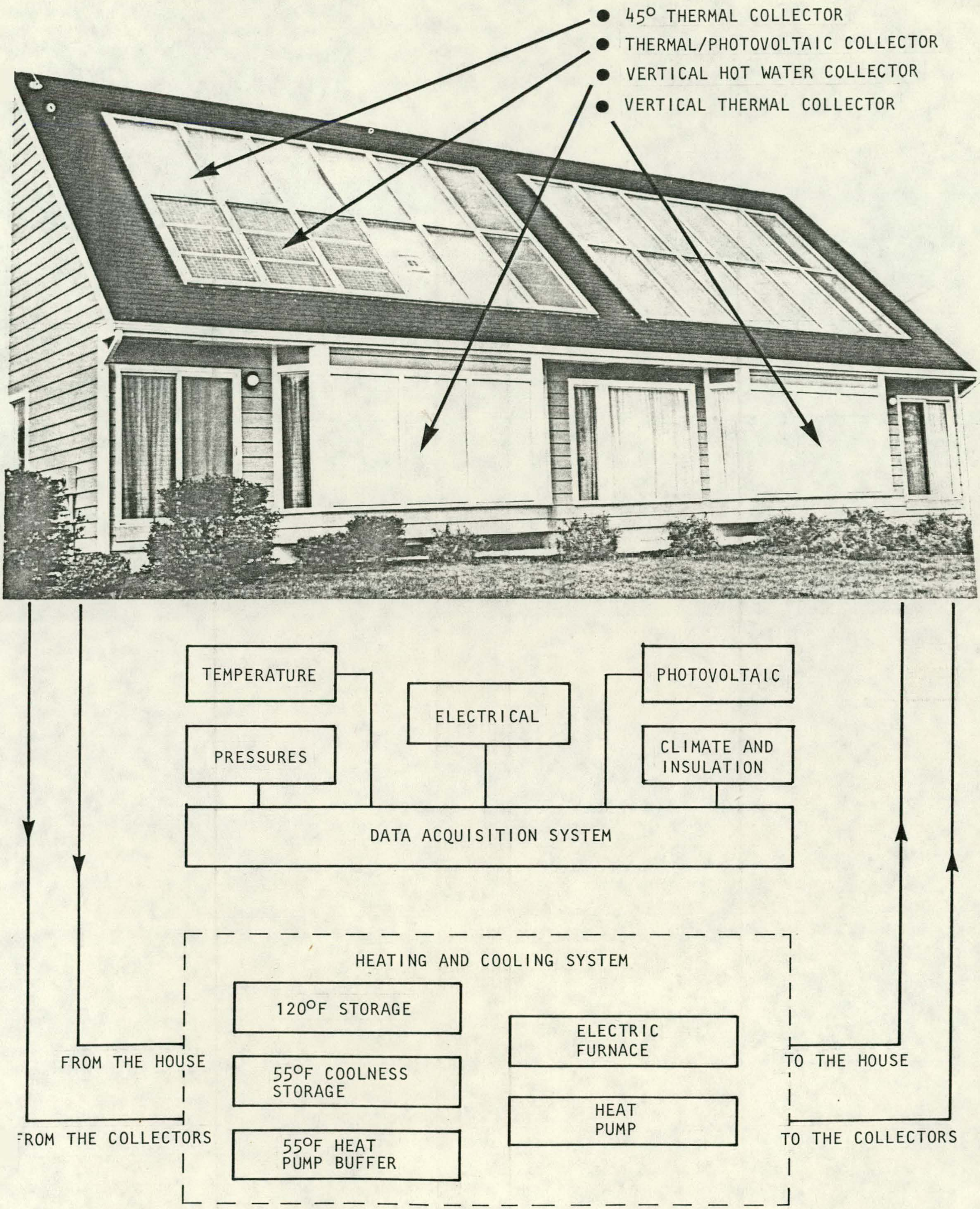
45° THERMAL COLLECTOR
THERMAL/PHOTOVOLTAIC COLLECTOR
VERTICAL HOT WATER COLLECTOR
VERTICAL THERMAL COLLECTOR
TEMPERATURE
PRESSURES
ELECTRICAL
PHOTOVOLTAIC
CLIMATE AND INSULATION
DATA ACQUISITION SYSTEM
HEATING AND COOLING SYSTEM
120°F STORAGE
55°F COOLNESS STORAGE
55°F HEAT PUMP BUFFER
ELECTRIC FURNACE
HEAT PUMP
FROM THE HOUSE
FROM THE COLLECTORS
TO THE HOUSE
TO THE COLLECTORS

Figure 1

SOLAR ONE DATA ACQUISITION SYSTEM BLOCK DIAGRAM

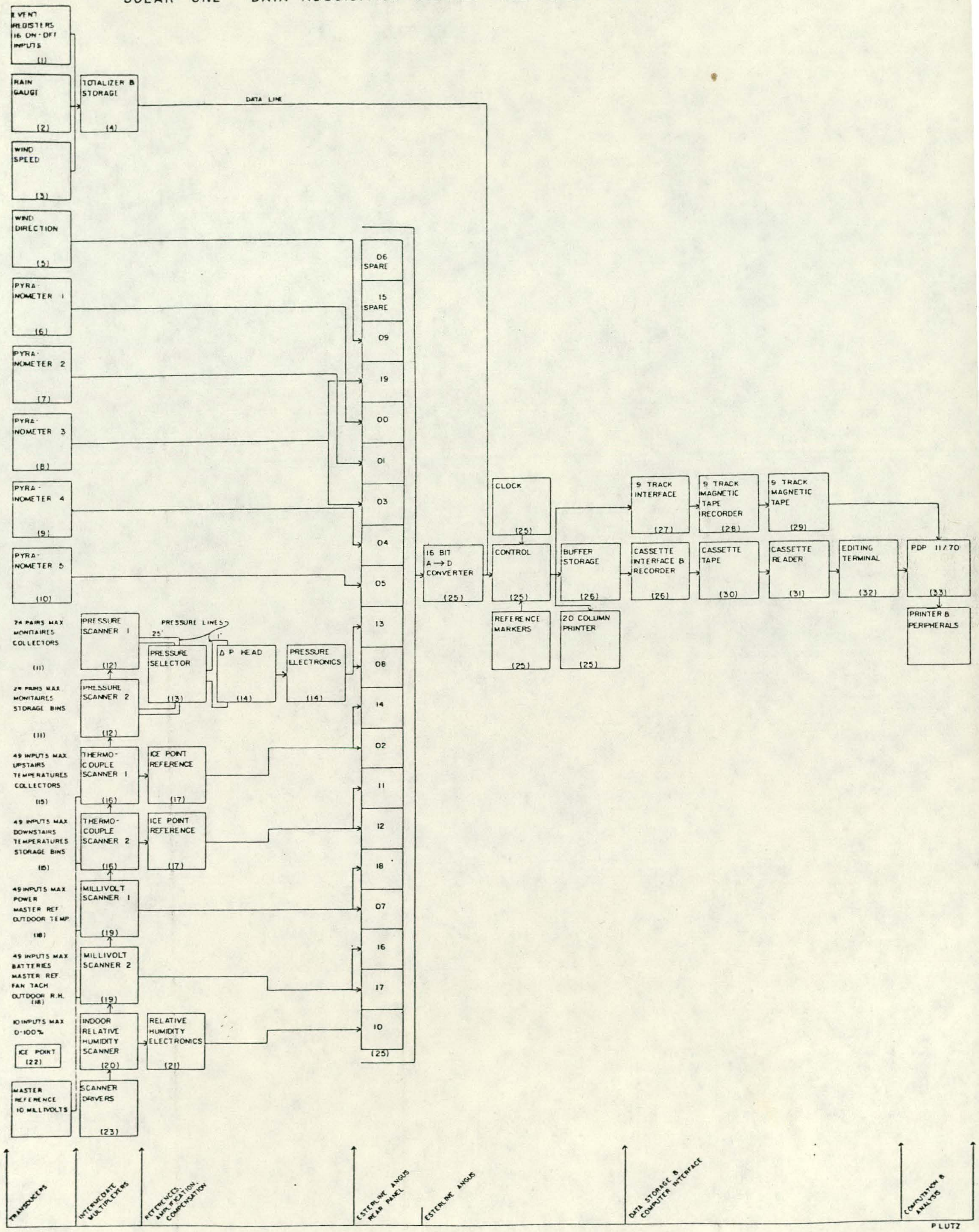

Figure 2

tape storage capability. The internal A to D has sufficient input amplification for Type J thermocouples, which are utilized for temperature measurement. 96 such thermocouples feed two outboard multiplexers (GTE stepping relays), which, under control of the Esterline Angus Timing Logic, select one thermocouple at a time is presented to the Esterline Angus 20-channel multiplexer. Each scan of the 20-channel multiplexer advances the 48-channel stepping relays one position. 48 scans of the 20-channel primary multiplexer are required to scan all of the inputs of the secondary multiplexer. This form of secondary analog multiplexing allows expansion of the input capability of the Esterline Angus from 20 to 200 inputs. Four stepping relays are utilized, two for low level millivolt inputs and two for thermocouple inputs.

While the normal scan rate of the D2020 for 20 channels is approximately seven seconds, the secondary multiplexed signals may be sampled only once every seven minutes. Two main rates of scanning, therefore, exist; once every seven seconds for the high-speed channels and once every seven minutes for the low speed channels. The inputs are separated according to the required sampling rate with pyranometers and other transient signals sampled once every seven seconds. Most temperature data is sampled by the low speed circuit every seven minutes. Digital sampling of wind speed (switch closure count), rain fall and event data is performed every 60 seconds and this data is interfaced directly into the data logger in digital form.

Total signal input capabilities of the system are shown in Table 1.

B. Data Handling

A unique data storage system was devised that utilizes standard 90-minute cassette tapes and a medium quality cassette recorder. In order to store the required quantity of characters, a high density format was developed that allows $3x10^6$ digits per 90-minute cassette, and operates at a 4800 baud-rate at 1-7/8 IPS. The digitized data is temporarily stored in semiconductor memory until a sufficient number of characters are generated to form one block of data. This block is then written on cassette tape along with coded status and time information. One 90-minute cassette contains two full days of data ($2.4x10^6$ characters).

The transfer of data to the University's computing center was accomplished with a modified Tektronic Graphic Terminal, capable of accepting parallel input data from the interface device and transmitting it to the PDP-11 central computing facility. The transfer rate of 4800 baud allowed one days data to be entered for computation in 45 minutes. Computation is performed in daily increments, being further subdivided into 7-minute blocks. After computation, output records of approximately $3x10^5$ characters allow sufficient resolution for later analysis if required, yet ease the storage volume problem so that the original raw data files needn't be saved. The first analysis performed on the raw data consists of a diagnostic check which proves extremely helpful in pinpointing hardware malfunctions.

The monitoring system operates on a 24-hour basis with scheduled preventive maintenance periods.

SYSTEM INPUT CAPABILITIES

1. 98 low speed, type J, thermocouple inputs; locally compensated; arranged in two groups of 49 each. Sampled a minimum of once every seven minutes.

2. 98 ± 0-10 DC millivolt, low speed analog inputs; arrange in two groups of 49. Sampled a minimum of once every seven minutes.

3. 36 digital (contact closure or BCD data) inputs arranged as nine 4-bit characters. Sampled once every minute.

4. 48 absolute or true differential pressures from 0-10 mmHg referenced to ambient. Sampled once every seven minutes.

5. Ten relative humidity locations; temperature compensated. Sampled a minimum of once every seven minutes.

6. Five pyranometers sampled once every seven seconds.

7. Wind speed and direction -- Wind direction sampled once every seven seconds while wind speed is integrated and sampled every minute.

8. Real time 24-hour clock and internal reference markers updated and read once per minute.

9. Redundancy on all low speed and one of the high speed inputs.

Table 1

A 9-track incremental recorder was installed after nine months of operation with the cassette system due to the inordinate amount of time required to serially transfer cassette data to the University central computer. Both systems run in paralle, reduce the possibility of hardware failure resulting in loss of data.

C. Methods

Several techniques developed for use in this data acquisition system may find use in similar data monitoring tasks. These are presented below.

a) Secondary Multiplexing

This was accomplished with four GTE rotary stepping relays. These devices were chosen for their dependability and cost. Gold flashed contacts reduce the possibility of induced thermal EMF and contact resistance. Each relay is housed in a wooden box with copper wire connecting the terminal strips to the relay. In order to ensure isothermal contacts for both junctions of each thermocouple, the terminal strips are mounted on a 1/4" thick aluminum plate, and the entire box then insulated with foam. The output from the dual set of wipers on the stepping relay directly feeds a battery powered ice point reference, also contained within the isothermal housing. Output from this device then feeds the 20-channel multiplexer of the Esterline Angus. Stepping power requirements for each relay is 50 volts, at 750 MA, and the automatic homing contacts ensure proper positioning for each seven-minute scan.

Ice point referencing for thermocouples is accomplished by routing the output wipers of the two thermal stepping relays through a battery powered ice point reference. This reference is housed within the relay enclosure and mounted isothermally on the 1/4" plate. This configuration delivers a fully compensated signal to the primary multiplexer. Differential pairs of thermocouples and millivolt signals are accommodated by two similar stepping relays, however, without ice point referencing.

Multiplexers are installed as close to the transducers as possible and outputs from each are shielded and run to the central data logger in conduit.

b) Digital Recording on Cassette Tape

The high density Symmetrically Amplitude Modulated Signal (SAMS) data storage system was devised to operate at a 4800-baud rate and at a 2600 BPI density on standard audio tapes. This was accomplished utilizing consumer quality cassette equipment and represents a speed advantage of twice that of any equipment available at that time, with the exception of 9-track recorders. The recording method consists of converting 4-bit BCD data into serial sine wave data with the amplitude of each complete sine wave representing a one or a zero. A commercially available cassette recorder will faithfully reproduce a 5KHZ tone. The amplitude of each cycle in that tone may be modified digitally (see Figure 3) to represent a digital character. This tone must be presented symmetrically, however, to a standard voice grade recorder to prevent DC offset in the recording electronics.

SAMS WAVEFORMS

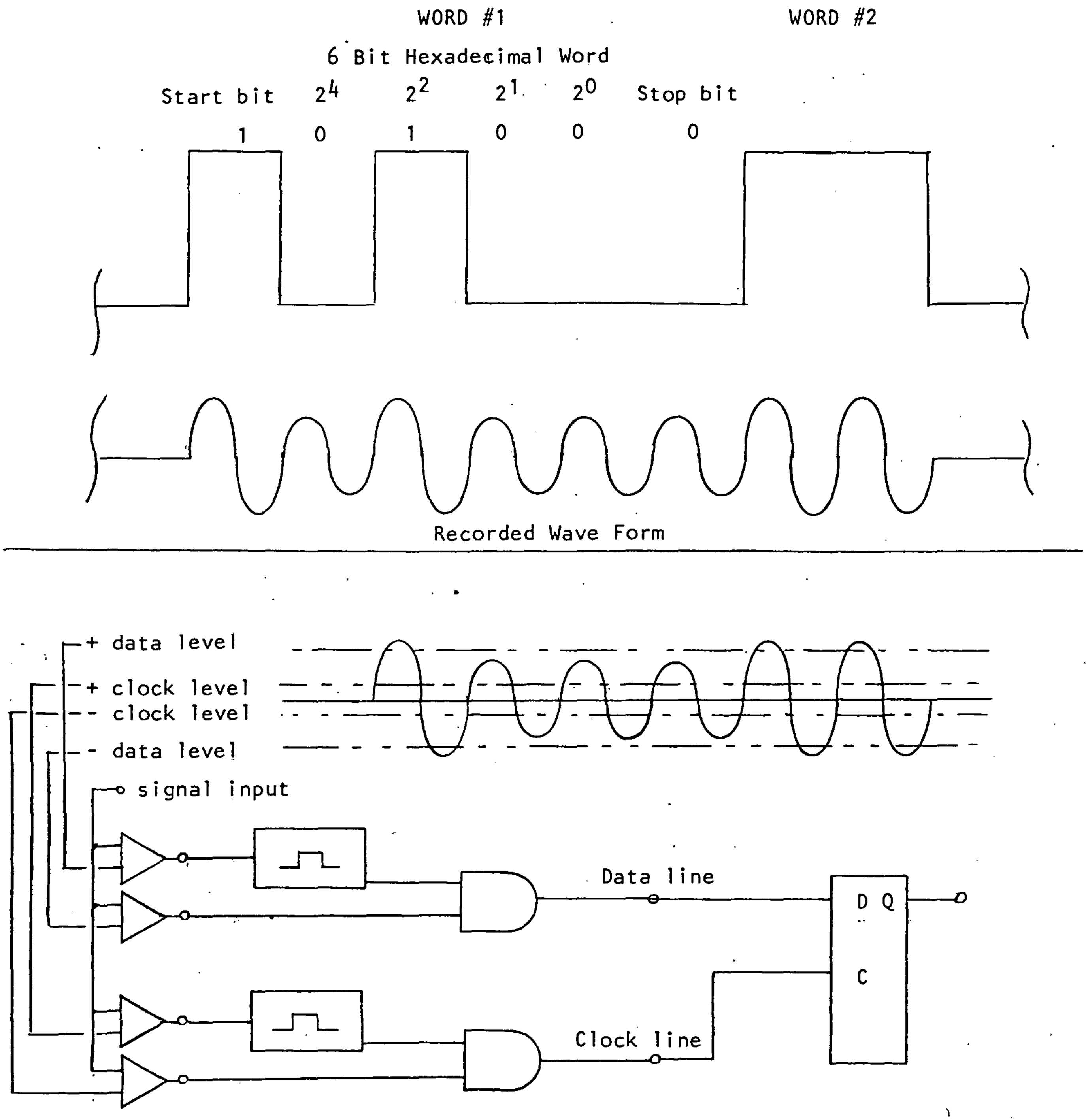

Figure 3

The character format utilized is a block of 723 hexadecimal (4-bit) characters, each with start and stop bits added. The 4-bit character scheme utilized has 14 valid states. An error detection scheme was implemented using the spatial relationship between the start bit and stop bit and the necessity of a valid character in between. While a parity bit would seem necessary for error detection, experience showed that errors did not appear singularly. Entire groups of characters were effected by the quality of the oxide coating such that parity would not have substantially increased the error detection rate, but would have reduced data density by 16%. Playback of the tape is accomplished again with consumer grade recorders interfaced with a logic device capable of decoding the SAMS recording. Of note is the fact that the SAMS is self-clocking and is, therefore, insensitive to wide variations of tape speed. Although the system is by nature amplitude sensitive, no special methods are employed to ensure constand amplitude recording or playback. It is felt that incorporating amplitude control could substantially reduce the error rate associated with the SAMS. The majority of errors result from drop outs on the tape, areas where magnetic oxides fail to adhere to the mylar film backing. High quality chromium dioxide tapes should be used to minimize the problem. This system is one of a very few non-saturation data recording techniques and represents the highest density system known at this time. It is to be again emphasized that this system utilizes cassette recorders in the $25-40 range. Due to the error rate observed for the SAMS (1 bit in 10^6), it is not recommended for critical digital data storage, however, it is more than adequate for low cost data monitoring applications.

c) Redundancy

Where data reliability dictated higher performance, signal path redundancy was employed around expected problem areas. Sufficient analog inputs existed to sample key signals twice with no decrease in sample rate due to the cyclical nature of the multiplex scheme. This proved to be significant, particularly when the primary multiplex (20 channel) relays became maladjusted. All of the secondary multiplexer outputs are fed to two primary multiplex channels simultaneously, as well as several of the more important high speed channels. Later in the program a 9-track incremental data recorder was installed to parallel the SAMS system and to take advantage of the large storage capability of 1/2" magnetic tape. This also generated a parallel method of introducing the acquired data to the central computing facility.

In other than real-time analysis systems, it is of primary importance to improve the reliability of critical data paths. This is more easily accomplished in the original design than as a retrofit. In a real-time analysis system, faulty areas are immediately identified and corrected, whereas with the intermediate step of data recording and batch processing, system faults may take several days to be identified.

d) System Limitations

The experience gained from this program should serve to reinforce some preached but oftentimes, not practiced, concepts in system design. In particular, the following characteristics of the data acquisition system should be carefully evaluated before implementing a new system in the same fashion.

1) The use of phone coupled data transmission was subsequently discarded in favor of matnetic recording because of data transmission rates and data error.

2) Had it not been for a rigorous daily manual checkout, the non-real-time aspect of data analysis could have left system failure undetected for several days causing unrecoverable loss of data.

3) The use of non-standard data collection equipment at that time offered a potential initial capital savings but in reality cost more than off-the-shelf equipment due to design, maintenance and debugging costs.

III. Results

The data acquisition system was operated from February 1976 until December 1977. At that time, many experiments in Solar One were changed and no longer demanded the sophistication of the system. Work on the project was performed according to the schedule shown in Figure 4. The main operating characteristics of the system are:

• Hardware cost	\$10,000
• Number of monitored data points	296
• Total number of data characters transferred	600×10^6
• Average system error rate	15%
• Period between system failures	40 days

IV. Conclusions and Recommendations

Based on the efforts associated with this project, the following conclusions have been reached:

A. The majority of the labor expense resulted from the time devoted to installing and interfacing transducer equipment, as well as developing computer software.

B. The generation of reduction software did not commence until the entire data acquisition generated a specimen data tape. A parallel effort in reduction and hardware would have reduced the completion time of the entire system.

C. Real-time analysis should be utilized whenever possible to prevent delays in identifying system faults. Where real-time analysis is not available, rigorous manual diagnostic routines should be employed daily to ensure data quality.

D. The technical problems associated with "scratch" building a data monitoring system are being reduced dramatically with large-scale integration and the availability of high power microprocessor equipment. As the microprocessor industry attempts to fill the low cost instrumentation market, dedicated LSI circuitry will take on modular characteristics which will interface with a minimum of support equipment. Complete data acquisition packages on a chip are already appearing complete with front end multiplexing and computational capability in the range of $200. "Scratch-built" systems as a result will become more attractive if these devices are properly utilized.

Table 4

DELIVERY TIMETABLE D.A.S. HARDWARE

- High Speed Cassette Interface
- Event Inputs Complete
- 9-Track Recorder Installed
- Cassette Interface Operational
- Temperature System Calibration
- Pressure System Calibration
- Master Reference Installed
- Power Data Monitored
- Redundant Channels Installed
- Cell Data Monitored
- Wind Instrumentation & Outdoor RH Removed
- Maintenance Schedule
- Flow Measurement Complete
- Batteries Monitored
- All Pressures Monitored
- All Thermocouples, Pyranometers & Windspeed Monitored
- Data Collection, Secondary Multiplex Driver's & Cassette System Complete
- Instrumentation Specified & Ordered
- Contract Awarded

JULY '75 | AUG | SEPT | OCT | NOV | DEC | JAN '76 | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEPT | OCT | NOV | DEC | JAN '77 | FEB | MAR | APR | MAY | JUNE | JULY

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Low Cost Microprocessor Based Data Acquisition System

by

J. H. Schlag, A. P. Sheppard, J. M. Wood
Georgia Institute of Technology
Atlanta, Georgia 30332

Abstract

A data acquisition system based on an Intel SBC 80/10 microprocessor is presently being used to monitor the performance of an experimental solar agricultural drying system. The current configuration of the system is given, however, the system is flexible enough to meet a wide variety of solar data acquisition requirements.

Introduction

This data acquisition system was designed to monitor the performance of a 1200 ft^2 hot air solar collector and storage system to be used for drying peanuts, tobacco, and forage crops.[1] Monitoring the system required data from up to 50 thermocouples as well as readings of the direct incident radiation, total vertical radiation, total angular radiation, total spectral radiation, wind velocity, wind direction, ambient air temperature and differential temperature. These data are general enough to characterize most solar installations so that only minor modifications to the data acquisition system would be required to use it for other applications.

Figure 1 shows the interrelationship of the Intellec 80/10 to the other components of the data acquisition system. Data enters the system through the 60 point cross-bar scanner. Fifty channels on the scanner are reserved for copper-constantan thermocouples and 10 are used for meteorological data. The thermocouple data is processed through the compensating amplifier. The data is then processed through a Zeltex 10 bit Analog to Digital Converter and sent to the microprocessor. Data is sampled every 10 seconds upon receipt of a signal from the real time clock and the microprocessor averages it over a programmable time period from every 30 seconds to once a day. It then outputs the averaged data to either a teletype or stores it in a memory buffer to be sent to a tape recorder.

Microprocessor

Figure 2 illustrates the configuration of the Intellec SBC 80/10 microprocessor. The CPU performs all of the system processing functions and provides a stable timing reference for all of the other circuits in the system. The Random Access Memory (RAM) contains 10^{24} x 8 bits of on-board temporary data storage. The Electrically Programmable Read Only Memory (EPROM) can contain up to 4096 x 8 bits of permanent program storage. The serial I/O interface can be configured as an EIA RS232 interface or as a teletype-compatible current loop interface. The Parallel I/O Interface provides 48 signal lines for the transfer and control of data to or from peripheral devices.

[1] Work sponsored under grants from the Georgia Institute of Genetics and the U.S. Department of Agriculture, Contract 12-14-7001-566.

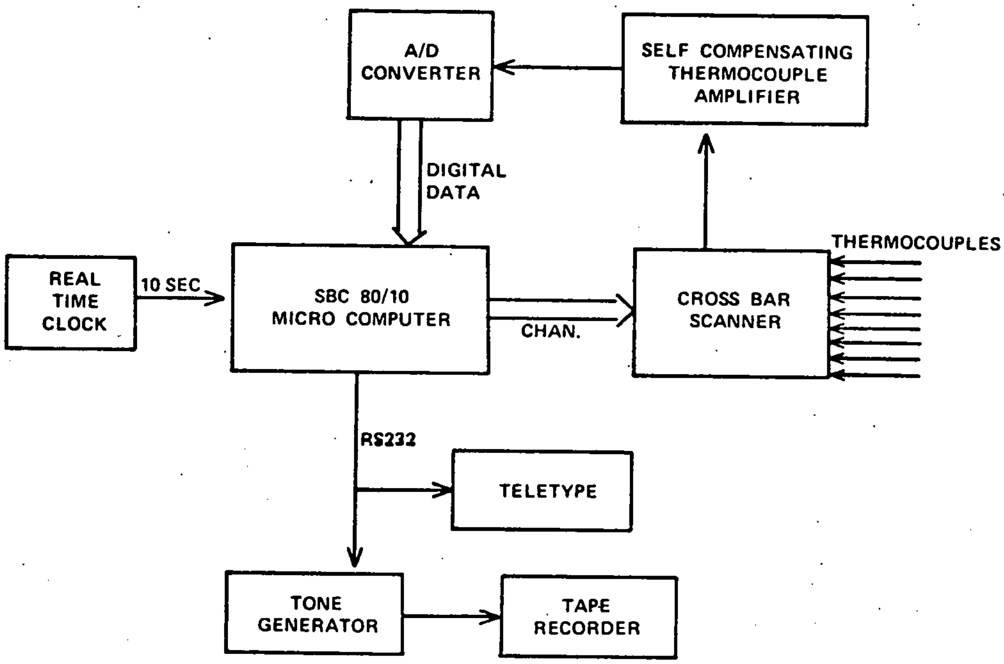

FIGURE 1. DATA ACQUISITION SYSTEM

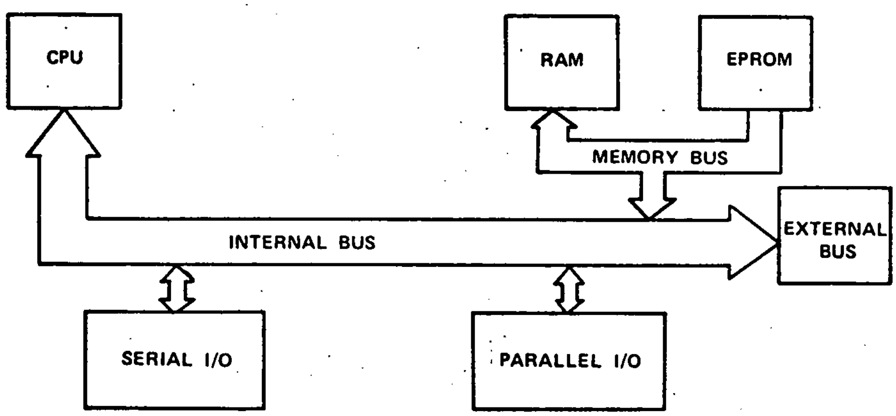

FIGURE 2. CONFIGURATION OF THE INTELLES SBS–80/10 MICROPROCESSOR

Figure 3 is a simplified software flow chart illustrating the micro-processor's decision processes in initiating data scans, averaging data, scaling data, and printing the data to either the teletype or to the tape recorder. Section 1 of the flow chart checks the real time clock and samples the data from each channel. Section 2 averages the data and prints it on the teletype or records it on the tape recorder.

Real Time Clock

The real time clock generates a 10 second flag to the computer by counting the 60 HZ line frequency down to .1 HZ as shown in Figure 4. A 60 HZ sine wave is shaped into a square wave with diode D1 and schmitt trigger J90. The square wave is divided by 600 by counters J15, J14, and J13. The resulting 10 second clock triggers flipflop J12 as a flag to the computer. When the computer reads the clock flag, it signals the scanner to send data and it also resets J12 to catch the next clock cycle.

Cross-Bar Scanner

The physical process of scanning is performed by a relay system that was originally constructed by Western Electric. The copper components of the relays and the small integrated construction of the relay system make it ideal for this application.

Copper-Constantan thermocouples are used in the system because Copper-Constantan offers several advantages over the Iron-Constantan we have previously used. Since copper does not rust like iron, time will be saved that was previously used to replace old thermocouples. Also erroneous signals caused by rusting thermocouples will be avoided. Copper Constantan's greatest advantage, however, is its ability to connect to copper wires or copper relay components without creating undesirable thermocouple junctions. This greatly simplifies construction of instrumentation that employs thermocouples.

The only two notable disadvantages are the reduced Seebeck coefficient and the greater non-linearity. The Seebeck coefficient drops from ~.052 V/°C for Iron-Constantan to ~.041 V/°C for Copper-Constantan. This reduction is easily compensated for with available amplifiers and creates no difficulty except in noisy environments. The greater non-linearity can be compensated for by applying 2nd order corrections thus reducing the error to ~1°C. This represents the practical limits of accuracy since noise can produce as much error.

Self Compensating Thermocouple Amplifier

Thermocouples have been used for many years as an inexpensive temperature transducer. The thermocouple transducer is made of two junctions of dissimilar metals. The voltage from the transducer is proportional to the difference in temperature of the two junctions. The advantages of this type of transducer are its linear response and its extremely low cost. The disadvantages are the very low transducer voltage outputs and the requirement for a reference temperature used for the difference comparison. The reference temperature is usually a point externally held at zero degrees centigrade. This paper presents an amplifier that produces both the high gain necessary to amplify the transducer voltage and a means for automatically compensating for the reference junction temperature.

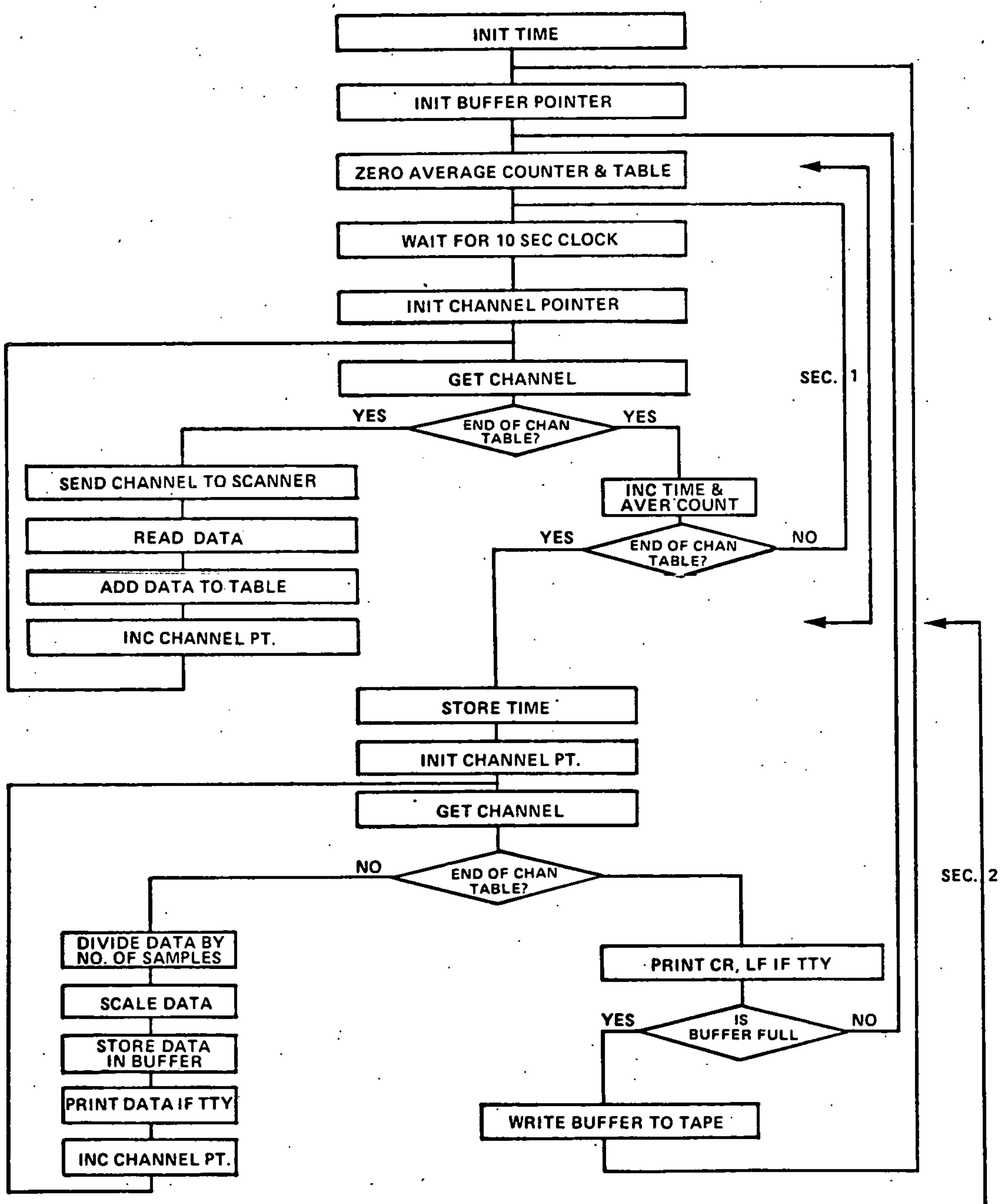

FIGURE 3. SOFTWARE FLOW CHART

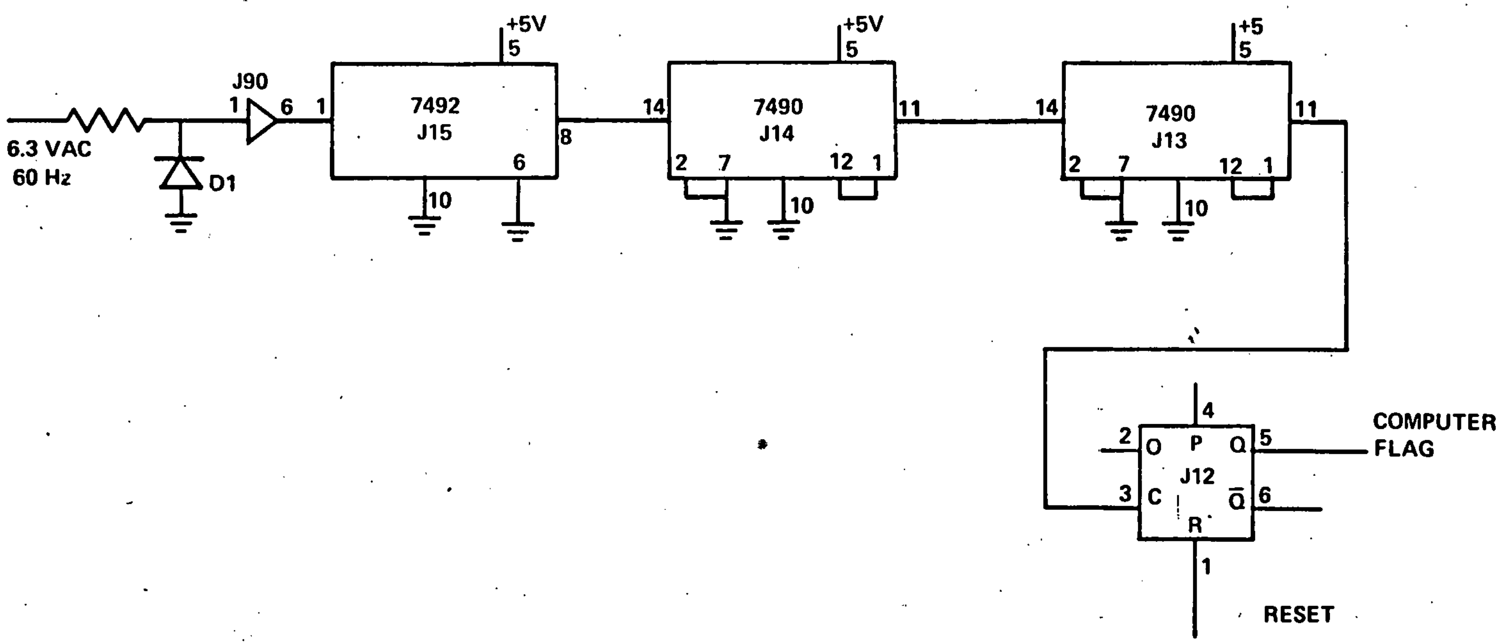

FIGURE 4. REAL TIME CLOCK

A thermocouple transducer consisting of two junctions of dissimilar metals is shown in Figure 5. The voltage from the transducer is:

$$V_T = \alpha\ (T_M - T_R)$$

where α = Difference in seebeck coefficient of the two metals

T_M = Measured temperature

T_R = Reference temperature

It is usually necessary to hold the reference temperature at a prescribed value, but in this amplifier a thermister is used to measure the reference junction and compensate for changes in reference temperature. This technique permits the reference junction to drift with ambient conditions.

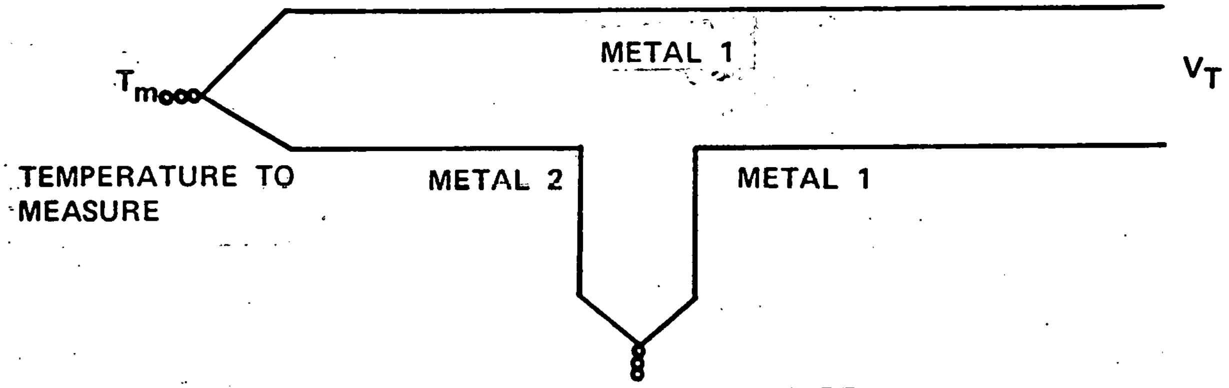

FIGURE 5. THERMOCOUPLE TRANSDUCER

A complete schematic diagram of the thermocouple amplifier is shown in Figure 6. The upper amplifier sections are used to provide very low drift gain and the lower sections are used to compensate for the reference junction temperature.

To develop the theory of operation a simplified schematic is shown in Figure 7. The thermolinear network Therm 1, Therm 2, R_{10}, R_{11} is replaced by its equivalent resistance $K_1 - K_2T$. The output of the thermocouple junction is:

$$V_T = \alpha\ (T_M - T_R).$$

The gain (G_1) of the instrumentation amplifier A1 is:

$$G_1 = -\frac{4 \times 10^5}{R_2} - 1$$

so that the output of A1 is

$$V_{A1} = -\frac{4 \times 10^5}{R_2} - 1 \quad \alpha\ (T_M - T_R) = -K_3\ (T_M - T_R)$$

$$K_3 = \alpha\ \frac{4 \times 10^5}{R_2} - 1$$

The output of an operational amplifier is minus the ratio of the feedback resistor to the input resistor times the input voltage. The output of A_3 is therefore

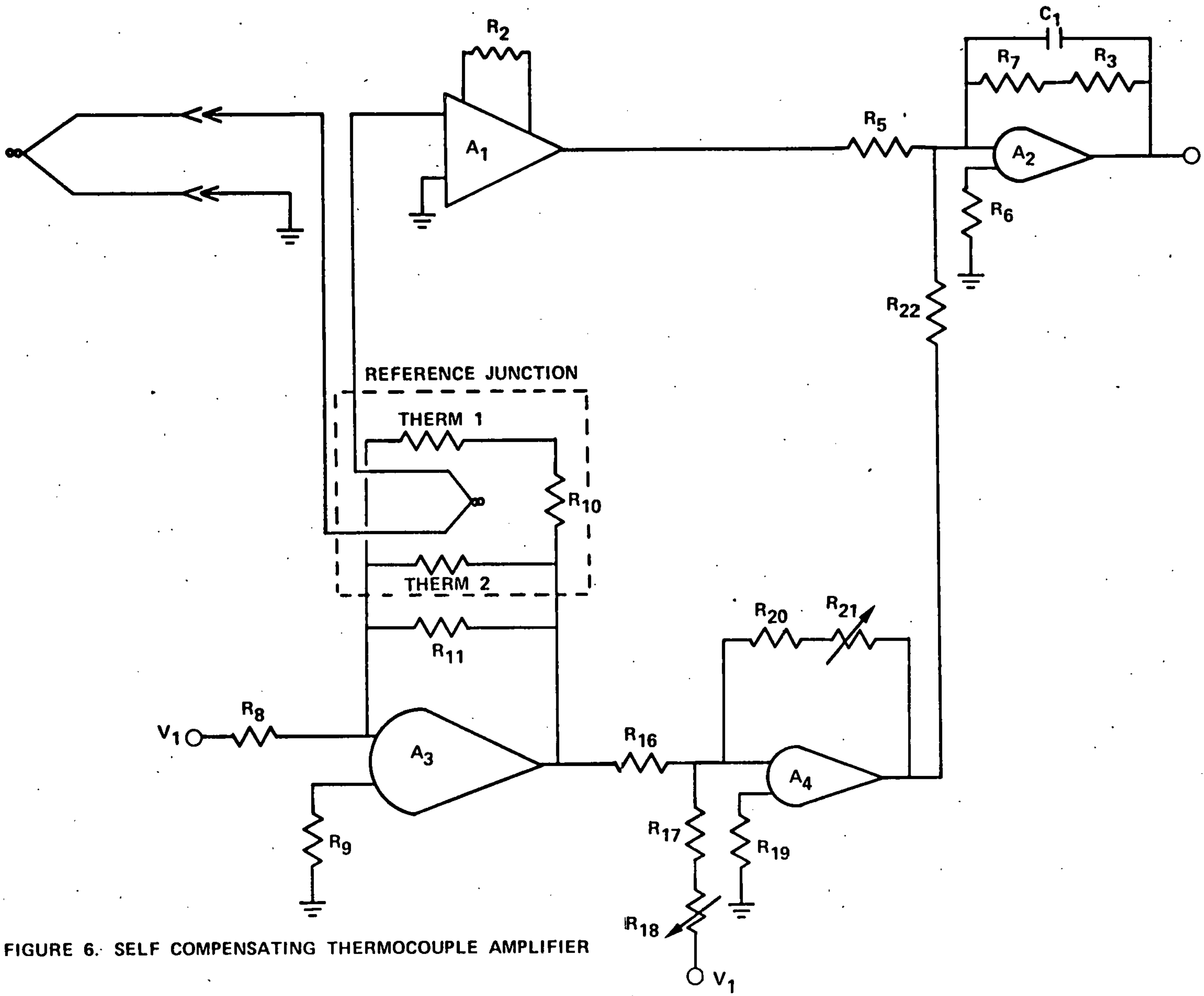

FIGURE 6. SELF COMPENSATING THERMOCOUPLE AMPLIFIER

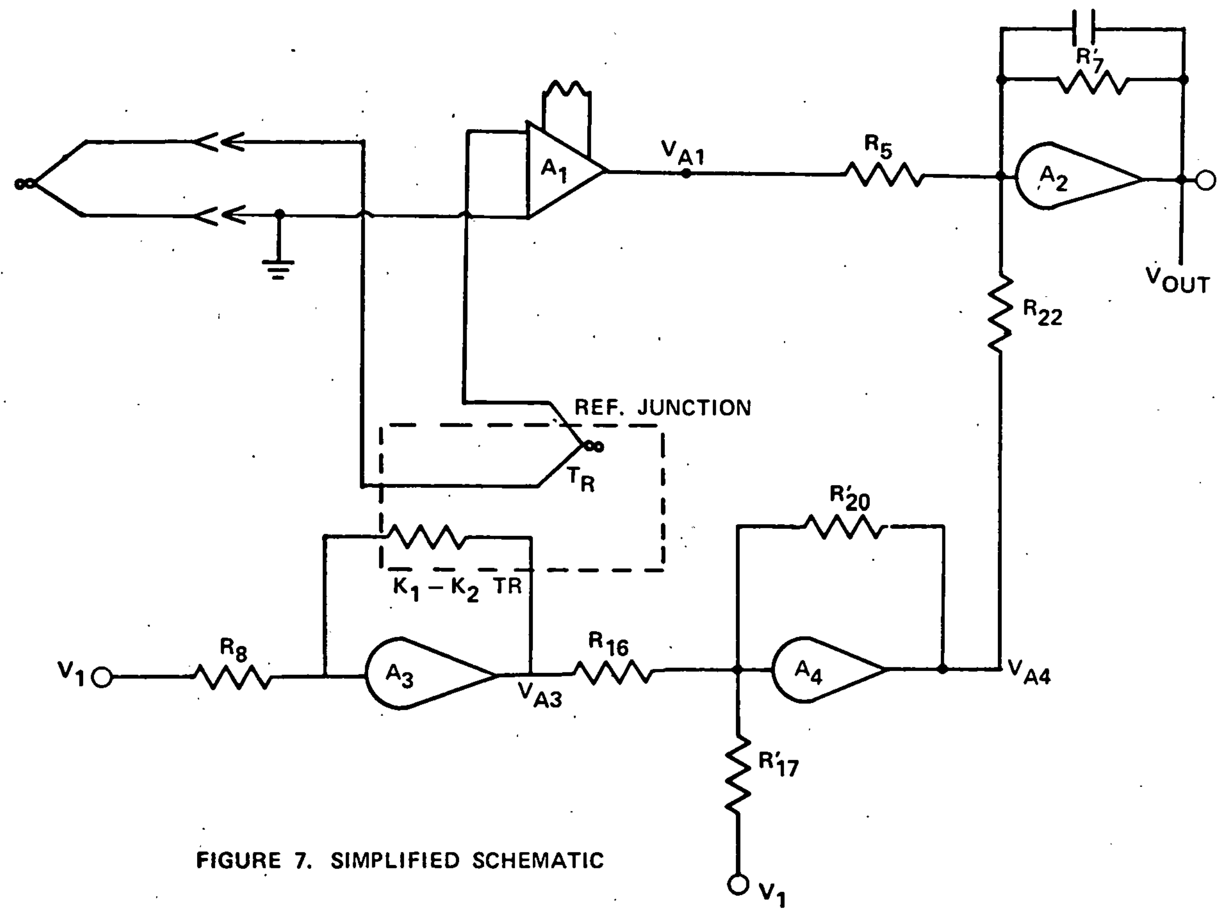

FIGURE 7. SIMPLIFIED SCHEMATIC

$$V_{A3} = -\frac{(K_1 - K_2T_R)}{R_8} V_1$$

The output of amplifier A_4 is likewise:

$$V_{A4} = -\frac{R_{20}'K_1}{R_{16}R_8} V_1 - \frac{R_{20}'K_2V_1}{R_{16}R_8} T_R - \frac{R_{20}'}{R_{17}'} V_1$$

Pick R_{17}' so that $\frac{R_{20}'K_1V_1}{R_{16}R_8} = \frac{R_{20}'V_1}{R_{17}'}$ or:

$$R_{17}' = \frac{R_{16}R_8}{K_1}$$

Then V_{A4} reduces to:

$$V_{A4} = - \frac{R_{20'} K_2 V_1}{R_{16} R_8} T_R$$

The output of amplifier A_2 is:

$$V_{OUT} = - \frac{R_7}{R_5} V_{A1} - \frac{R_7}{R_{22}} V_{A4}$$

Substituting for V_{A1} and V_{A4}

$$V_{OUT} = \frac{R_7 K_3 T_M}{R_5} - \frac{R_7 K_3 T_R}{R_5} + \frac{R_7 R_{20'} K_2 V_1}{R_{22} R_{16} R_8} T_R$$

Pick $R_{20'}$ so that the last two terms cancel or:

$$R_{20'} = \frac{K_3 R_{22} R_{16} R_8}{R_5 K_2 V_1}$$

The reference temperature terms cancel and the output voltage depend only on the measured temperature T_M.

$$V_{OUT} = \frac{R_{7'} K_3 T_M}{R_5}$$

$R_{7'}$ is picked so that full scale voltage is produced for full scale temperature.

Analog-to-Digital Converter

The Analog-to-Digital Converter used by this system is a ZD461 10 bit Zeltex ADC M-series converter. It has a maximum conversion period of 10 u.sec.

Tape Recorder

The tape recorder used by the system is an inexpensive cassette type. The only modification made to it was a circuit to allow it to be turned on or off electrically instead of manually. It was chosen for its low cost and ease of operation. The data is stored in a memory buffer by the microprocessor and sent to the recorder in RS232 format through an audio-oscillator. The buffer storage allows several records to be stored on the tape at one time, thus avoiding the use of excessive amounts of tape by not starting and stopping the tape for each record. A separate tone decoder circuit is used to convert the audio tones on the tape back to standard RS232 format to play the data back to a computer for analysis.

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DATA ACQUISITION AND PROCESSING WITH A HP 9825 DESK TOP CALCULATOR CONTROLLED INSTRUMENTATION SYSTEM IN THE LOS ALAMOS SOLAR MOBILE/MODULAR HOME*

by

J. C. Hedstrom
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

ABSTRACT

Data has been taken in the solar Mobile/Modular Home with a Hewlett Packard 9825 calculator from October, 1976 until the present. This paper describes the data system and data reduction techniques and presents some of the typical results obtained.

The Mobile/Modular Home Unit #1 at the Los Alamos Scientific Laboratory is a factory-built residential unit 44 feet long and 24 feet wide. It has an active air system with 340 ft^2 of single-glazed flat black collectors built into the south side of the house at a tilt of 60°. The storage unit consists of an insulated bin 3 ft high, 4 ft wide and 8 ft long, loaded with 1536 pint glass jars filled with water. The jars are spaced 5/8 inch apart on a triangular grid to allow air flow through the bin. One fan is used to move the air while four automatic dampers are employed to obtain the various operating modes. Domestic hot water is preheated with a fin tube coil in the collector outlet duct. The unit has been in operation since March, 1976.

The house has a total of 63 sensors of various types. Thermocouples are used to measure air temperatures and thermisters are used to measure water temperatures. A Baritron pressure transducer is used to measure the pressure differential of a pitot tube initially calibrated with an air monitor to determine air flow rates. Wattmeters are used to measure electrical power consumption. A weather station is mounted on the roof to measure ambient dry bulb and dew point temperatures, wind speed and direction. An Eppley 8-48 pyranometer is mounted on a 60° tilt to obtain solar insolation.

Data acquisition is done with a Hewlett-Packard HP 3050 system which consists of a 40-channel scanner, a HP 3495 digital multimeter, a digital clock and an integrating counter. The scanner has a speed of 3 channels per second. The multimeter can read to 1μv. Thermocouple signals have been externally referenced in a 150°F reference box. The integrating counter is used to accumulate Watt-hr pulses from the wattmeter on the total house power.

The system is controlled by a HP 9825 desk top calculator. The calculator has a total of 23K bytes of memory and a tape cartridge

*Work performed under the auspices of the U. S. Department of Energy and funded by the Research and Development Branch for Solar Heating and Cooling, Office of the Assistant Secretary for Conservation and Solar Applications.

capacity of 250K bytes. The data program takes 13K bytes of memory. This program took about one week to develop and get operational. The calculator has auto start capability in the case of power failure by reloading the program from the first file on the tape. The calculator is programmed in HPL (Hewlett-Packard language) which is extremely versatile. The calculator has error detection capability which means the program can loop to a particular part of the program on a particular error, correct the error condition and continue running.

The primary goal of the data system is to reduce all data instantaneously and, thereby, avoid further data reduction. This is done by sampling the data and computing flow rates, temperature differentials and heat flows throughout the system. The cycle time for this task is about 34 seconds. The heat flows are integrated into a 16-term energy array that is accumulated throughout the day and zeroed at midnight. A heat flow is added to a particular energy array dependent on the mode of operation of the solar system.

Output devices include a X-Y plotter, a 120-column printer and the tape cartridge. These devices generate output data on a 34-second, hourly, daily, monthly and yearly basis on site.

Five temperatures are plotted every data cycle on the plotter. A typical plot is shown in Figure 1. Also plotted is the control mode of the system. This plot is extremely valuable in evaluating the detailed performance characteristics of the system as well as pointing out operational problems with the system.

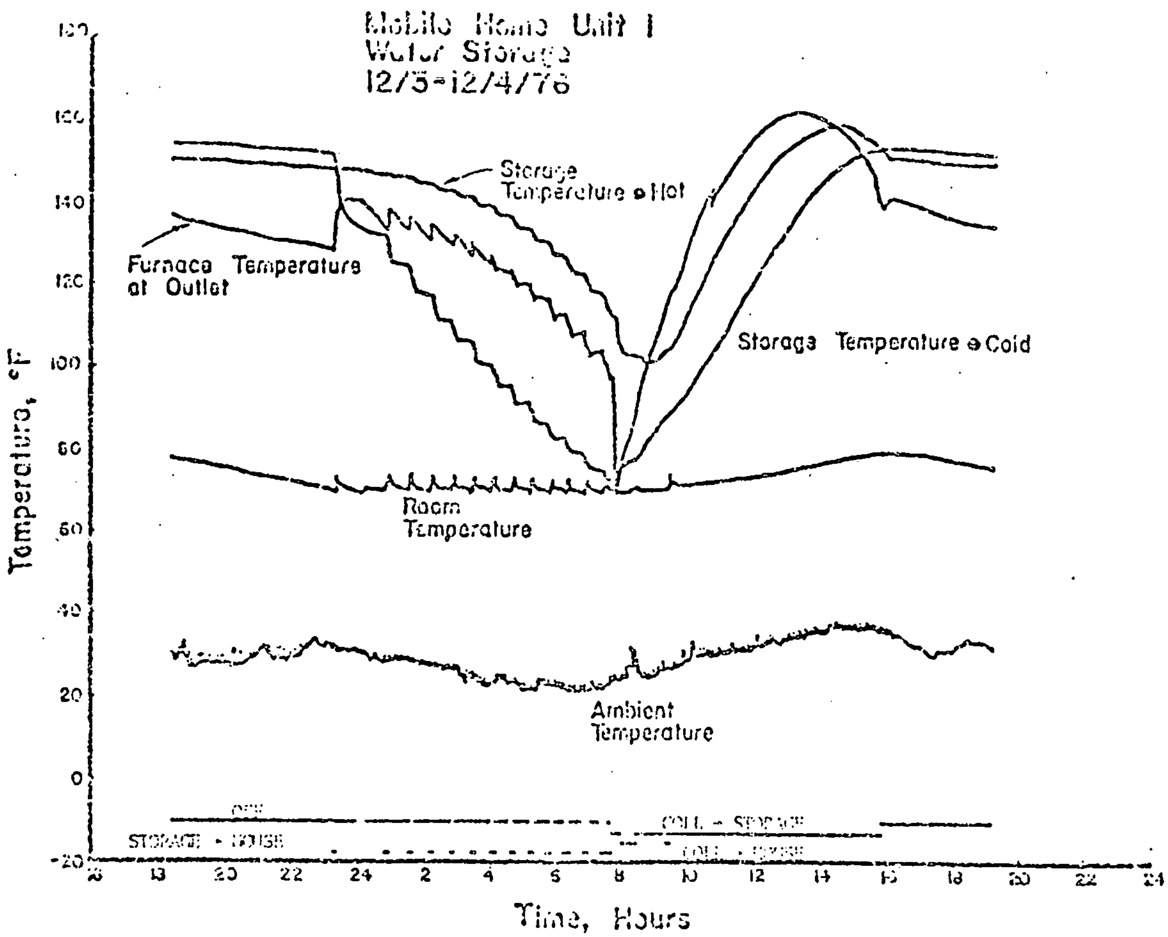


FIG. 1 THIRTY SECOND DATA PLOTTED ON-LINE WITH X-Y PLOTTER

Data is printed hourly on the printer and stored on the tape cartridge. An example of the hourly printout is shown in Table I. The printout contains the major temperatures throughout the system, the calculated heat flows and the integrated energy balance terms.

TABLE I HOURLY DATA PRINTED ON PRINTER AND STORED ON TAPE

DATE	TIME	TRM	TA	T DP	W VEL	TW VEL
12678	1100.11	66.33	31.45	9.61	0.83	1.24
MODE	MODE1	CFM	V ZERO	DP FLOW	TAMAX	TAMIN
15.00	15.00	802.44	-.0580	0.0289	34.25	15.33
TCIN	TCOUT	TAIR IN	TFIN	TF OUT	TS IN	TS OUT
93.56	156.65	146.60	138.40	134.49	134.58	100.32
TC 1	TC 2	TS HOT	TS COLD	TS AVE	TH IN	
175.37	170.66	120.24	92.94	107.47	119.01	
TDW IN	TDW OUT	TDW S	TAIR IN	TAIR OUT	GPM	
104.29	116.76	111.54	146.60	114.11	0.92	
QSUN	QCOLL	QSTOR	QHSE	Q FURN	Q DW	
308.78	110.58	71.89	0.00	0.00	16.94	
E SUN	E COLL	ESTOR CH	E HSE CH	E FAN	E DW	
712.82	219.59	146.23	8.65	28.74	21.84	
E DEMND	E ELECT	ESTOR DS	EHSE TOT	E FURN	E DW AUX	
387.06	128.29	211.12	204.45	0.00	16.29	
E DEL	EF LOS					
180.70	-0.70					

The tape cartridge can hold 11 days of data. At the end of the month the accumulated tapes are reaccessed to obtain the daily summaries which are accumulated for the monthly totals. An output for the month of December, 1976, is shown in Table II. An energy flow chart is also constructed from the monthly data and is shown in Table III.

The monthly totals are combined into a yearly summary table as shown in Table IV. An energy flow chart for the year is presented in Table V. The percent solar for the 1976-1977 heating season was 66%. The percent solar for this season through February is 72%.

This method of data acquisition and reduction requires a minimum of effort once the program has been written and is operating properly. However, like most data systems, it should be observed daily to minimize the amount of missing or bad data. Our data loss is about 5% per month which occurs mainly from faulty instrumentation or tape cartridge errors. Missing data is substituted with estimations from similar days. Using a calculator or computer online to reduce the data requires that the program be correct since it is very difficult to rework the finished results.

TABLE II

DAILY SUMMARY DATA
FOR DECEMBER 1976

Date	Coll In	Coll Out	HSE DEL	FURN Aux	Fan	HSE Tot	STOR CH	HSE CH	FURN Loss	DHW	UN-BAL
120176	2072	434	347	97	65	509	252	26	105	39	-10
120276	2305	569	458	73	66	597	332	41	124	37	-10
120376	2319	551	439	0	57	496	300	43	113	46	-6
120476	2237	499	385	0	52	436	274	24	107	32	-1
120576	974	200	142	20	67	228	106	43	61	4	-6
120676	562	50	27	526	93	646	37	60	43	-1	-19
120776	2079	514	419	329	75	824	307	46	82	75	-15
120876	2245	514	417	23	61	502	336	22	73	45	2
120976	1689	356	283	0	41	324	228	16	53	30	-3
121076	573	96	73	211	83	367	56	33	41	3	24
121176	2250	550	440	245	75	760	330	30	95	40	20
121276	2259	514	413	0	55	468	322	31	74	40	1
121376	2270	500	420	0	50	470	300	15	65	40	50
121476	2082	480	410	0	55	465	290	25	70	42	38
121576	2232	490	400	0	57	457	300	20	73	40	24
121676	2299	496	395	0	57	452	323	21	89	38	-19
121776	2177	467	351	0	53	404	295	22	87	45	-45
121876	2280	428	335	0	57	392	272	22	71	42	-15
121976	1806	346	265	0	44	309	213	10	56	46	-15
122076	2163	439	345	60	56	461	230	22	71	37	-9
122176	2132	421	332	61	57	450	262	28	66	45	-12
122276	2216	469	374	45	58	477	287	38	73	45	-11
122376	2013	418	327	29	56	412	258	24	70	36	-5
122476	2162	434	342	47	57	447	271	29	68	42	-11
122576	2203	428	331	3	55	389	261	27	65	35	-3
122676	2058	432	344	46	55	445	270	22	68	46	-13
122776	2111	416	324	0	50	374	263	10	66	46	-12
122876	2269	448	342	0	54	396	270	18	73	40	-5
122976	2250	450	353	12	57	423	278	23	70	57	-18
123076	2043	401	310	0	48	357	240	12	63	63	-21
123176	672	99	74	156	60	289	51	28	40	11	4
Dec. Totals	61001	12906	10215	1983	1827	14025	7872	830	2276	1184	-121

*Units: BTU/hr ft_c^2

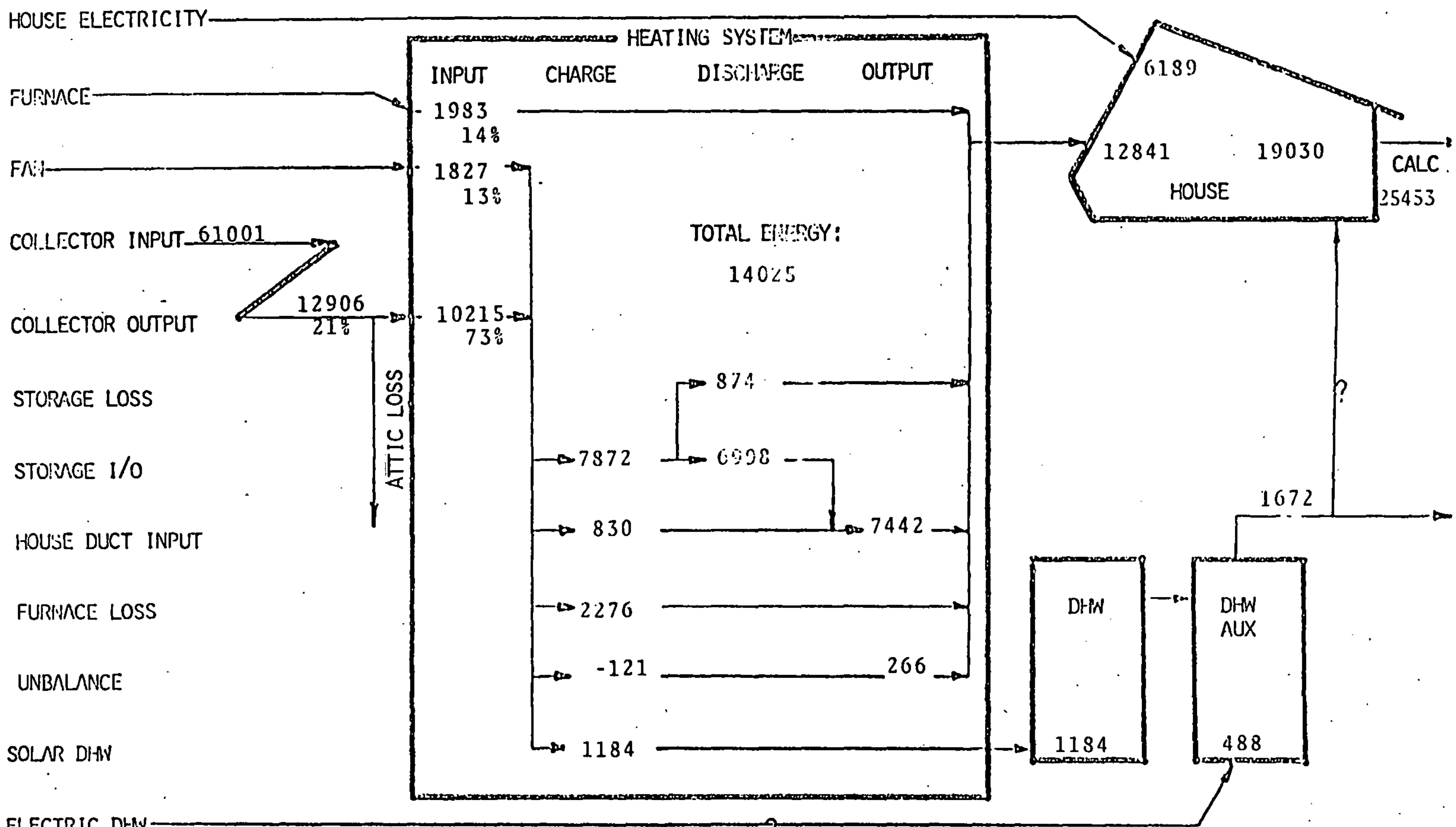
Collector Area: 340 ft^2

Floor Area: 1056 ft^2

TABLE II (cont)

Date	Stor Loss	Stor DSCH	HSE Duct	Un-Bal	HSE SOL	HSE ELEC	DHW AUX	HSE CAL	TA MAX	TA MIN	DD	TSTR MAX	TSTR MIN
120176	-4	255	263	8	470	183	9	933	29	15	43	152	64
120276	106	226	242	15	560	188	15	861	29	24	38	155	67
120376	44	256	281	11	450	181	8	848	40	16	37	158	75
120476	36	239	239	23	405	181	15	830	38	22	35	156	86
120576	-228	335	348	24	225	180	16	793	36	22	36	121	71
120676	48	-11	53	-24	647	217	22	879	19	15	48	78	64
120776	273	34	77	-13	749	228	46	898	36	10	42	144	63
120876	111	226	236	14	457	184	15	783	42	22	33	158	68
120976	-77	306	290	29	294	195	17	760	41	24	32	143	86
121076	-123	180	260	-24	365	211	15	798	35	20	37	76	66
121176	254	76	45	81	720	167	15	884	36	17	38	154	64
121276	97	226	247	10	428	189	14	794	43	18	34	161	73
121376	74	226	245	46	430	195	15	788	42	21	34	159	87
121476	60	230	255	38	423	180	30	790	42	23	33	155	87
121576	68	232	240	36	417	189	22	795	42	24	32	152	86
121676	73	250	281	-28	414	171	17	801	43	19	34	153	81
121776	75	220	238	-41	359	275	6	757	44	23	32	147	106
121876	71	201	226	-18	350	262	14	853	41	23	33	147	134
121976	-95	308	295	8	263	192	15	800	39	22	35	140	118
122076	47	233	237	9	424	186	7	810	29	20	40	138	74
122176	-14	276	279	13	405	205	15	890	34	19	39	137	72
122276	38	249	270	6	432	204	13	878	36	15	40	138	71
2376	-6	264	271	12	376	208	15	863	36	16	39	136	74
2476	57	214	228	5	405	198	7	822	38	18	37	138	71
122576	-14	275	284	16	354	194	14	868	34	15	41	138	89
122676	37	239	245	2	398	194	15	819	42	16	36	138	74
122776	51	213	211	-1	328	200	14	681	41	30	29	140	97
122876	1	269	266	15	356	220	8	818	37	20	36	142	105
122976	10	269	276	-3	366	198	14	810	40	17	37	139	84
123076	12	228	225	-6	295	219	14	762	43	25	31	138	104
123176	-205	256	286	1	279	195	25	783	30	28	36	134	63
	874	6998	7442	266	12841	6189	488	25453	37	20	1126	0	0

TABLE III MONTHLY ENERGY FLOW CHART FOR DECEMBER, 1976



UNITS: BTU/MONTH FT² COLLECTOR

COLLECTOR AREA: 340 FT²

FLOOR AREA: 1056 FT²

DEGREE DAYS: 1126

TABLE IV

YEARLY SUMMARY TABLE FOR 1976 - 1977

Month	Coll. Input	Coll. Output	Monthly Efficiency	Solar Delivered	Furn Aux	Fan	Total Demand	Degree Days	Percent Solar
Oct	55223	11808	21	8983	774	1420	11177	563	79
Nov.	59018	12715	22	9637	3023	1611	14271	864	68
Dec.	61001	12906	21	10215	1983	1827	14025	1126	73
Jan	54211	9804	18	7732	6441	1940	16114	1235	48
Feb	54183	9198	17	7186	2431	1453	11071	892	65
March	58805	9625	16	7577	2295	1918	11789	882	64
April	47108	6327	13	4709	1416	1146	7271	492	65
May *	16474	1518	9	1014	0	291	1305	59	78
TOTAL	406023	73901	18	57053	18363	11606	87023	6113	66

Units: BTU/Month ft^2 Collector

Collector Area: 340 ft^2

Floor Area: 1056 ft^2

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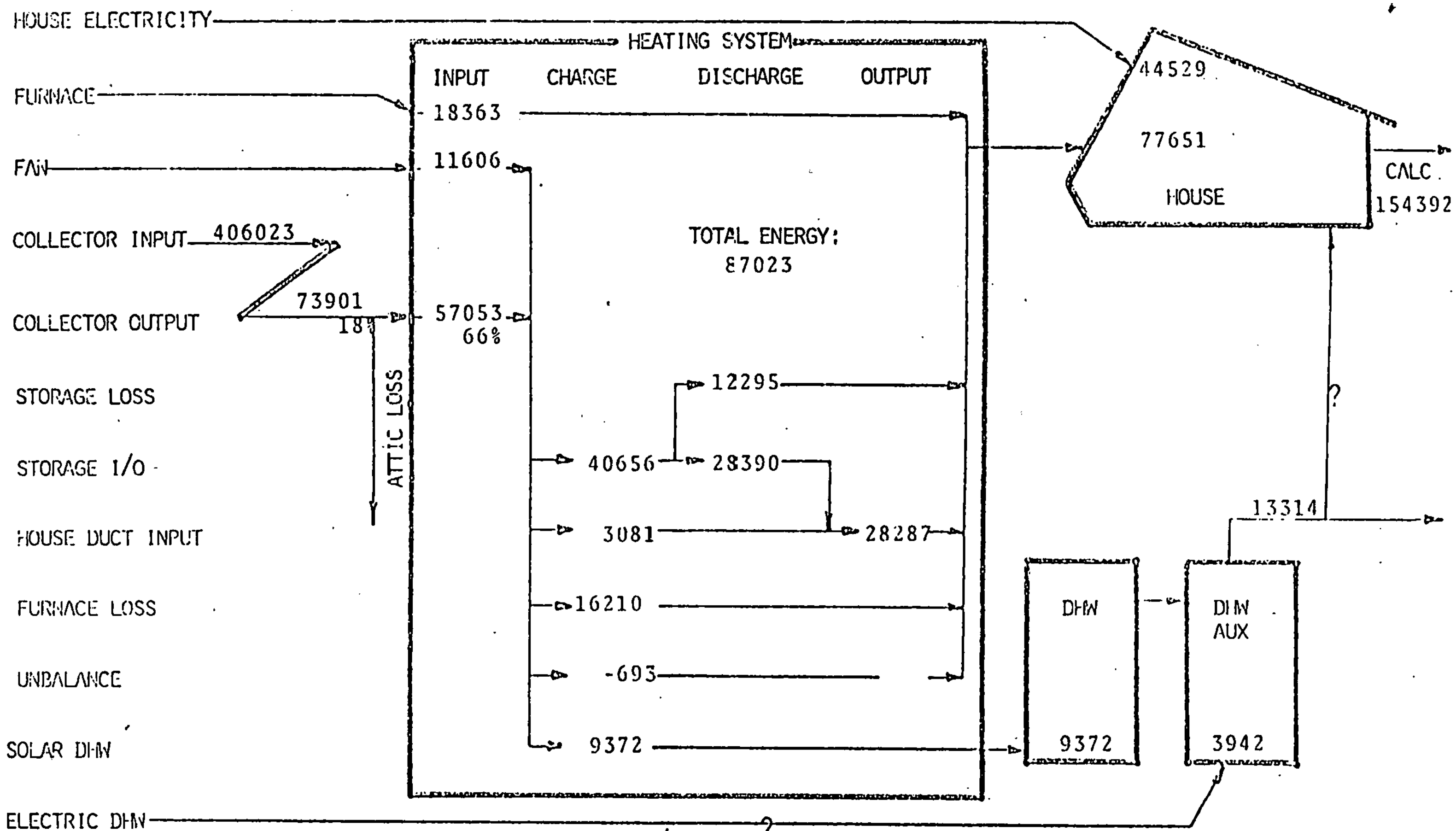
*May 1 to May 9

TABLE V

YEARLY ENERGY FLOW CHART FOR 1976-1977



UNITS: BTU/MONTH FT^2 COLLECTOR

COLLECTOR AREA: 340 FT^2

FLOOR AREA: 1056 FT^2

DEGREE DAYS: 6113

A MICROPROCESSOR CONTROLLED FLOW, FLOW RATE, REAL AND ELAPSED TIME MEASURING SYSTEM

Dr. William P. Moran
Associate Professor of Physics
Solar Energy Research Laboratory
University of Tulsa
Tulsa, Oklahoma 74104

ABSTRACT

Six Intel 8253 programmable interval timers (PIT) have been interfaced to the Heath H-8 (Intel 8080 A) microprocessor bus. The counters, 3 per chip, measure flow and flow rate from liquid, gas, and electric power meters. Other PIT's are used to schedule, to keep real time, and provide programmable delays or interrupts.

INTRODUCTION

The Intel 8253 programmable interval timer consists of three 16 bit (or 10^4 BCD) down counters with software control of the operation. This device is tailored for the 8080 family of microprocessors. It enables the computer to measure any signal which can be converted to a frequency or to a time, and easily interfaces to any transducer which produces a pulse train output. These possibilities cover the requirements for devices related to flow rate or total flow measurement. In addition it is easy to keep real or elapsed time and to generate programmable delays to control scheduling. Other functions described by Intel are: programmable rate generator (divide by any N), binary rate multiplier, and programmable controller (e.g., motors).

OPERATION OF THE 8253

The 8253 has three independent counters each with an input for the pulses to be counted, a gate which externally enables the counter, and an output which signals when the counter has reached zero from the initially programmed value. The three counters may independently operate in any of the five programmable modes.

The simplest mode for flow metering is just that of an event counter which may be initialized and may be read without interrupting the count. If the count changes less than 2^{16} between observations then the counter does not even have to be initialized. In this mode the gate is enabled and the output unused. All pulses reaching the input are counted without need for computer intervention. The next simplest mode of operation suited to steady flows or to elapsed time measurement counts a fixed frequency when a gate enable signal is received. Again, the output is not used and the counter is initialized only if the absolute value of the gate duration is needed. By using the output a controllable timer is produced which does not have to be observed or tested by the computer.

A third mode of operation is suitable for signalling completion of some task either to the operator or to the computer. In Mode Ø (Intel notation) the output goes high and stays high until that counter's mode is reset. This is ideal for activating signal lights or relays. In Mode 1 the output acts as a retriggerable one-shot which means that each pulse to the gate resets the counter. This is suitable for generating system status signals. For example as long as some or all of the system pumps are running a signal is maintained. Another example would be to select periods of time during which a pulse rate exceeds a programmable threshold. The wind speed could be scaled and applied to the gate. The counter would be initialized with a value and a fixed frequency counted at the input. Thus as long as the wind speed exceeded a certain value the PIT would produce a given output. When the wind pulses came less often than the predetermined time the PIT would reach its end of count and change to output state. Analog instruments can be configured to produce similar logic signals. Thus the pyranometer can be connected to an analog comparator which in turn controls the gate of the PIT or resets the gate periodically. As long as insolation is above or below a threshold the PIT output is known. It makes a transition when the threshold is crossed. The initial count and clock rate of the PIT provides a delay in the response to the threshold crossing which is readily adjustable. Thus fluctuations shorter than any desired time-span can be ignored.

The other programmable modes of operation of the output are: rate generator which is a divide by N, square wave rate generator which changes the output at the midpoint of the count, software triggered strobe (timing begins on computer command) or hardware triggered strobe (timing begins on gate command).

In the system which we have described in another paper there are two spare 8 bit parallel I/O ports. These provide a way to read status words into the computer from either operator switches or from the PIT output. By reading these ports as a part of the basic data cycle, program flow can be modified by external conditions without use of interrupts. The PIT allows only the counter to be read not the control word register or the gate or output status. Thus the use of the parallel I/O port as an external switch register is important in fully utilizing the potential of the PIT. As set up now the fundamental data cycle is 10 sec. Thus data is synchronized to this degree. This is not an important loss of temporal resolution since the response times of system components are longer than sample period.

INTERFACING TO THE H-8

Interfacing the 8253 is simplified by the similarity of the H-8 bus to the Intel bus. Each chip is treated as 4 output ports (3 counters and a mode word) or 3 input ports (counters only). This each chip requires 4 port addresses or 4 memory locations when using memory mapped I/O. Since the 8080 A has 256 I/O addresses this is not an excessive demand.

The board we have built holds 6 chips or a total of 18 PIT's. The decoding logic takes the 8 bit I/O address (A_0 - A_7) and generates a chip select pulse from IOR, IOW and lines A_2 - A_7. Lines A_0 and A_1 go to all chips and select one of three counters or the control word register. Lines A_2 and A_6 are decoded in a 74LS139 dual 2 to 4 line decoder. Lines A_5, A_4, A_3 with the output of A_7, A_6 are decoded in a 7442 4 to 10 line decoder. This produces 24 addresses of the form 24X, 25X, 26X inoctal. These are combined with A_2 in three more 2 to 4 line decoders to produce the addresses 240 + N, 244 + N, etc. at the six 8253 chip selects. In the 8253, $\overline{CS}$, A_0, and A_1 address the selected counter or control register. The RD WR signals are decoded by the presence of IOR or IOW on the bus and a chip select in a 7410 triple three input nand gate. These logic chips along with 74LS04 address buffers and 74LS240 data input and data 74S 240 output 3-state buffers constitute the whole interface, Figure 1. Signals to the inputs, gates, or outputs of the 8253 are delivered by two 25 pin connectors and ribbon cable.

The board is constructed on a 6"x12" Vector board 0.1" spacing, .042" dia. holes. Standard Heath 25 pin female connectors communicate to the bus and 25 pin male connectors interface to ribbon cables. The bus connectors are secured to the board by 2 pad Circuit-Stik strips. A wire wrap pin is inserted in the other pad. The same procedure is used on the input connector. Thus all on-board connections (except power) are wire wrap. Power is drawn from the Heath 8V bus and regulated by two 7805, 5V regulators on the board mounting bracket. The 8V, 5V, and ground are distributed by 0.25" Circuit-Stik bus. The only discrete components are isolation capacitors and filter capacitors. Power consumption is about 11 watts at 8V.

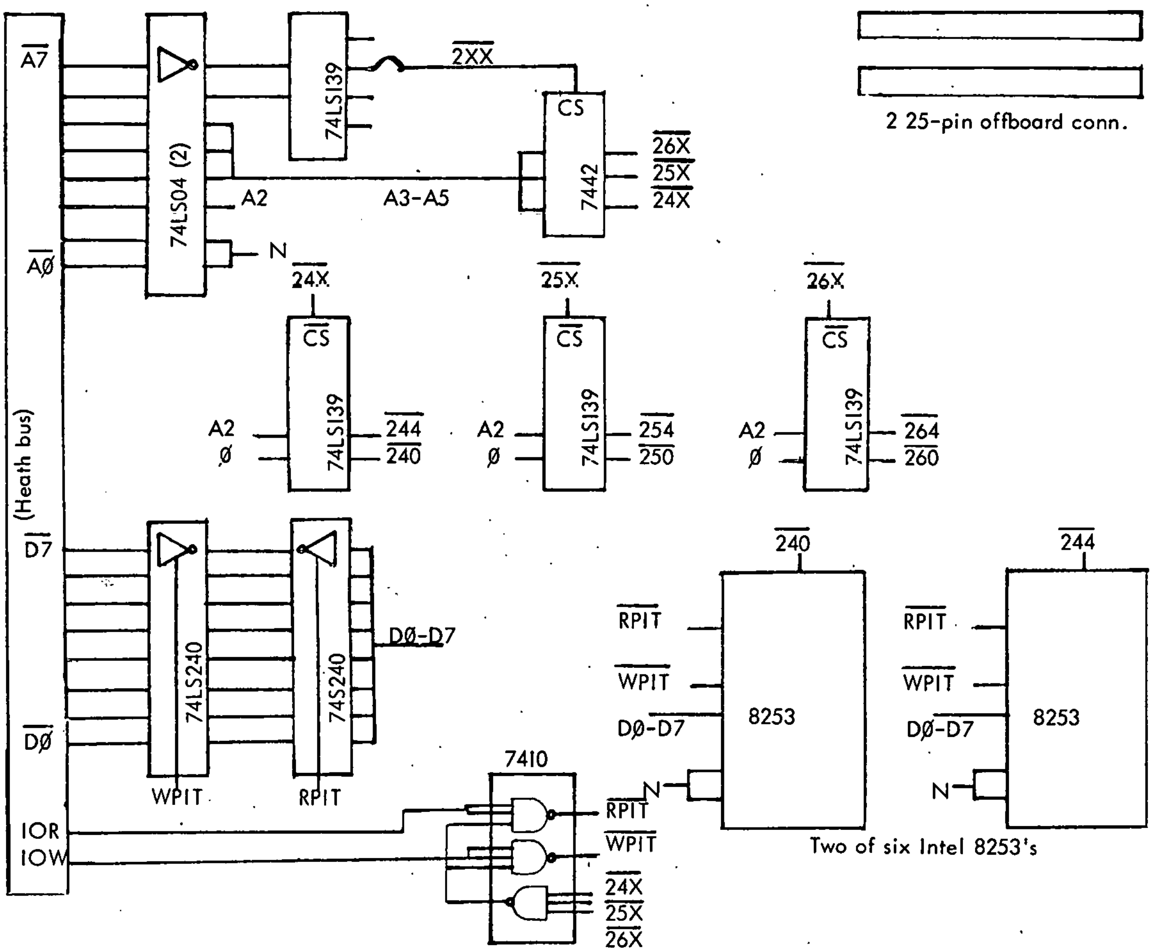
DIGITAL SIGNALS TO BE MONITORED

Six of the eighteen PIT's are configured as simple counters to monitor three turbine flow meters, two electric meters, and the wind speed meter. Three of the PIT's are configured as timers with a gate enable input and a fixed frequency input. Two gas valves and a mode timer will utilize these. Three more timers are configured for full in, out, gate access as variable delays, dividers, or interrupt generators. The remaining six PIT's are uncommitted at this time.

Experimentation is being done to utilize the PIT as a digital integrator in conjunction with precision voltage to frequency converters (e.g. Burr-Brown VCF-32). This is an efficient way to achieve long term integration without requiring large numbers of samples of the data to maintain numerical precision. The high precision (.01% at 10 k Hz) VCO's are suitable for the time scale of solar variables; integration for the span of hours, variability on the scale of minutes.

The versitility of the 8253 indicates that it could be effictive in reducing parts count in instruments and controls outside computers. The cost per counter is high ($8-50) but not unreasonable compared to ordinary logic counters or registers and their control circuits.

FIGURE I. INTERFACE LOGIC FOR 18 PROGRAMMABLE INTERVAL TIMERS



Low Cost Monitoring System

By

R. D. Cummings
Modular Systems Division
43 Second Avenue
Burlington, Massachusetts 01803

and

D. J. Peck
Daystar Corporation
90 Cambridge Street
Burlington, Massachusetts 01803

ABSTRACT

This paper describes the formulation of a low cost monitoring system for solar water heaters and the results obtained from subsequent testing.

The low cost monitoring system development and installation was funded by the Electric Power Research Institute, Palo Alto, California. The system was installed on solar water heating systems in Wakefield, Rhode Island, and, subsequently, in Tyngsboro, Massachusetts, under the direction of the New England Power Service Company, Westboro, Massachusetts.

Daystar Corporation has been engaged in solar system performance monitoring programs since 1974. For each system developed since that beginning we have addressed three simultaneous problems:

(1) Accuracy

(2) System Cost

(3) Data Reduction Cost

We have employed manual methods of data reduction for short term tests and computer-oriented methods for longer term tests. We have found that accuracy can be achieved by painstaking attention to detail, and that computers can reduce data reduction cost but only by paying a large capital cost to start with. For this project we sought a midground low system cost, reasonable data reduction cost, and good accuracy.

Low Cost Monitoring System Formulation

For a solar water heating system with electric backup, we wish to know:

- the solar energy delivered
- the water energy used
- the electrical energy delivered
- the parasitic losses

The electrical energy delivered is easily measured by means of a kilowatt hour meter. The water energy used is also easily measured by means of a water meter keyed into the temperature rise across the water tank by means of a digital pulse recorder (DPR).

The difficulty, if any, in performance measurement is that the parasitic losses cannot be measured, so that they must be calculated from the energy balance equation:

$$E_{parasitic} = E_{electrical} + E_{solar} - E_{use}$$

This makes accurate measurement of the solar energy delivered mandatory.

The solar energy supplied to the water heating system is calculated using the energy transport equation for the fluid circulation loop through the collectors. This equation is written as follows:

$$E_{solar} = \int_{t_1}^{t_2} w \; C_p \; (T_1 - T_2) \, dt$$

E_{solar} = solar energy delivered to the storage tank during the time interval from t_1 to t_2

Where: w = mass flow rate through the collector loop

c_p = fluid specific heat

T_1 = fluid temperature entering the storage tank or heat exchanger from the collectors

T_2 = fluid temperature leaving the storage tank or heat exchanger going to the collectors

dt = incremental element of time

Monitoring of the two temperatures poses no significant problems, but continuous monitoring of fluid flow rate requires expensive and highly sophisticated instrumentation. Daystar has developed a technique which eliminates the necessity of continually measuring flow rate.

For a given solar system, there are many system variables which determine flow rate through the system; these include circulator size and type, piping length, diameter and routing, heat exchanger configuration, heat transfer fluid, collector and array size and type, etc. Once installed, however, the above become constants, as the system geometry, installation configuration and fluid properties taken together establish unique relationships for determination of flow rate in a particular system. In the operating system, then, the flow rate varies only with temperature, the sole independent variable. Flow variations occur as the fluid properties (density, viscosity, specific heat) vary with fluid temperature.

Recognizing system dependency upon the single independent variable, temperature, one may readily establish a single curve relating flow vs. temperature by measuring variation of system flow rate over a range of fluid temperatures. This may be done by installing an in-line flowmeter downstream of the tank or heat exchanger and monitoring, by thermocouple, the temperature of the fluid passing across the flowmeter. A flow vs. temperature curve is determined which is unique to that system. Once this curve is established for an operating system, it is only necessary to monitor T_1 and T_2 in order to calculate E_{solar} since C_p is also a function of fluid temperature.

To express this in different terms, if the system is operating and the temperature T_2 is known, then from the curve the flow rate is also known.

To allow calculation of E_{solar} without use of an on-site computer, the equation is written in summation form (also noting W and C_p as functions of T_1 and T_2):

$$E_{solar} = \sum_{n=1}^{n=n} w(T_2) \times C_p \left(\frac{T_1 + T_2}{2}\right) \times (T_1 - T_2) \times t$$

Since heat transfer takes place continuously between T_1 and T_2, Cp is a function of average fluid temperature, $\frac{T_1 + T_2}{2}$ rather than of T_2 alone.

The period of solar operation is divided into n intervals of equal length, t (i.e., 5 minutes, 30 minutes, 1 hour, etc.) Average values of T_1 and T_2 are established and the equation is solved for each interval. These values are then summed to give the total E_{solar}. Any value of ΔT can be used, but it should be short enough to produce acceptable accuracy.

System Test Results

The system philosophy discussed above was utilized for the first time at South County Hospital, Wakefield, Rhode Island. The system was being monitored by means of a Rho Sigma computer at the time of installation of the Low Cost Solar Energy Delivery Monitoring System. Figure 1 is a schematic of the system used for measurement of solar energy delivery. Figure 2 shows results of system fluid flow vs. heat exchanger outlet temperature. Table 1 is a comparison of energy delivery as calculated by the Rho Sigma and by the low cost monitoring system.

This experience proved to us that we could successfully correlate flow vs. the temperature at the outlet of the system heat exchanger.

The second utilization of the Low Cost Monitoring System was at the Tyngsboro location. The schematic for this system is shown in Figure 3. The calibration curve for the flow meter is shown in Figure 4. Test results are shown for a two-week period in July in Table 2. In implementing the system at this location, we became well aware of the need for proper placement of thermocouples for accurate results and of the need to properly account for changes in the energy stored in the hot water tank.

LOW COST MONITORING SYSTEM

S. COUNTY HOSPITAL, WAKEFIELD, R.I.

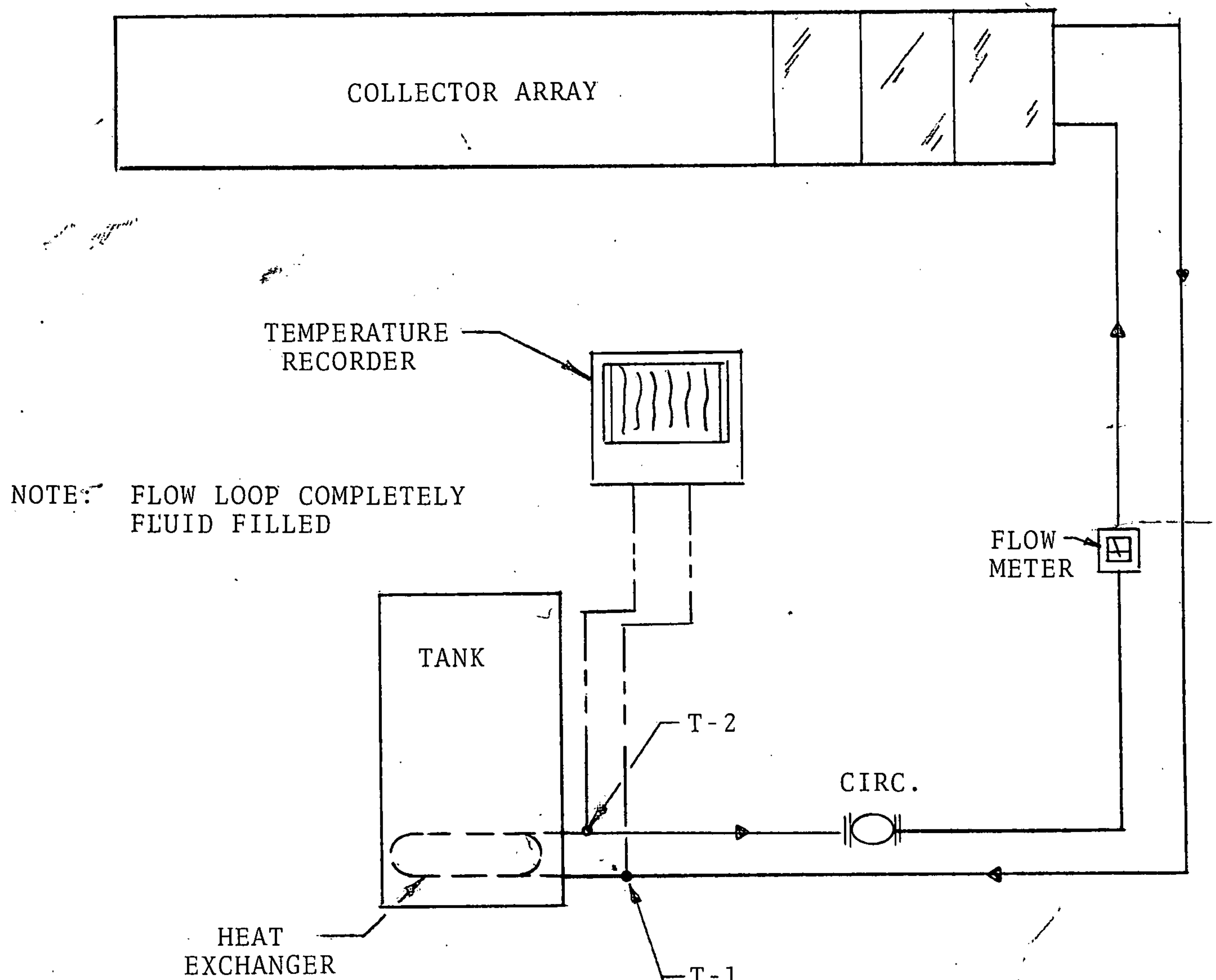


Figure 1

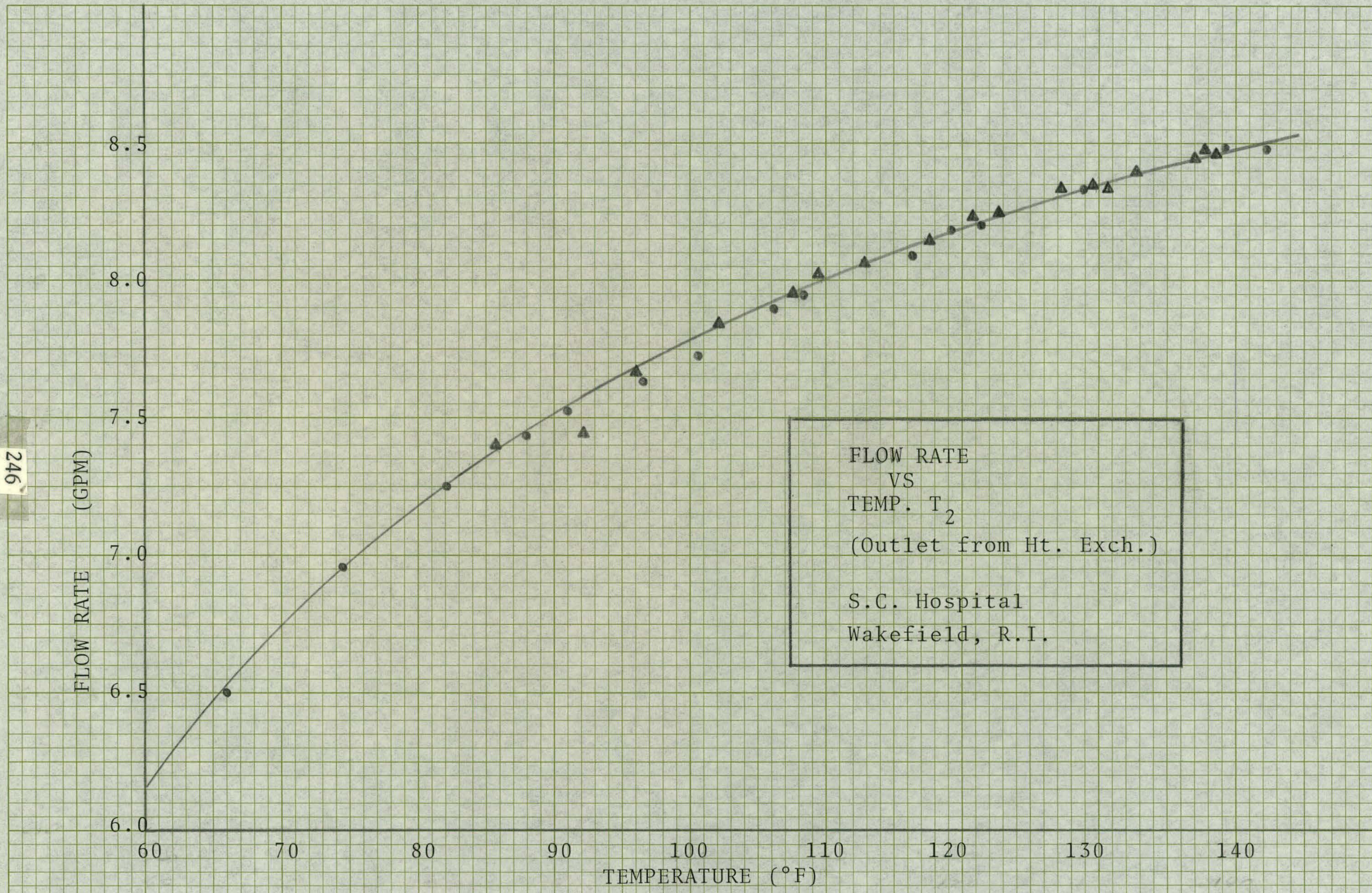
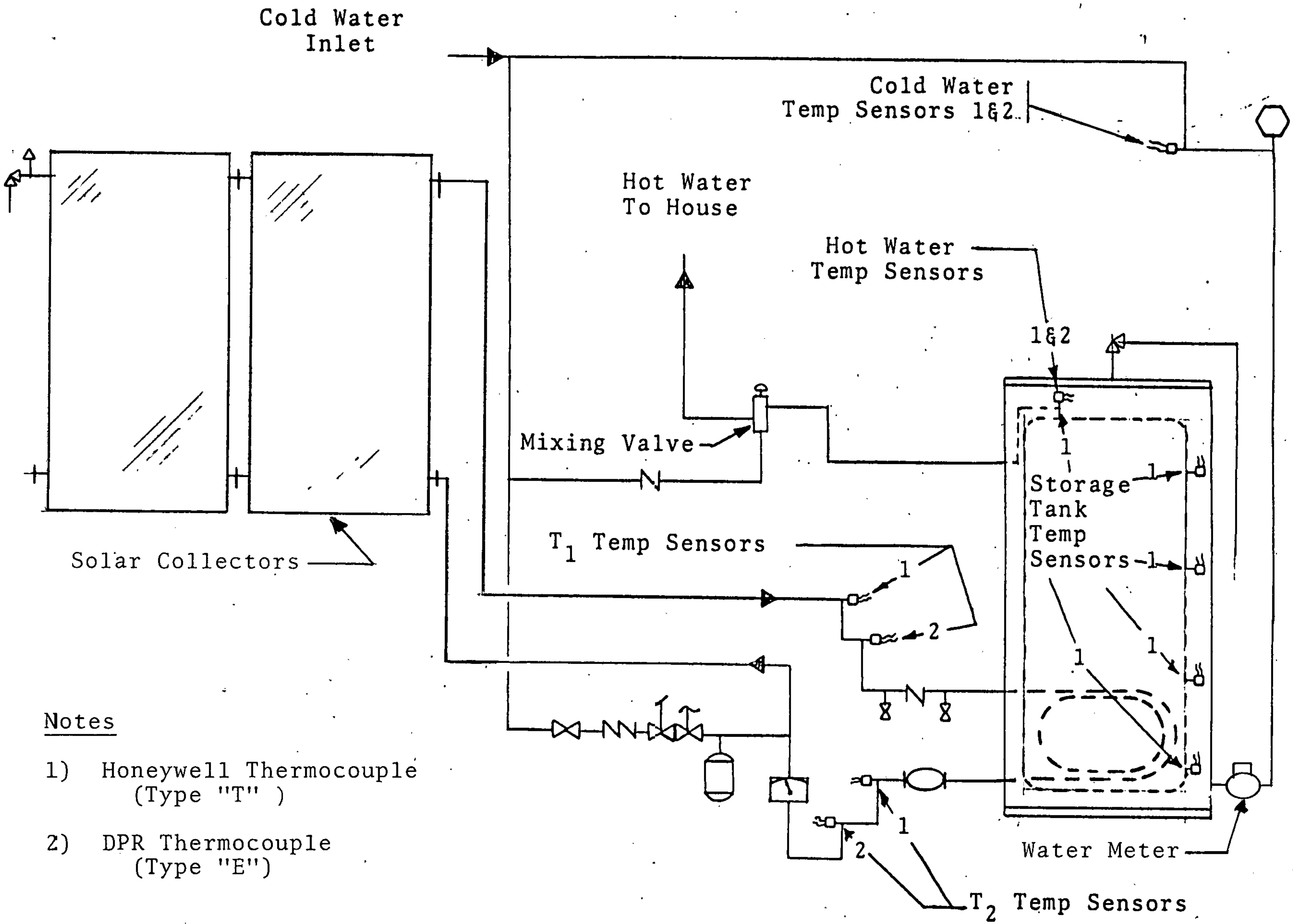

8.5
8.0
7.5
7.0
6.5
6.0
FLOW RATE (GPM)
60
70
80
90
100
110
120
130
140
TEMPERATURE (°F)
FLOW RATE
VS
TEMP. T2
(Outlet from Ht. Exch.)
S.C. Hospital
Wakefield, R.I.

Figure 2

Table 1
SOLAR ENERGY DELIVERY COST COMPARISON
SOUTH COUNTY HOSPITAL

DATE	COMPUTER ($BTUx10^{-3}$)	LOW COST MONITORING ($BTUx10^{-3}$)	VARIANCE
1/20	169	149.5	- 12%
1/21	142	132.8	- 6%
1/24	97	98.4	+ 1%
1/25	15	30.8	+100.5%
1/26	157	146.5	- 7%
1/27	99	93.9	- 5%
1/28	98	95.7	- 2%
1/29	127	124.8	- 2%
1/30	146	130.3	- 11%
2/ 1	148	132.0	- 11%
2/ 2	173	165.7	- 4%
2/ 3	7	8.4	+ 20%
2/ 4	65	72.3	+ 11%
2/ 5	0	0.	-
2/ 6	118	115.8	- 2%
2/ 7	127	130.7	+ 3%
2/ 8	195	173.7	- 11%
2/ 9	103	117.9	+ 14%
2/10	136	127.8	- 6%
2/11	144	142.0	- 1%
2/12	142	139.1	- 2%
2/13	9	8.2	- 9%
2/14	202	181.4	- 10%
2/15	41	43.4	+ 6%
2/16	156	141.8	- 9%
	2816	2702.9	- 4%

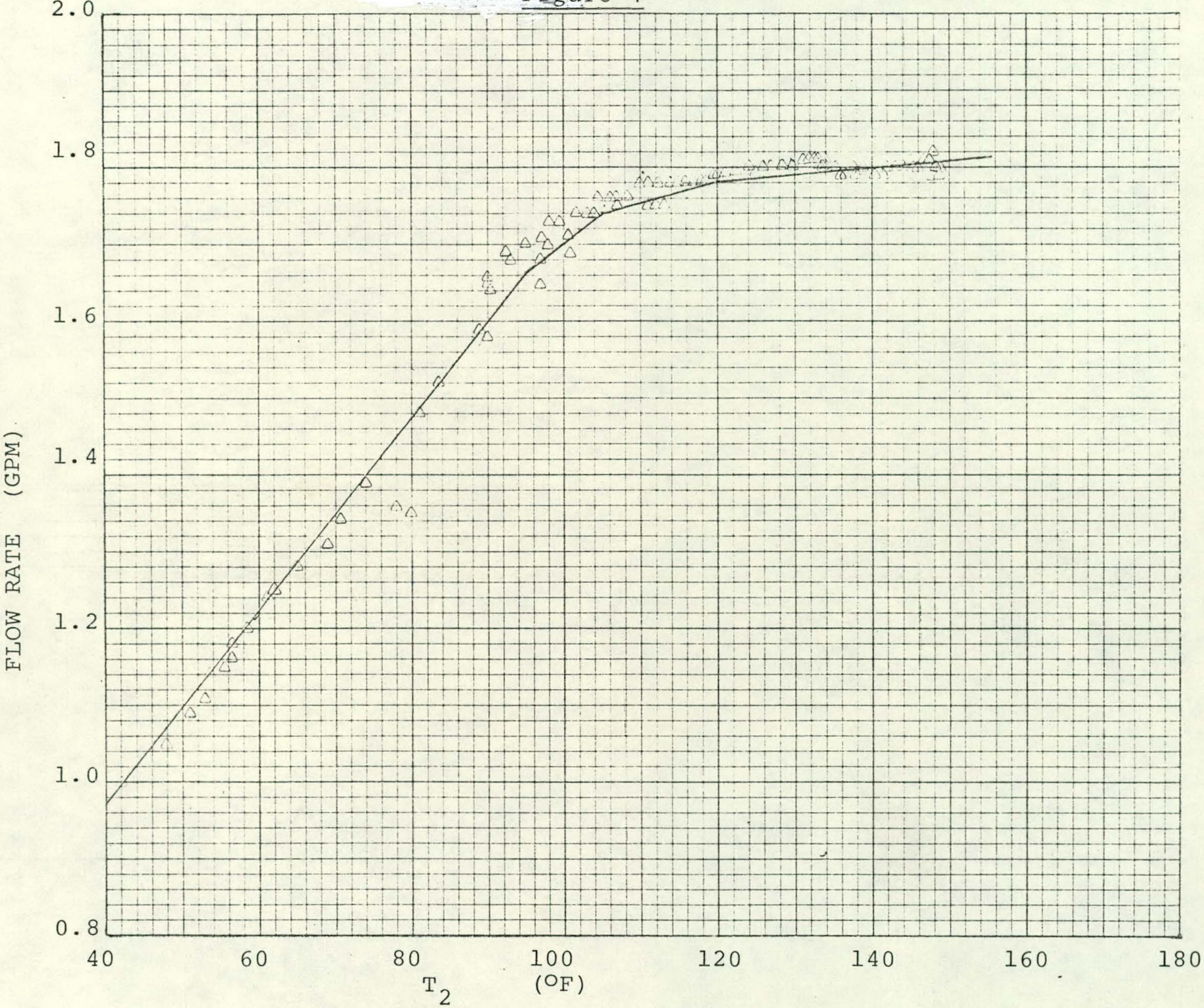
Notes: Computer error ± 5%
Low Cost Monitoring error ± 7% ± 3% Data Reduction Error



Final Instrumentation Layout

Figure 3

Figure 4



FLOW RATE VS FLUID TEMPERATURE, T_2

Tyngsboro System

Table 2

RESULTS FROM LOW COST MONITORING SYSTEM, TYNGSBORO

RESULTS FROM DPR RECORDINGS

	E_{solar} BTUx10^3	E_{KWH} BTUx10^3	%Solar	E_{H_2O} BTUx10^3	Hot Water Use Gal.
Week #1	38.8	2.2	95	21.5	35
	37.0	1.9	95	13.5	21.5
	40.8	2.0	95	36.1	50
	34.7	6.7	84	30.8	46.5
	0	11.7	0	14.3	22
	37.5	2.1	95	10.9	16
	14.6	1.0	94	6.3	10
Weekly Subtotals	203.4	27.6	88	133.6	201
Week #2	14.5	1.1	93	6.4	12
	39.0	7.4	84	48.1	77
	32.0	11.5	74	28.3	42
	7.4	38.0	16	37.7	51
	38.0	6.6	85	18.0	26
	20.3	1.5	93	18.0	30
	36.3	7.1	84	3.0	5
	6.5	0.5	93	11.9	18
Weekly Subtotals	194.0	73.6	72	171.4	261
Totals	397.4	101.2	80	305.0	462

A LOW COST APPROACH TO PERFORMANCE MONITORING FOR THE EVALUATION OF A SOLAR DOMESTIC HOT WATER SYSTEM

Joel Greenstein & Jay L. Lipeles
AZTEC SOLAR CO.
P.O. Box 272
Maitland, FL 32751
April 1978

The performance monitoring of solar heating and cooling systems can be very costly in terms of both time and equipment. Since heat losses occur on a twenty four hour basis, systems must be subjected to continuous surveillance. The data must be recorded automatically as human monitoring, channel selection or other forms of participation in the collection process is expensive and inconvenient. On the other hand, sophisticated monitoring systems are themselves expensive and can not normally be justified. The need for an automatic monitoring system that is simple enough to keep costs reasonable and yet sophisticated enough to provide data acquisition and control functions has arisen.

In order to establish the performance of its solar water heaters as a part of a complete system, the Aztec Solar Co. has conducted a controlled experiment. The program was carried out under contract to the National Bureau of Standards and entailed the operation of a typical solar domestic hot water system. For 65 days water was drawn automatically from the system in accordance with a pre-set schedule (see Table I). This water draw of 87 gal/day simulated the useage of an average family of about five people. In conjunction with the water draw schedule data were to be automatically collected at both regular and irregular intervals. An automatic monitoring system thus had to be designed which would perform two basic functions.

The first function of the monitor is to control the experiment. Water must be drawn at particular times in specified volumes in order to simulate family use habits. Therefore the time of day must be available to the control logic. The water draw schedule can be built in or can be a variable with means for setting the monitor.

The second function of the device is to collect data. The data consist of various temperatures, time of day, drawn volume of water and the states of various equipment. The data are to be collected before and after each draw, at predetermined times during daylight hours (see Table II), and at such events as circulation pump on or off and auxiliary heater on or off. The voltage drawn by the heater is also collected. The data are to be displayed and recorded.

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A system has been developed to meet these requirements and is shown schematically in Figure 1 as well as pictorially in Figure 2. This system controls the experiment by sending commands to a solenoid valve. The valve allows water to drain through a flowmeter. The flowmeter sends signals back to the control system where the flow rate is integrated in real time and compared with the schedule. When the correct volume of discharge has accumulated the valve is closed. The automatic monitoring system contains a built in digital clock for the time of day reference. The water draw schedule and the hourly data survey events were built in rather than externally provided.

The data collection was accomplished by an automatic sequencer. When either the clock or an interruption (e.g. pump activation) provides the proper trigger the sequencer samples each data channel, reads the output on a digital voltmeter and activates a digital printer. Thus a line is printed for each data point. A sample of the output is shown in Figure 3. The printed line display includes the day, time of day to the nearest second, the conditions of the circulation pump and the auxiliary heater (on, just off, or remained off), a channel code, the digital voltmeter reading and the number of gallons currently drawn. The paper tape forms a permanent record and can be keypunched for future machine analysis.

The instrumentation used to provide data to the automatic monitor consisted of a Cox AN8-4 flowmeter, Fenwal UUA33J1 precision thermistors, a Hewlett-Packard Digital Voltmeter (HP34701A) with a BCD module and a 4 digit display. The printer was a Hewlett-Packard digital thermal printer with BCD option (HP5150A). The flow meter is of the turbine type with sinusoidal output. The frequency of the sine wave is proportional to the flow rate. The automatic monitor sums the cycles and thus computes the total volume discharged. The precision thermistors are devices whose resistance decreases with increasing temperature. The resistance of the thermistor is calculated from the voltage drop across it, which is recorded. Thermistors were placed to record the temperature in the solar collectors, tank inlet and outlet ports, and ambient air in the collector vicinity.

The system performed well in general but in retrospect improvements have been suggested. The main problem encountered was that there were several power failures due to tropical storms which caused the clock to reset and lose track of the time of day and the date. An uninterruptable power supply would have eliminated this problem. The method of data recording chosen was adequate for this experiment but may prove lacking for longer tests. If a significantly larger group of data is to be collected, a means of recording whose output can be directly fed into data processing equipment is required. The digital printer would have to be replaced by either a magnetic tape recorder or a paper tape punch.

The experiment lasted for a period of 65 days during which approximately 25,000 data entries were recorded without significant human interruption. The cost of the entire program was approximately $19,000. However, this figure includes the cost of the solar heaters, the storage tank with the auxiliary heater, solar controls and circulation pump, hardware installation, the engineering development of the automatic monitoring system, the reduction of some of the data and report preparation. Future use of the data collection system will involve only the costs of a production version of the monitor and the associated instrumentation.

TABLE I

WATER DRAW SCHEDULE

Time of Day (EST)	Gallons
0700	5.0
0800	7.5
0900	5.0
1230	7.5
1900	7.5
2030	20.0
2130	10.0
2200	5.0
2230	10.0
2250	10.0

TABLE II

SUPPLEMENTAL DATA COLLECTION TIMES

1000	1500
1100	1600
1200	1700
1300	1800
1400	

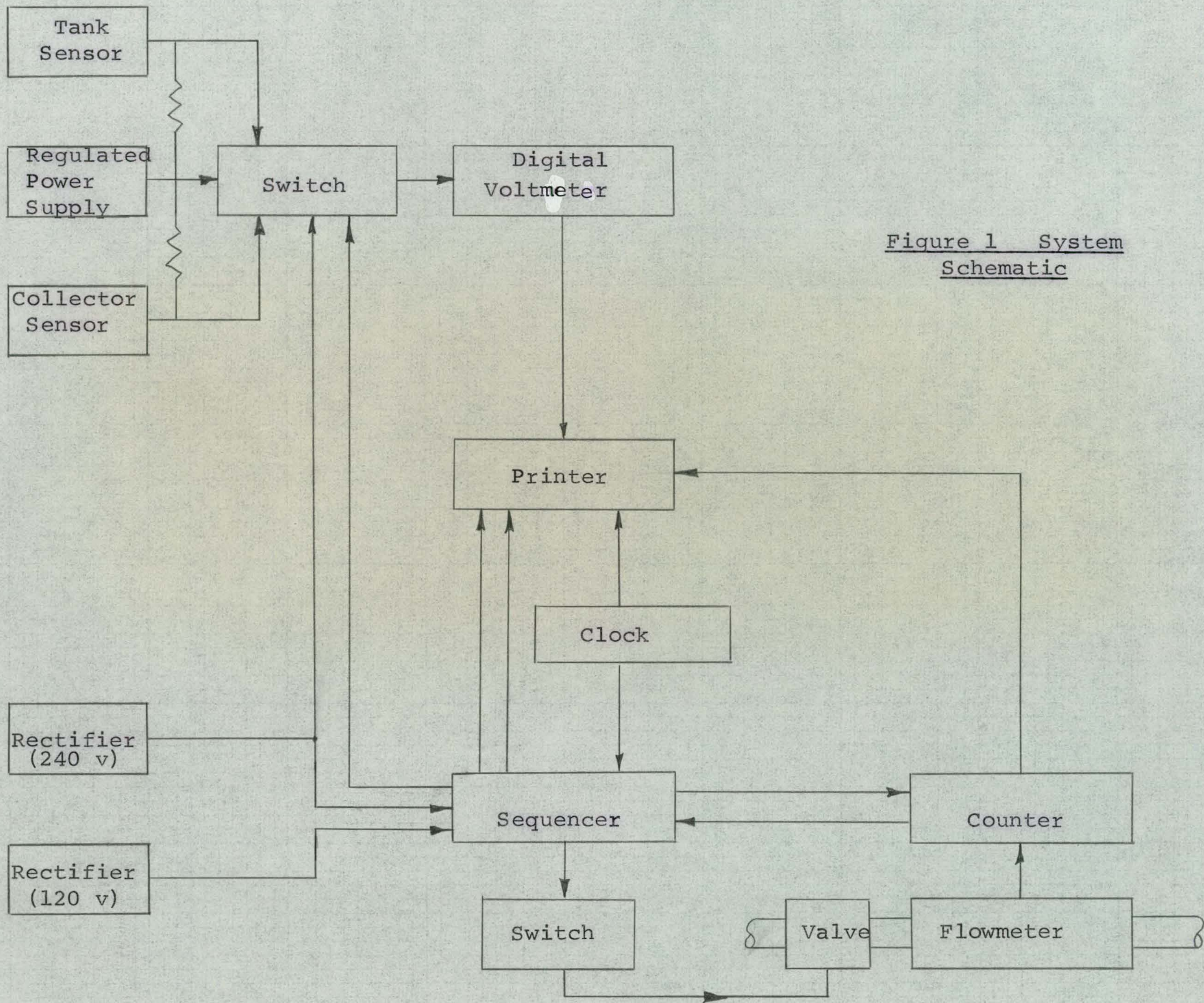
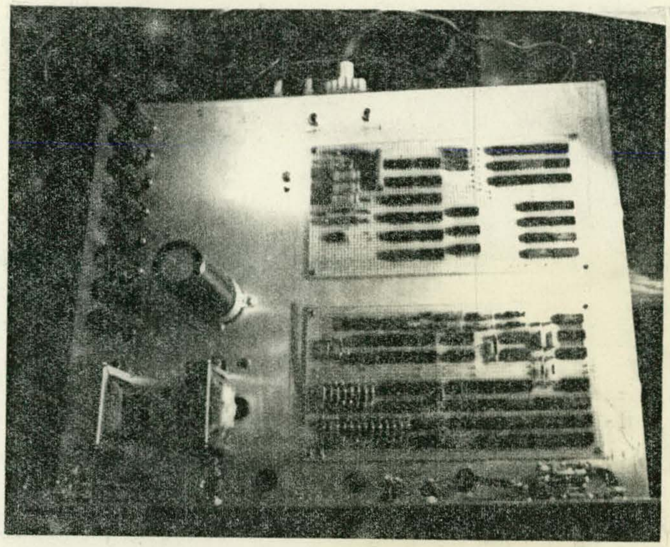


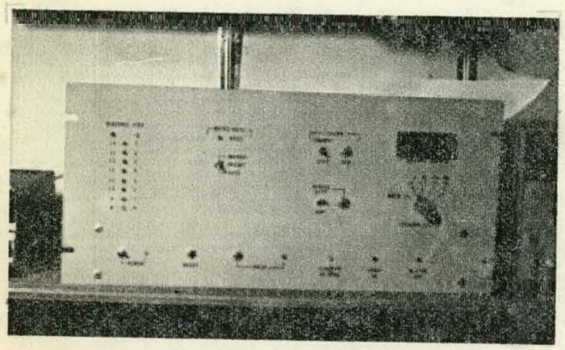
Figure 1 System Schematic



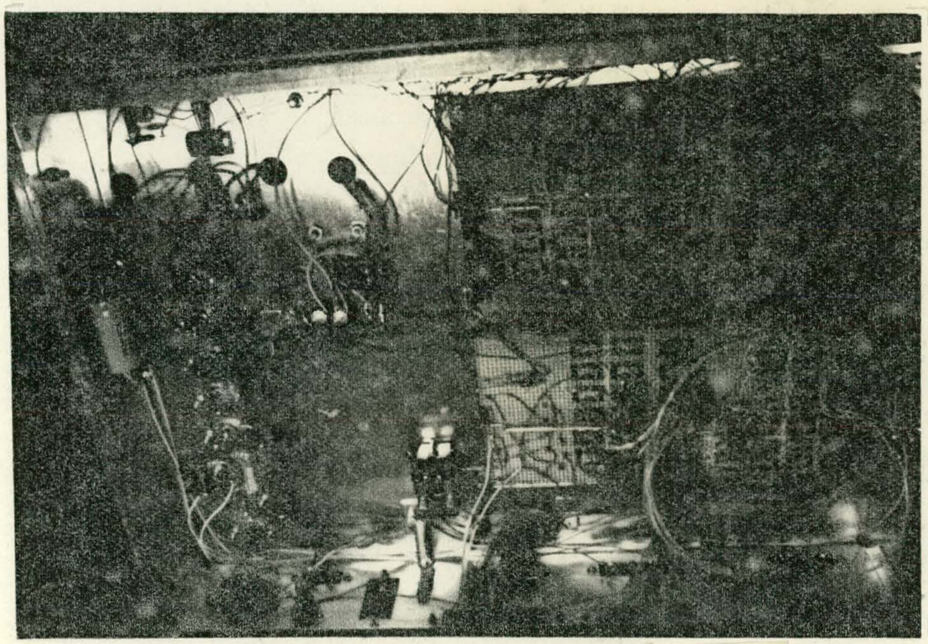
Top view showing flat packs and other components.

Fig. 2

Automatic Monitoring System



Front panel showing indicator lights, display and controls.



Underside view showing wiring.

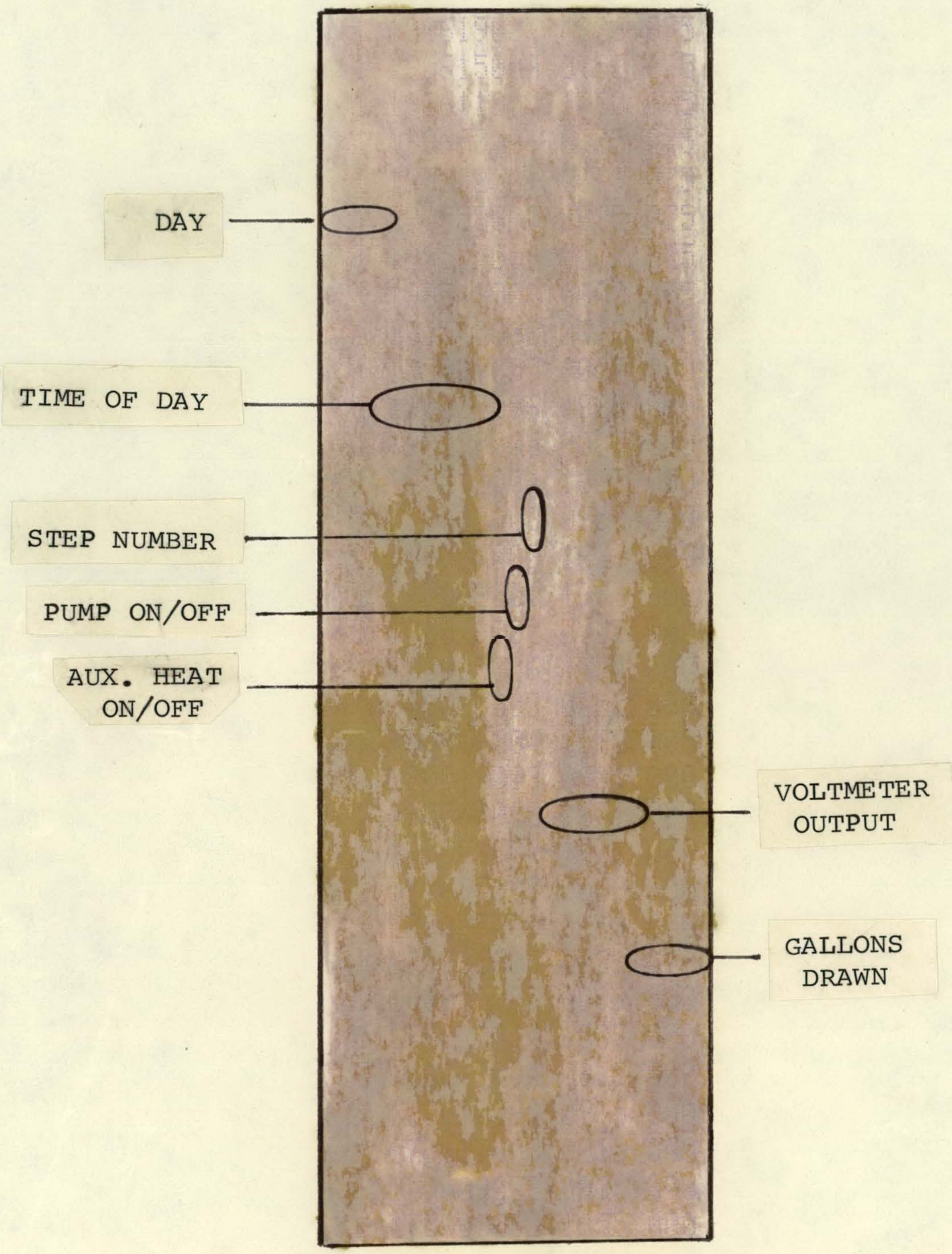


Figure 3

Sample Output

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Simple, Low Cost Monitoring Methods For Solar Hot Water System

B. M. Whitehurst, P.E.

Route 6, Box 338, New Bern, N.C. 28560

Many of the solar hot water systems used for supplying either domestic hot water and/or space heating were constructed and installed by the "do-it-yourselfer". Most of these systems work to some degree, however, little has been written about simple techniques which can be used to evaluate the efficiency of these systems. The purpose of this paper is to show simple methods that can be used to evaluate the performance of both the thermosiphon systems and a forced flow system.

Forced Flow System

The key to the monitoring of a forced flow system is a very sensitive thermometer calibrated in 0.1°C units. With the flow in a flat plate collector of about 0.02 to 0.05 gpm/ft.^{2} the temperature rise in one pass through a panel (15 ft.^{2} to 20 ft.^{2}) will be from 1.5°C to 3.0°C. A difference of 0.1°C will thereby limit the change from 3% to 7%. Thermometers of this accuracy can be purchased from a scientific supply house for about $15 each. Only 2 are needed. Measurement with this technique eliminates efficiency effects caused by high Δ t's across the panel. This technique is sensitive enough to observe the change in solar intensity with the time of day, and can be used by the "do-it-yourselfer".

Mercury thermometers calibrated in 0.1°C are quite inexpensive provided the user does not demand Bureau of Standards Calibration or calibration by the supplier. The computation of heat output requires only the temperature difference be accurate. Two thermometers can be calibrated against each other for differential accuracy even though they may indicate a somewhat higher or lower temperature than actually exists. The calibration technique is quite simple. The 2 thermometers can be placed in a container of water and the temperature measured at 4 or more different places across the full range of the thermometer. A graph or table of the data will then suffice for converting the observed data to the true difference. In most cases the thermometers will be of high quality, and differences will not be observable.

Figure 1 shows a solar panel with thermometers inserted through rubber stoppers in the inlet and outlet positions, and a small pump for circulation of the water or fluid. The source of water used for testing the panel should be large enough so the temperature rise of the total system will be relatively small. It is well known that as the temperature of the system increases above ambient that the efficiency of sunlight conversion will decrease even with selective surfaces. The performance of the panel should be measured under conditions close to ambient to eliminate this effect. A temperature difference between the panel inlet and outlet of greater than 5°C should be avoided.

Figure 2 presents observations made from a panel constructed by students at the Beaufort Technical Institute.

Figure 3 indicates that the observations were sensitive enough to observe the solar insolation change with the time of day.

Figure 4 is a plot of the temperature rise in the 50 gallon supply drum of water used for the tests. Computations from this data cross check the observations of panel heat output as seen in Figure 3.

Thermosiphon System

The thermosiphon system works on the principles of natural convection. The greater the temperature gradient, the greater the density difference will be. The greater the density difference the higher the flow rate. The key to monitoring the heat output of a thermosiphon system depends on the determination of the flow rate of the system. This paper presents 2 simple ways of measuring the flow rate in a thermosiphon system. One method is to measure the rate of change of the hot water interface in a tank of known dimensions with the aid of an inexpensive surface thermometer. Another technique is to plot the temperature at the bottom of the thermosiphon storage tank and select the point where the temperature rise accelerates.

Rate Change of Hot Water Interface

Figure 5 shows a typical set-up for a thermosiphon system. The head tank should be 2 feet or more above the outlet of the solar panel to be tested. The head tank should be insulated except for a strip down one side large enough to insert the surface thermometers. It is preferable to use 2 surface thermometers held in place by a small magnet. With this set-up the time is measured for the hot interface to travel from the top thermometer to the bottom thermometer. The flow rate can then be computed from the time data and tank dimensions.

A 5 gallon head tank matched with a 16 to 24 $ft.^2$ panel provides sufficient working time to make the measurements. A rule of thumb would be to provide a tank with a volume from about 0.2 to 0.5 gallons per square foot of panel surface. A smaller tank could result in too rapid a movement of the interface, or the destruction of the tank thermocline. Conversely the larger tank interface will change so slowly as to introduce significant measurement errors in the interface location. It is best to allow the system about 5 to 10 minutes to stablize before locating the top interface. This time will allow the pipes and other material in contact with the hot fluid to equilibrate.

In the event that a surface thermometer is not available, excellent accuracy can be obtained by feeling the interface with your fingers, marking it, and measuring the distance between the two marks.

With the flow rate, and the temperature difference across the panel known, the heat output can be computed using classical formulas.

Graphic Computation of the Flow Rate

Figure 6 and 7 show the plot of data taken from a thermosiphon system as described in Figure 5. It is best to plot the observations taken from time 0 from both the inlet and outlet, and locate the points where temperature rate changes. As can be seen, these rate changes are easily observable. The plotting of both temperatures allows a cross check for verification.

It is interesting to note in both figures, how the time was constant for both cycles of volume turnover of the 5 gallon head tank. As you would expect, the heat output during the first turnover was much greater than during the second because the temperature level of the first cycle was essentially ambient, and the second cycle was 25°C above ambient. The data showed the heat collection for the first cycle to be 143 Btu/hr./ft.^{2} of panel surface on November 19, 1977. The second cycle was 109 Btu/hr./ft.^{2} of panel surface. Revere Copper & Brass Co. indicate that the lower value for the second turnover is about what would be expected due to the temperature level above ambient. On the day of this test an identical forced flow panel system had an output of 152 Btu/hr./ft.^{2} over the same time span of the day.

Figure I

FORCED FLOW SYSTEM

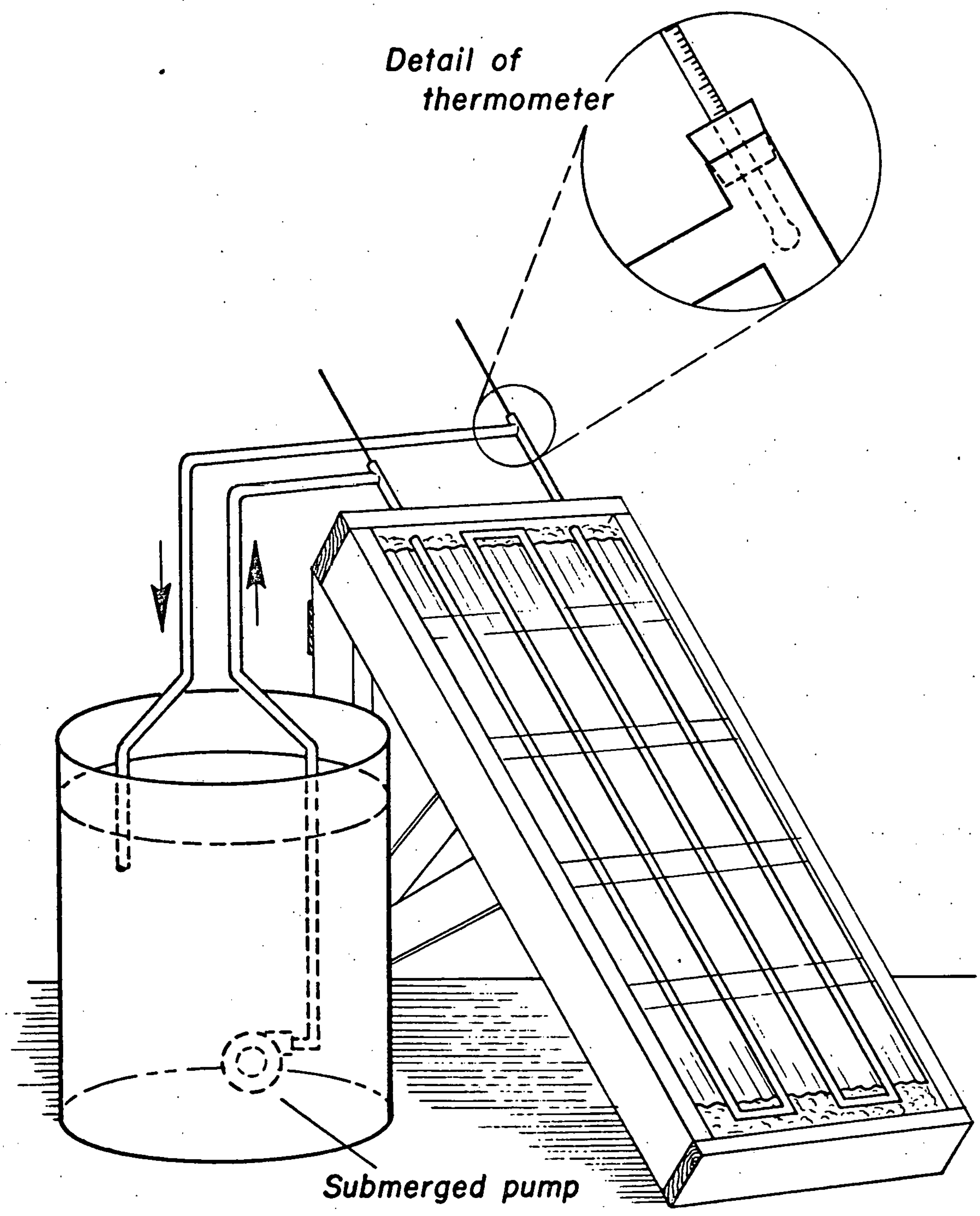
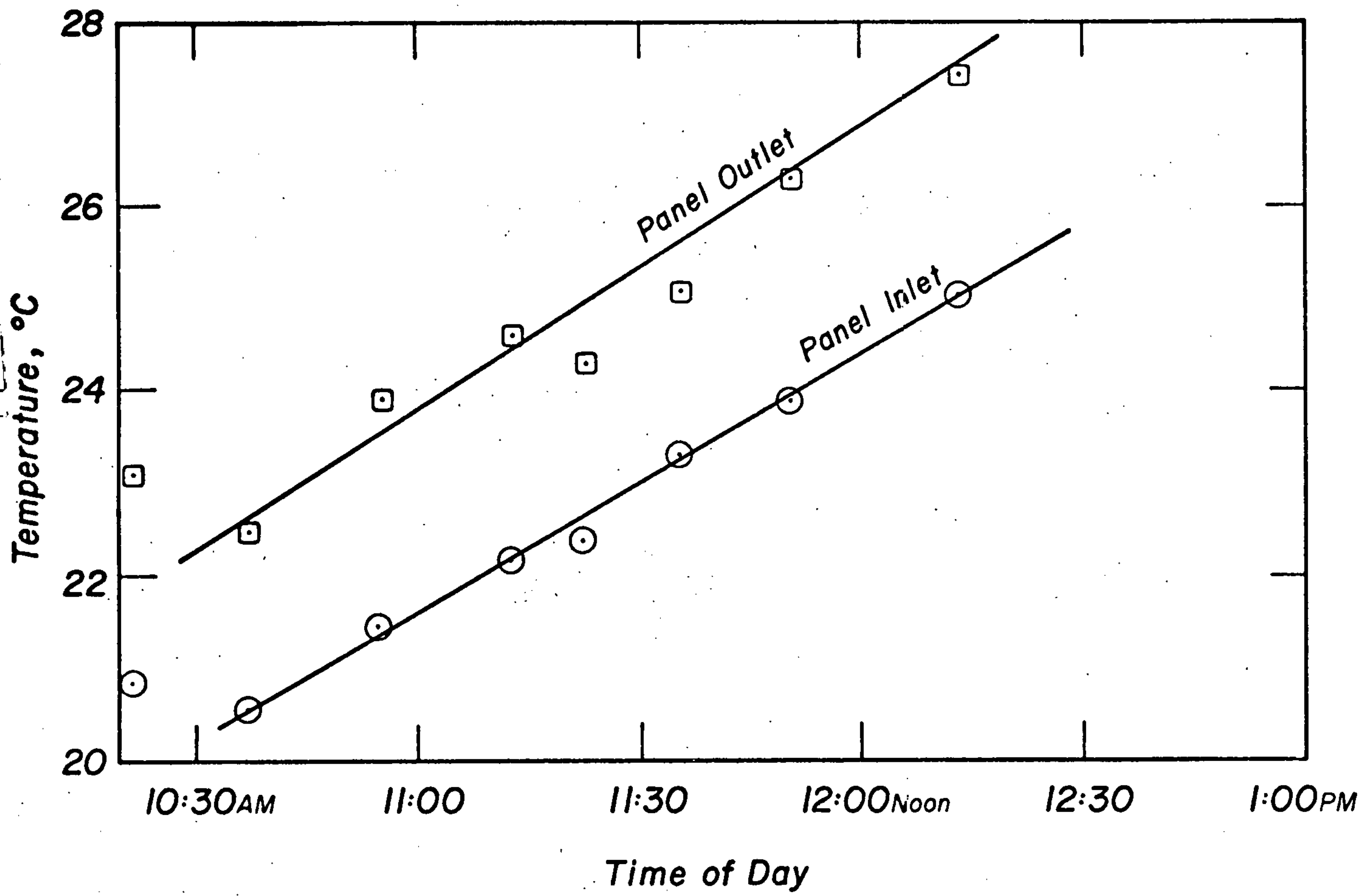


Figure 2

SOLAR PANEL TESTS, FORCED FLOW SYSTEM



Pump flow 1.16 gpm or 0.072 gpm / ft.^{2} of panel surface. (Panel area 16 ft.^{2})

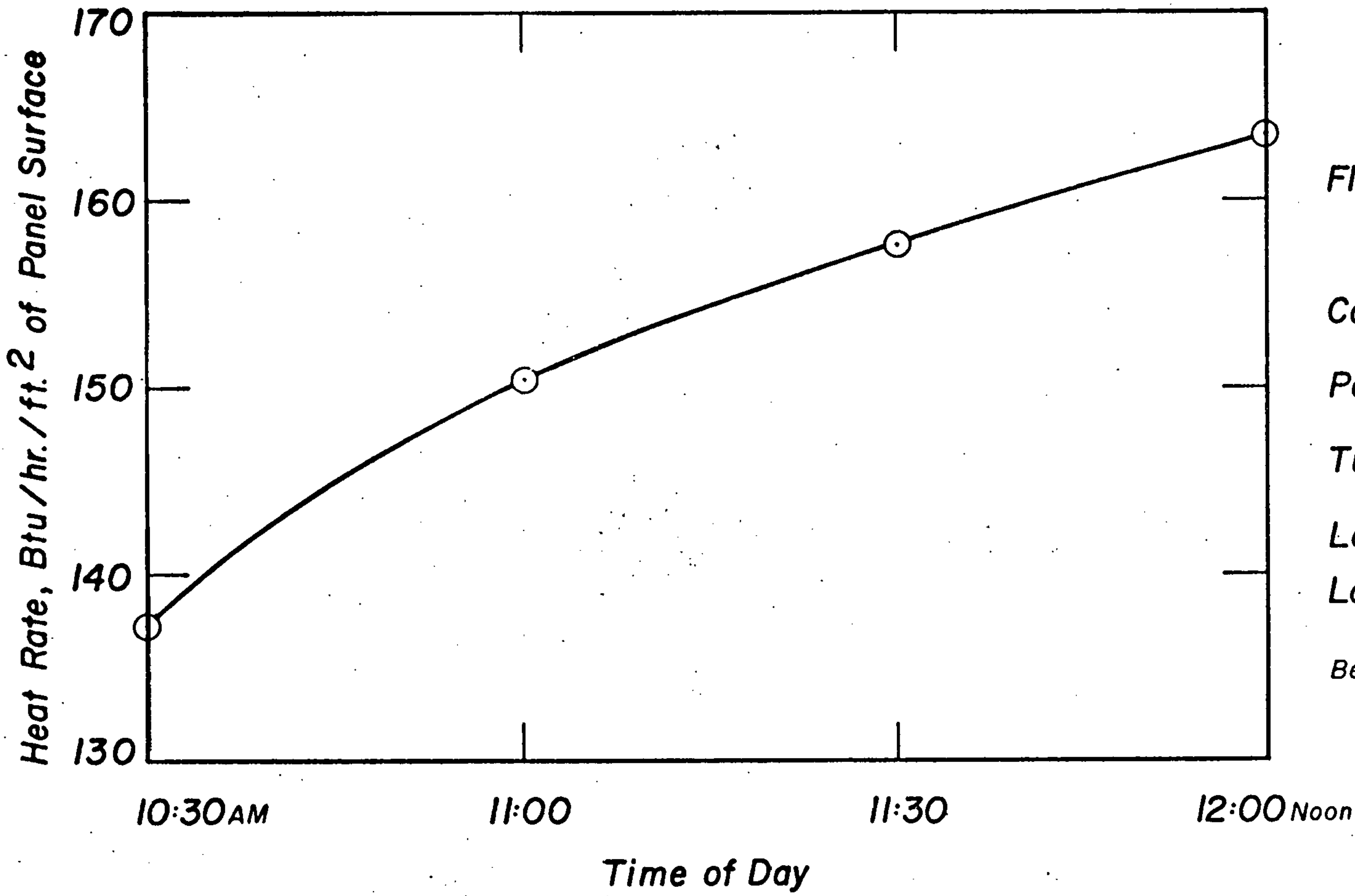
Δt

10:30 = 2.1°C (3.78°F)
11:00 = 2.3°C (4.14°F)
11:30 = 2.4°C (4.32°F)
12:00 = 2.5°C (4.50°F)

Beaufort Tech. 11-19-77

Figure 3

SOLAR INSOLATION CHANGE WITH TIME OF DAY



Flow through panel 0.072 gpm per sq. ft.

Corrugated galvanized.

Painted black.

Tubes on 6" centers.

Latitude 35.5° N

Longitude 77.0° W

Beaufort Tech 11-19-77

Figure 4

SOLAR PANEL TEST, FORCED FLOW SYSTEM

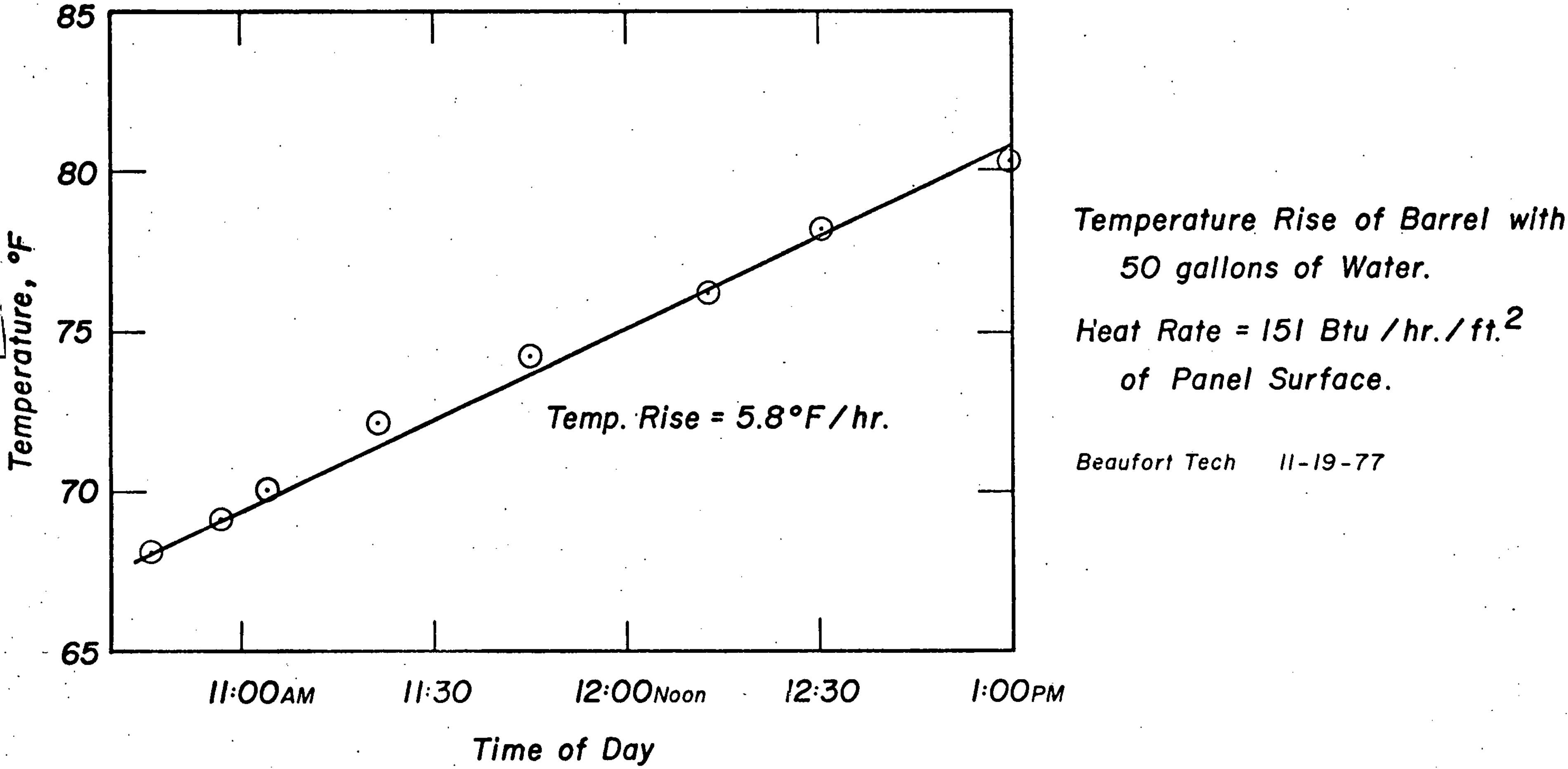


Figure 5

TYPICAL THERMOSIPHON SYSTEM

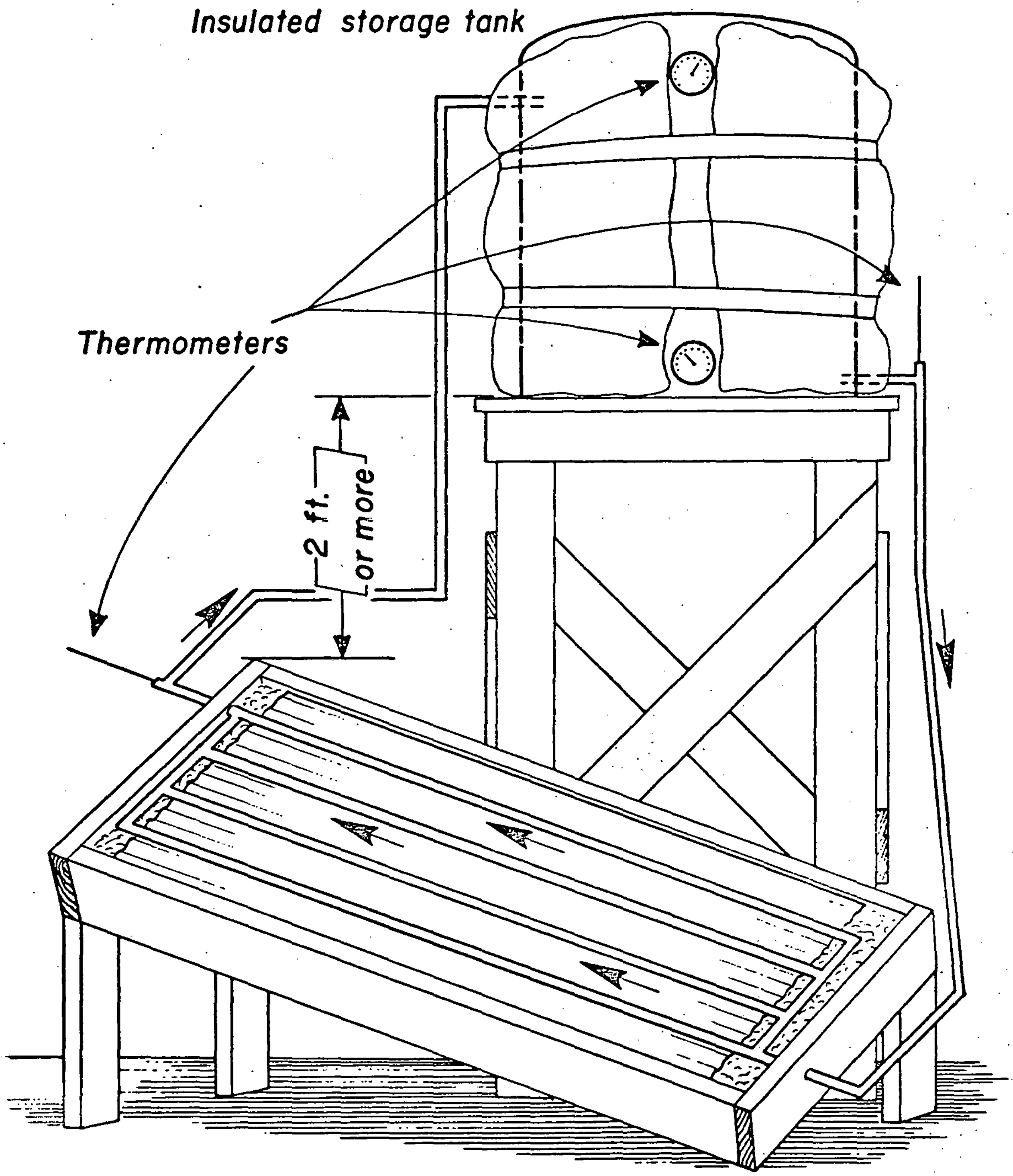


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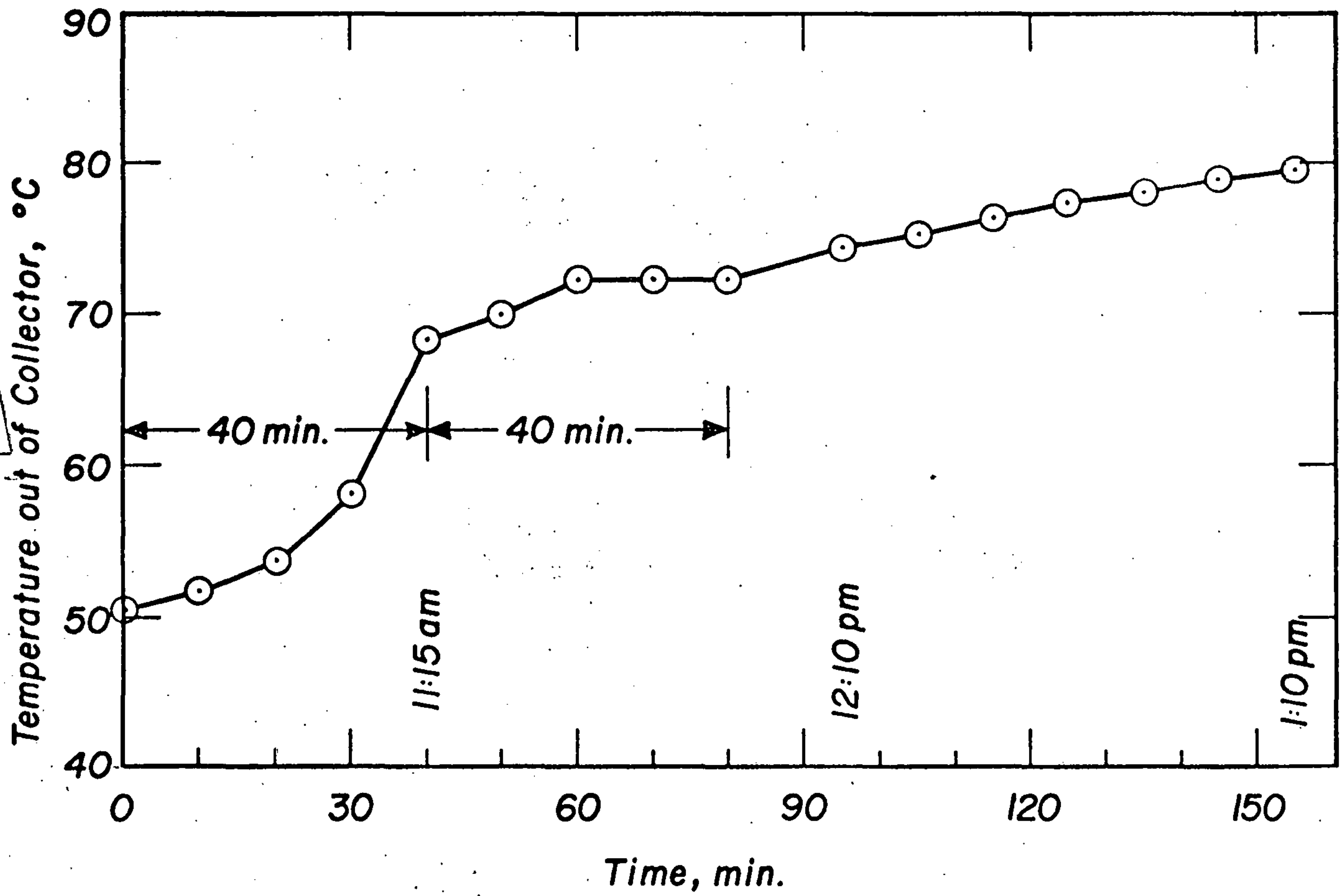
Figure 6

THERMOSIPHON SYSTEM - HOT SIDE OF COLLECTOR



Collector surface 21.67 ft.^{2}

Computed flow rate 7.5 gph

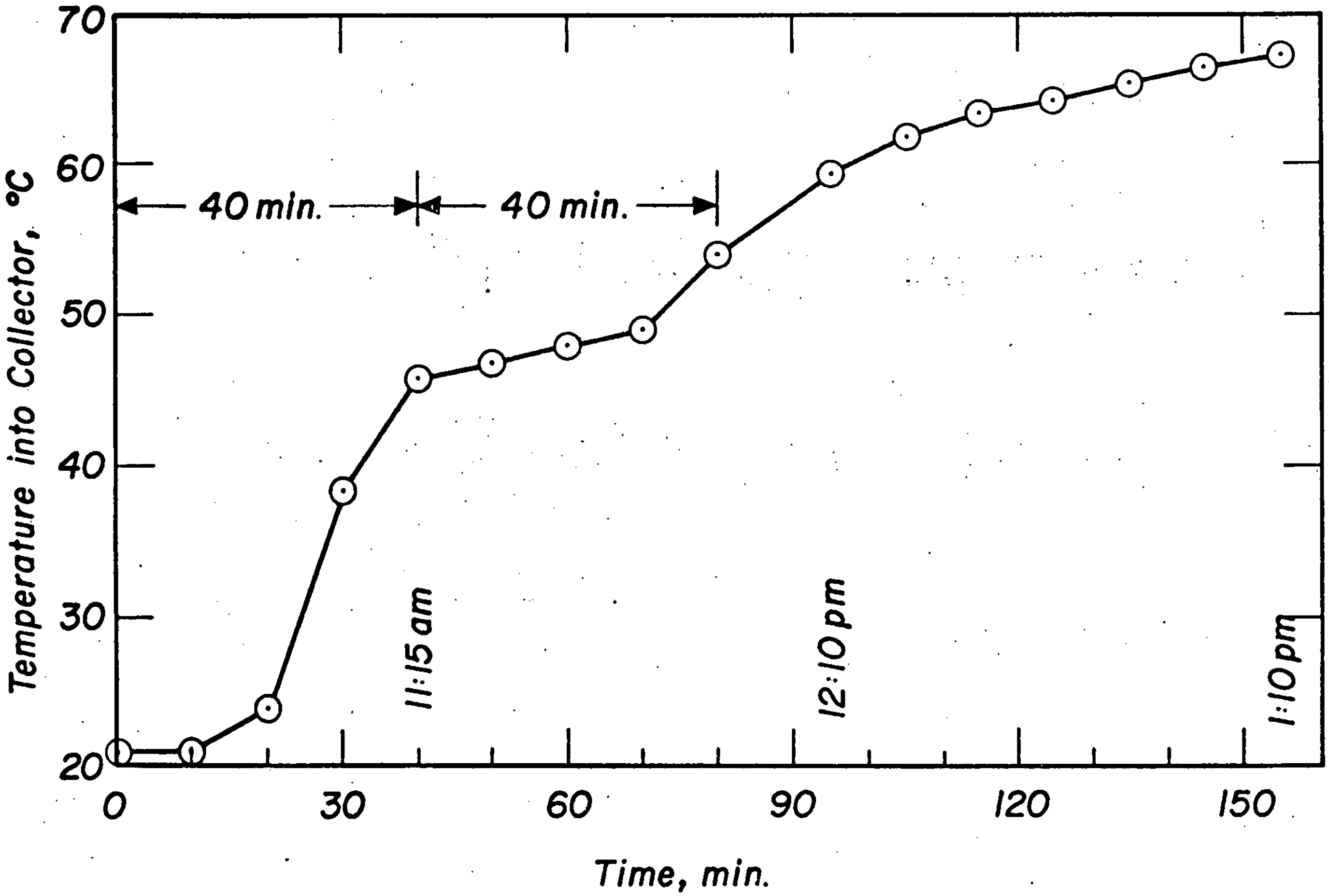
Latitude 35.0° N

Longitude 76.8° W

Pamlico Tech 11-12-77

Figure 7

THERMOSIPHON SYSTEM - COLD SIDE OF COLLECTOR



Collector surface 21.67 ft.²

Computed flow rate 7.5 gph

Latitude 35.0° N

Longitude 76.8° W

Pamlico Tech 11-12-77

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LOW-COST MONITORING OF SOLAR SYSTEM PERFORMANCE

JERRY RUSSELL
CONSERDYNE CORPORATION
4437 San Fernando Road
Glendale, California 91204

This paper describes work done at Conserdyne Corporation in developing economical methods for metering the energy productivity of small solar domestic hot water systems. The paper summarizes the results of an extensive data-collection program using an electro-mechanical technique to monitor the performance of Conserdyne Solar Systems, and describes a second all-electronic metering technique. Standard linear and MOS/LSI integrated circuits are used in the new system to hold costs to a very low level, while providing accuracy comparable to microprocessor-based data acquisition systems.

INTRODUCTION

Today, the solar industry is working to change solar heating from a laboratory curiosity to a mass-market reality. Before this transition can come into being, however, the solar industry must demonstrate that solar heating devices can actually save energy and money. Of course, solar energy itself is, in many respects, already a proven technology. There is a wealth of data demonstrating exactly how solar heating devices perform in controlled conditions, in experiments performed by qualified scientists and engineers using highly sophisticated, very expensive metering equipment. However, in spite of this wealth of data on every aspect of solar system performance, there is wide spread skepticism as to whether commercially available solar heating products will perform as advertised. This skepticism may be well founded, judging from a widely publicized recent study of solar domestic hot water systems installed on the east coast under the HUD initiative program, which showed that most of the systems performed very poorly, due to faulty design or incorrect installation.[1] We at Conserdyne believe that low-cost monitoring techniques can play a vital role in winning consumer confidence for solar heating products, by providing a very broad, statistical data base showing that consumer-marketed solar systems can perform well under real life conditions.

At Conserdyne, we have installed some type of monitoring equipment on every solar-heating product we have sold. We've found that the simple fact that we are even willing to meter our systems' energy productivity goes a long way towards building consumer confidence in our products. And the data we've collected so far has been very encouraging, and has greatly increased our own confidence level in our products' uniform quality. Of course, since we've been simply adding the costs of our metering program onto our overhead, and have been working totally without government financing, we've had to take the "low-cost" constraint very seriously. Nevertheless, we've collected some data that we consider very worthwhile, and we have now refined our metering techniques to the point where we are willing to recommend them to other corporations and agencies interested in promoting the rapid commercialization of solar energy.

SOME EARLY RESULTS

With many of our water heating systems, we installed a "metering pack" consisting of a direct-reading flowmeter and a cumulative running-time meter, which we connected to the back-up heating unit (see Fig. 1). By looking at the household's total water usage, we were able to estimate the total water-heating energy requirement; and by looking at the running-time meter, we were able to estimate the energy supplied by fossil fuels or electricity. Taking the difference between the total energy requirement and the back-up energy supply, we arrived at an estimate of the solar heating units energy production. During the period from November, 1976 through September, 1977, we collected data from twelve systems located at various sites in Southern California. These systems showed an annualized average energy savings of 9.4 million BTU's, with a standard deviation within the sample population of 2.2 million BTU's.

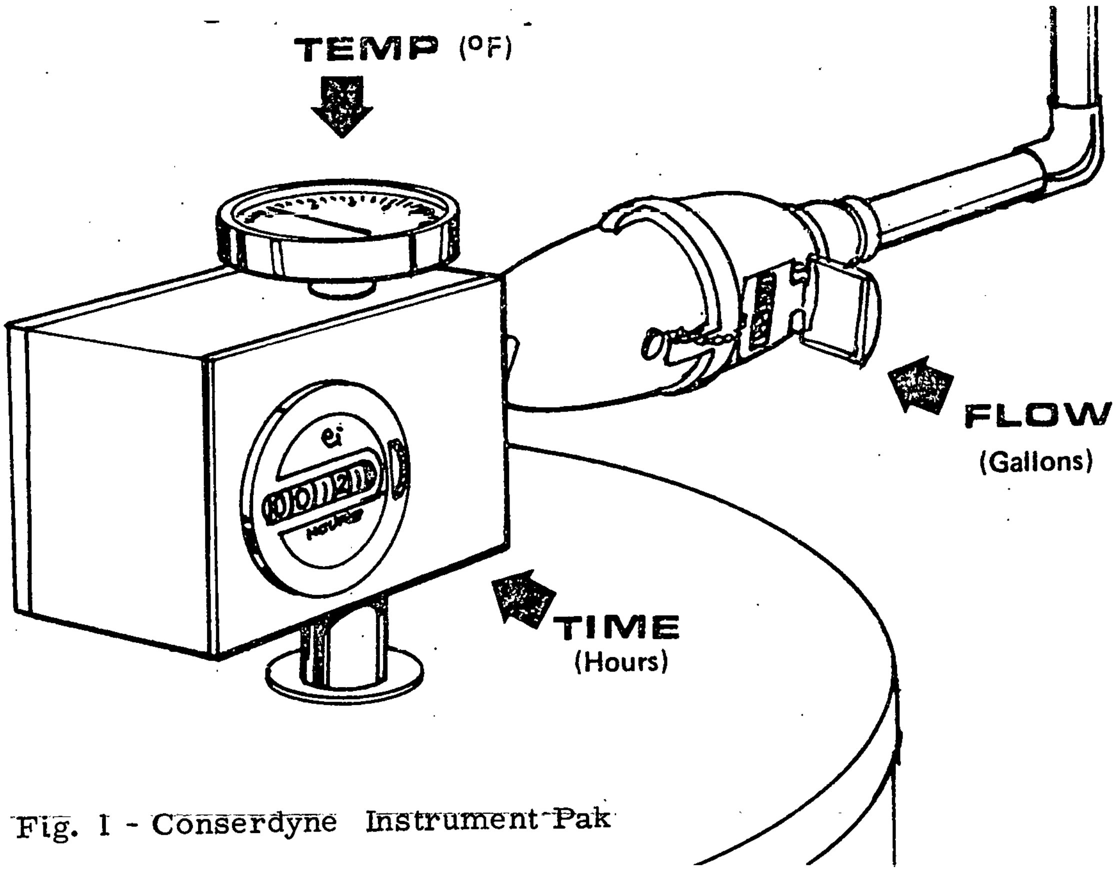

Fig. I - Conserdyne Instrument Pak

We also made an estimate of the errors to be expected with this approach, because of the many unmeasured variables used in the equations solving for the solar energy output. Possible errors were on the order of ± 50%, which we considered too high. Furthermore, evaluation of the results involved some time consuming and subjective

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hand calculations. Therefore, we started to work on a new metering approach, which would be direct-reading and accurate as well as low-cost; the results of this development program are discussed below. Nonetheless, our original program did fulfill its basic objective: namely, to satisfy ourselves and our customers that our units were, indeed, saving energy.[2]

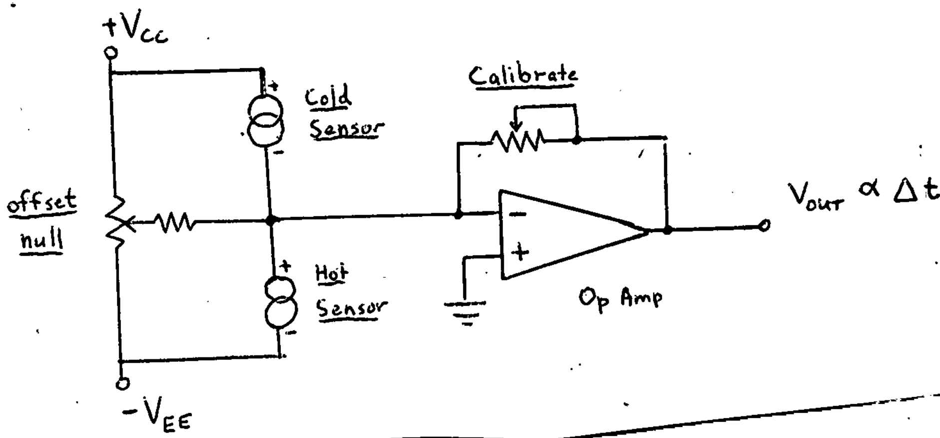
A NEW CONCEPT IN BTU METERS

Our most recently-developed metering package is an electronic BTU meter. This meter is, conceptually, quite similar to a single-function data-acquisition system. Just as a microprocessor-based system would, this BTU meter measures the temperature differential between the inlet and outlet temperatures of the storage media, multiplies the result by the flow rate through storage, and continuously integrates the result through time, to yield a direct read-out of the total energy output of the solar heating system. (Another read-out indicates accumulated gallons of flow.) However, in our low-cost version of the data-acquisition system, we were able to eliminate many of the items which have previously made such systems moderately expensive - including the microprocessor itself. Four-function calculators, less keyboards, but otherwise similar to the ones that can be bought at any department store for under $10.00, provide all the computing power necessary for data storage and display in the low-cost BTU meters, while a few assorted CMOS gates and counters perform all necessary logic functions. Thus, our cost to make this BTU meter, including the necessary sensors, is less than $150.00, and we expect to be able to make them available to the solar industry for less than $250.00 - an unprecedented low cost for this type of equipment.

CIRCUIT DESCRIPTION - TEMPERATURE SENSING

A major semiconductor manufacturer has recently introducted an integrated-circuit temperature sensing device which acts as a current source directly proportional to absolute temperature. This integrated circuit incorporates a temperature-sensing PN silicon junction, an amplifier, and linearizing circuitry. It is laser-trimmed at the wafer stage to provide an initial calibration. Thus, the circuitry required to interface with a pair of these sensors and produce a voltage directly proportional to the difference in temperature between the two sensors can be quite simple, in contrast to the complexity and cost of interfacing with thermocouples or platinum RTD sensors.

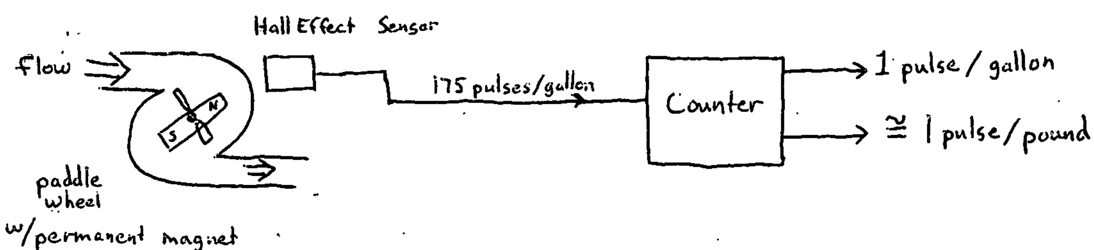
Fig. 2 - Temperature - Differential circuitry



FLOW SENSING

For our low-cost BTU meter, the usual turbine-meter approach was out of the question. Instead, we used a thermoplastic paddle-wheel-type flowmeter originally intended for use in monitoring the water consumption of apartment dwellers for billing purposes. The paddle-wheel in this flowmeter turns a small permanent magnet inside the meter body. In the original application, this magnet turned a disc, which was coupled to a gear chain and mechanical counter indicating the total flow through the meter. We modified the meter by removing the mechanical accumulated-gallons register and replacing it with a hall-effect magnetic field sensor. In the modified meter, as water flows through the meter body and turns the paddle-wheel, the hall-effect sensor detects the motion of the magnetic disk, and produces a train of pulses at a rate proportional to the flow. A CMOS ripple counter is used to reduce the frequency of pulses to exactly one (1) pulse per gallon for input to the gallons counter circuitry, and to a precisely-defined arbitrary rate - approximately one (1) pulse per pound of flow - to control the BTU counter circuitry.

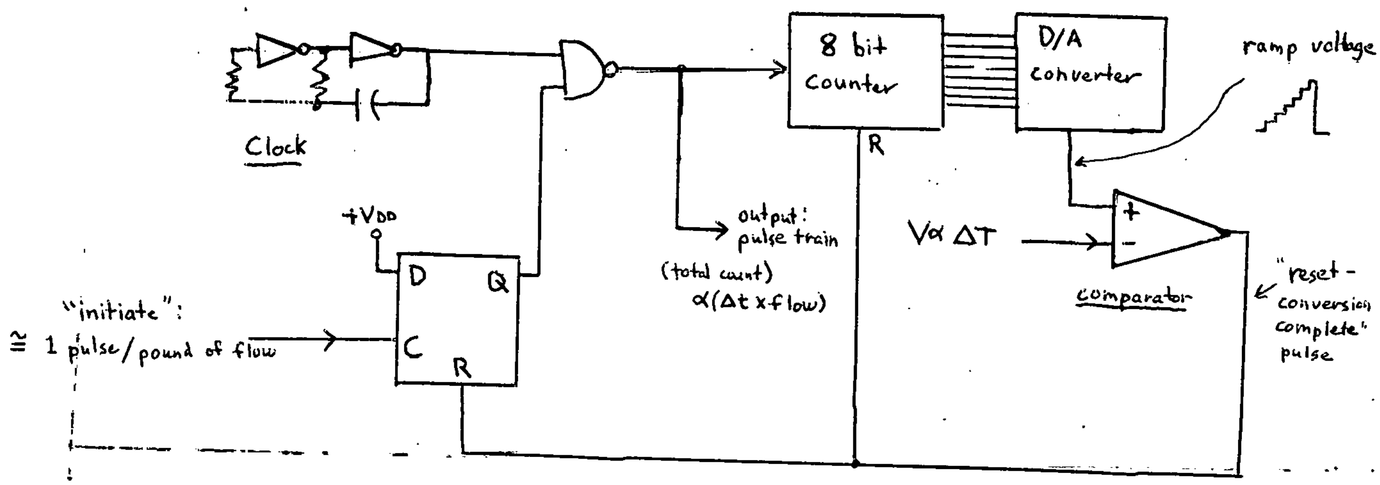
Fig. 3 - Flow Sensing



ANALOG TO DIGITAL CONVERSION

Typically, microprocessor-based monitoring systems have used very fast, multiplexed A/D converters of the successive-approximation type. Since our BTU meter needed only one channel of A/D conversion, and since speed requirements were minimal, we were able to use a simple ramp-type A/D conversion scheme, using an 8-bit counter, a D/A converter, and a comparator. This converter is designed so that, upon receiving an "initiate" command, it produces a train of pulses (at constant rate) whose length is proportional to the analog signal from the temperature-input circuit - i.e. from O pulses for $\Delta t \leq 0$ up to 256 (2^8) pulses for $\Delta t \geq \Delta t$ max, where Δt - max is the full-scale limit of the A/D conversion. Now, the "initiate" command for the A/D converter is taken directly from the flow-sensor output, so that the total number of pulses at the output of the converter is directly proportional to the temperature differential multiplied by the total flow - i.e. directly proportional to the heat output of the solar heating system.

Fig. 4 - A/D Conversion



DATA STORAGE & DISPLAY

The output of the A/D conversion is fed into another ripple counter, which divides by an appropriate integer to give exactly 1 count per 100 BTU. This count controls a gate which executes the "+" function of a 4-function calculator, in which a "1" has already been entered. Thus, each time another 100 BTU's are accumulated, the "+" function of the calculator is executed, and the number in the display window of the calculator is incremented by 1. Thus, the display indicates the total accumulated BTU's output by the solar heating system (x 100), since the display was last cleared.

DATA/RESULTS

As of this writing (3/6/78) we have had a BTU meter installed on one of our systems for about two weeks - a period corresponding, roughly, to the duration of the worst flood in recent memory in So. California. Therefore, we don't consider our results from the BTU meter at this time to have any statistical validity. However, we have had a few sunny days, on which our domestic hot water system (consisting of a 30 square foot collector panel and 66 gallon storage tank) was able to produce 24,600 and 28,000 BTU's, respectively. These results tended to confirm the results of our earlier metering program.

NOTES:

1. Smith, Robert O. and Meekar, John. "Domestic Hot Water - a learning experience." Solar Age, March, 1978, Pg. 16

2. Kraye, Howard. Proving Solar Pays (unpublished paper - available from Conserdyne Corporation)

TESTING PROCEDURES FOR EVALUATING EFFECTIVENESS OF SOLAR ASSISTED DHW SYSTEMS IN LOW COST PUBLIC HOUSING PROJECTS

Milton Meckler, P.E., President, The Energy Group, Los Angeles.

Abstract

Describes a testing and monitoring program to evaluate a solar assisted domestic hot water heater system for a low cost public housing project. Covers selection of units; protection from unauthorized sources; public education; computer simulation; verification of test results; selection of major instrumentation and control items, and personnel training.

Description of Project

The use of solar augmentation for heating domestic hot water (DHW) particularly in a favorable climate such as Phoenix, Arizona, did not initially appear to be a difficult task--at least not until we began to understand the formidable problem of retrofitting a representative low cost housing project for the City of Phoenix Housing Authority. This work was conducted in association with Richard E. Joachim & Associates, Consulting Engineers, whose offices are also located in Phoenix.

Development of a testing and monitoring plan for evaluating a prototype, solar assisted domestic hot water (DHW) heater system for a typical low cost public housing project located in a transient neighborhood in Phoenix, Arizona, actually presented some unusual challenges. Among these were the need to protect sensitive instrumentation for access only by authorized personnel; provide exterior protective screening around the perimeter of the roof to minimize potential damage from vandals while avoiding shading of the solar collectors; interconnect with the existing DHW systems in such a manner as to discourage tampering by unauthorized personnel; and develop a project public education program aimed at emphasizing how project goals could benefit tenants through lowering utility costs, etc. These were some of the key social engineering items we also had to address in the design of the testing and monitoring system.

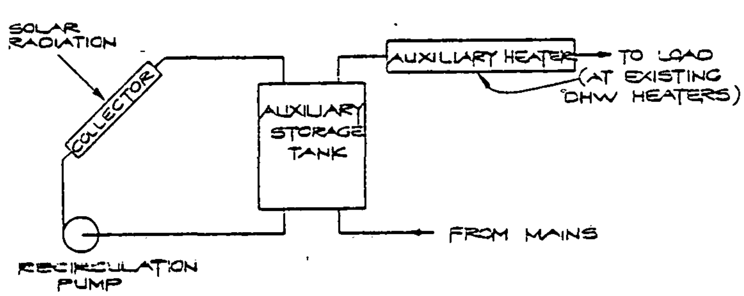
Background of Project

The purpose of our initial studies and ultimately the planned demonstration program was to assess the feasibility of retrofitting low cost public housing projects, estimate any cost savings and establish criteria for maintaining such solar installations within an overall modernization program being developed for low cost housing projects located within the City of Phoenix. A 38 unit two-story low cost housing project located within a transient neighborhood was designated by the City of Phoenix Housing Authority as the demonstration site for two principal reasons, namely:

a. That project environment, scale, age, tenant profile and location was reasonably typical of other low cost housing projects, and

b. That all of the buildings which face either east or west along their major axis, are unshaded and can be easily split into two sections of comparable occupancy, one retrofitted and the other remaining unchanged.

After visiting and inspecting the site, our initial efforts were directed toward comparing a central, built-up solar system for each building versus use of separate package type, prefabricated solar systems complete with integral storage tank, collectors, required appurtenances and auxiliaries delivered to the job site and ready for system interconnection with one or more dwelling units. Early layout studies indicated that, mounting the solar collectors at the latitude plus 20° or at 53° tilt angle to the horizon facing due south would maximize the winter solar gain. Furthermore, our economic studies clearly indicated that a central built-up system would cost approximately double a package type, decentralized system capable of meeting the basic requirements indicated schematically in Figure 1. Additionally, significant savings were to be gained using a decentralized system because of the favorable economics of lower factory versus higher on-site assembly labor costs required for built-up solar systems. In view of project budgetary constraints it was decided to proceed with a decentralized system. Two types of decentralized solar systems were considered.



SOLAR DHW SYSTEM SCHEMATIC

FIG.1

The first system considered consisted of a preassembled roof-top package comprising the collector panel, storage tank, pump, complete with integral piping to facilitate interconnection with existing piping presently serving various DHW heaters in each of the test dwelling units. The second solar system investigated consisted of a built-up decentralized system comprising a roof-top mounted solar collector with piping extended to a remote auxiliary storage tank and pump assembly physically located adjacent to the existing DHW heater located in each dwelling unit as shown in Figure 2.

After detailed analysis of the various test floor plans, it was decided that there was not adequate space within each dwelling unit to accommodate the remote auxiliary storage tank assembly. Consequently self-contained roof-top solar packages arranged as illustrated in Figure 3 were selected for final design.

For purposes of this demonstration project it was assumed that the 19 units to be retrofitted would be those in the west half of the existing project illustrated in Figure 4, corresponding to the following dwelling unit combinations, namely; 12-two bedroom units, 3-three bedroom units, 3-four bedroom units, 1-five bedroom unit, altogether totalling 19 units.

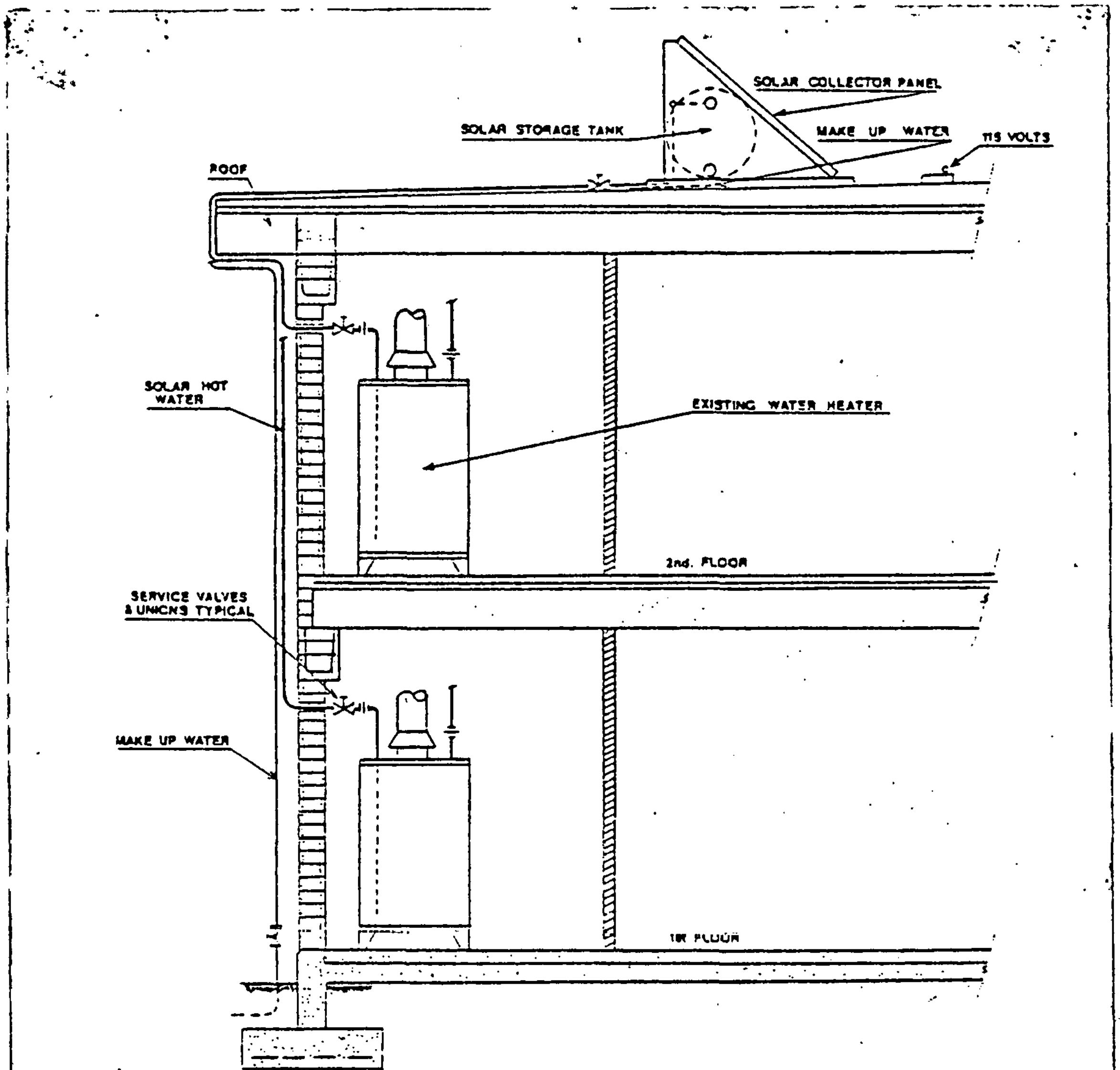
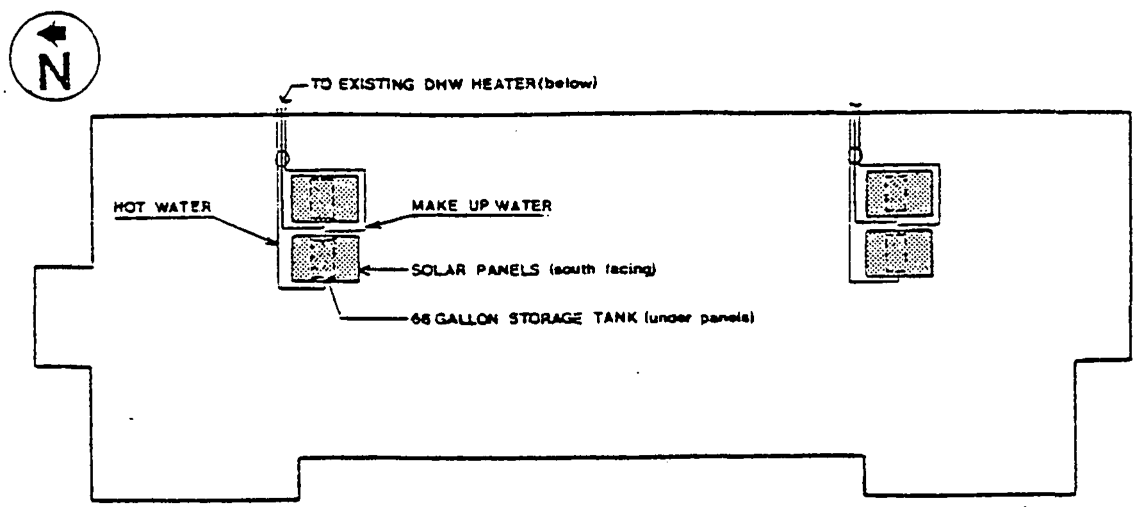


Fig. 2 TYPICAL SOLAR SYSTEM SCHEMATIC LAYOUT



TYPICAL ROOF LAYOUT

FIG. 3

During our preliminary engineering studies the following key system design parameters were established, a) solar collector - one collector of approximately 29 square feet of effective collector surface for each apartment, located on the roof directly over the point of use, b) DHW storage tank--one 66 gallon insulated tank located in the solar panel assembly on the roof, c) DHW storage tanks--existing in each apartment.

Developing Simulations for Dwelling Units to be Tested

Solar design parameters were evaluated by employing the TRNSYS computer program. TRNSYS, which is an acronym for Transient Simulation Program was initially developed by the Solar Energy Laboratory, University of Wisconsin, under grants from the RANN program of the National Science Foundation and from the Energy Research and Development Administration. This computer program represents over three years of development, testing and widespread use, and has proven to be one of the most reliable solar analysis programs presently available.

In applying the TRNSYS program, basically one models the solar system by representing it as a set of components, interconnected so as to accomplish a specified task. A typical solar water-heating system consists of a solar collector, an energy storage unit, an auxiliary energy heater, a pump and several temperature sensing controllers, etc. One obvious characteristic of TRNSYS is its modularity. Because the system consists of a number of separate, interacting components, it is possible to simulate the performance of the system by collectively simulating their performance. With a program such as TRNSYS which has the capability of interconnecting system components in any desired manner, solving differential equations and facilitating information output, the entire problem of system simulation reduces to a problem of identifying all of the components and formulating a general mathematical description of each.

By employing TRNSYS we were able to reduce the complexity of system simulation because it essentially reduces a large problem into a number of smaller problems, each of which can be more easily solved independently. Project DHW requirements were estimated employing the ASHRAE recommended profiles representative of apartment occupancy.

Approximately twelve alternatives were simulated by TRNSYS to determine an optimum demonstration configuration for the basic solar heating configuration illustrated in Figure 2. Notice that the domestic solar system can be reduced to four primary components, namely; the solar collector panels, the DHW storage tank, the auxiliary heater (in our case the existing DHW heater) and the circulating pump.

Three key system parameters were varied in our computer simulations, namely the size of the collector surface, the DHW storage tank volume, and the magnitude of the DHW load. Due to the small tank sizes required for auxiliary storage needs we were unable to employ tank stratification to any advantage. Therefore, all auxiliary DHW storage tanks were assumed to be fully mixed.

Description of System Operations

Referring to Figure 5, note that system power is de-activated by placing the "On-Auto-Off" switch in the "Off" position or in the event of power failure, solenoid valves SV_1 and SV_2 are closed and solenoid valve SV_3 is opened. Fortunately we have isolated each solar collector from the rest of the system by means of valves SV_1 and SV_2, and therefore it can be drained by the action of SV_3 provided a vacuum breaker valve is installed at high point of the solar collector circuit.

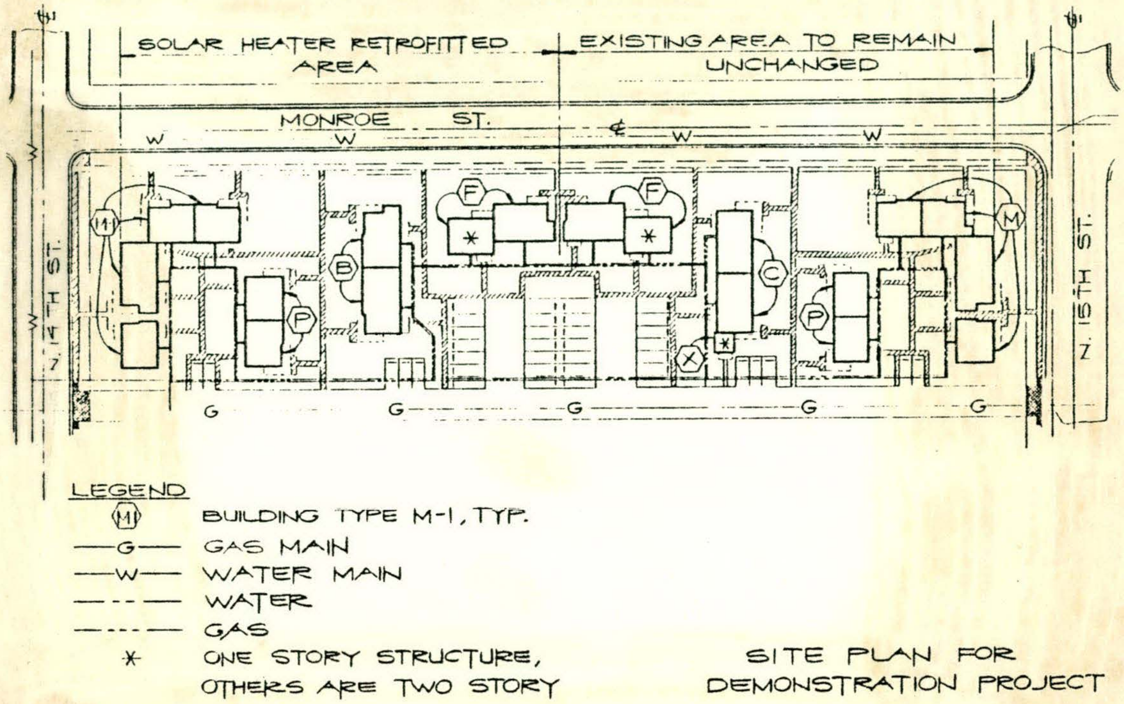


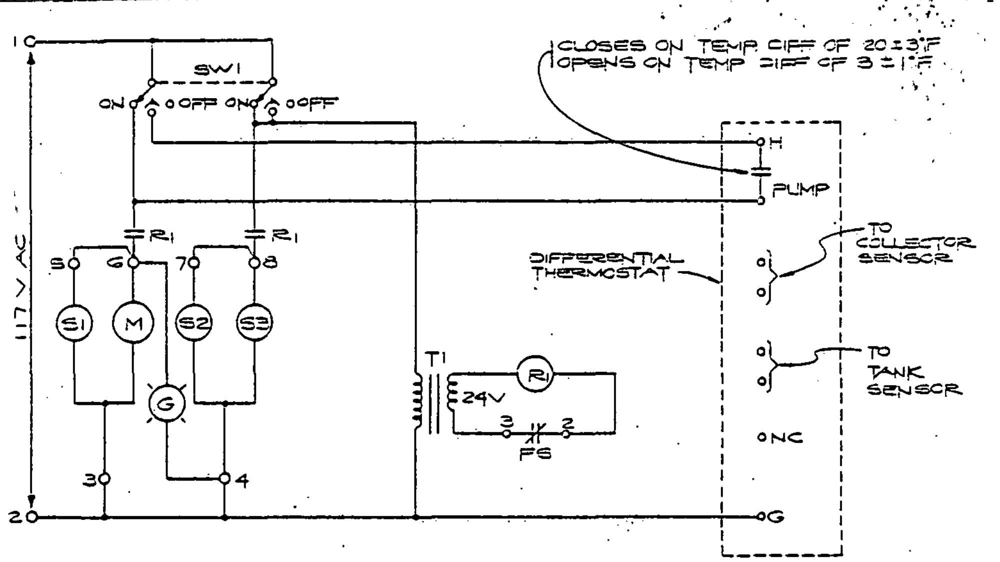
FIG. 4

Referring to Figure 5, notice also that when the selector switch is moved from the "Off" position to the "Auto" position, power is applied to the differential temperature relay and to the auxiliary control transformer causing T_1 safety shut-off relay R_1 to become energized, thereby closing the circuit to solenoid valves SV_2 and SV_3 as well as energizing the circuits to SV_1 and to the pump P_1 motor.

Should the temperature of the water in the solar collector rise above the temperature of the water in the storage tank by a predetermined amount, the differential temperature relay closes the contact between its terminals (H) and the circulating pump, opening solenoid valve SV_1 and starting the pump P_1 motor.

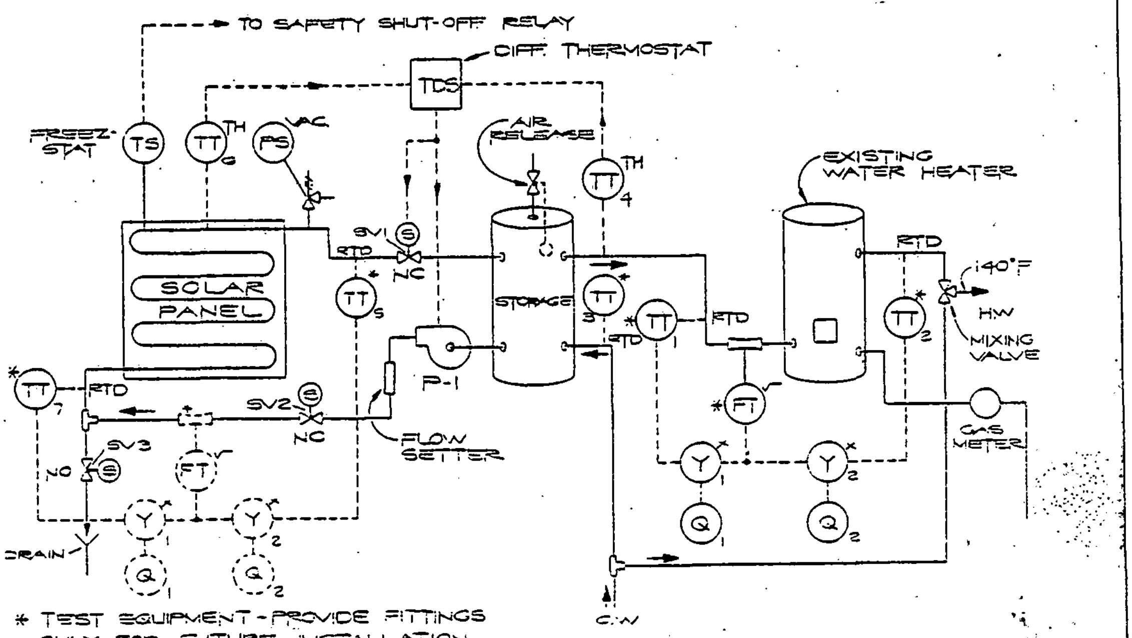
The pump begins to fill the solar collector, forcing the trapped air into the auxiliary storage tank, where it is released to the atmosphere by action of the air release valve. When the solar collector is completely filled, the system begins normal operation, drawing cool water from the bottom of the auxiliary storage tank and returning the heated water to the top of the tank. The flow of water is maintained constant by a flow control valve installed in the discharge of the pump. System operation is indicated by a pilot light, which is activated when pump P_1 motor is energized.

Should the solar flux to the collector decrease to a point at which temperature of the water leaving the solar collector would be only



S1 – SOLAR PANEL OUTLET SV-(NC)- S - SOLENOID
S2 – PUMP DISCHARGE SV(NC)
S3 – DRAIN SV(NO) FS – FREEZESTAT
M – PUMP MOTOR SW1 – SELECTOR SW. ON-AUTO-OFF
R1 – RELAY T1 – 117/24V TRANSFORMER
SV – SOLENOID VALVE DT – DIFFERENTIAL THERMOSTAT

SOLAR WATER HEATER CONTROLS



* TEST EQUIPMENT - PROVIDE FITTINGS ONLY FOR FUTURE INSTALLATION

P&I DIAGRAM
SOLAR AUGMENTED
DOMESTIC WATER HEATER SYSTEM

FIG. 5

slightly above the temperature of the water in the auxiliary storage tank, the differential temperature relay drops out, closing solenoid valve SV_1 and deactivating the pump motor. Should the solar flux to the collector increase to produce a differential temperature sufficient to actuate the differential temperature relay, the run cycle and subsequent cycles commence circulating water in response to heating potentials, since the collectors can not be drained de-activating the differential temperature relay.

The system may also be run, under manual control, by placing the selector switch SW_1 in the "On" position. Operation in this mode is as described above except that the contact of the differential temperature relay is bypassed and the system will continue to circulate water to the auxiliary storage tank even for the case water exiting the collector which is colder than the water in the auxiliary storage tank. The manual mode of operation should, therefore, be used only while testing the system.

Since there are times when outdoor temperatures may fall below freezing, a safety freezstat was provided to de-energize the solar system and drain the solar collectors should the temperature within the collectors approach 32°F. This safety feature acts to protect the system in both manual or automatic operational modes.

Since the auxiliary storage tank discharge line is connected to the cold water inlet of the existing DHW heater whenever hot water is drawn from the auxiliary heater, it is replaced with hot water from the auxiliary storage tank, preventing the temperature in the existing DHW heater from falling below preset minimum levels and thus keeping its gas fired heater off. For the condition where unusually large water usage should occur, or during long periods of solar flux, outlet domestic water heater temperature may fall below desired temperature levels and the direct gas fired water heater automatically comes on to supplement the heating capacity normally provided by the solar system.

PHOENIX PROJECT #PH-76079.00

Solar Htr ___ Rental Unit No ______

No Sol. Htr ___ Clasif. ____________

Date	Time	Q_1	Q_2	Q_1-Q_2	Gas Ft^3	Gas BTU

Q_1 = BTU from Solar Storage Tank

Q_2 = BTU from Water Heater Tank

Av. Gas BTU/100 Ft^3 ____________

FIG. 6

The outlet of the existing gas fired DHW heater will be provided with a mixing valve to prevent the DHW supply from reaching the user at a temperature over 140°F. Actually only 110°F supply water is required since there are presently no dishwashers or washing machines in use.

Developing the Test Plan

Having first established that characteristics of the demonstration solar system we were to test, it was then possible to develop an appropriate test plan and procedures for use by City of Phoenix Housing Authority personnel, under our supervision. Basically the test plan developed calls for retrofitting one of the 19 unit groups with individual solar collectors, while leaving the other 19 dwelling units unchanged, and observing the difference in fuel usage and cost of operation for the two groups.

The first objective of our test plan was to establish the efficiency of the existing DHW heater. To this end, each of the 38 water heaters will be provided with a totalizing gas flowmeter and fittings into which a water flowmeter and a water temperature sensor located in the DHW heater supply line may be readily installed. These instruments, together with an integrating BTU meter actuated by the water flow and temperature sensors, will provide the totalized value of the BTU delivered by each existing DHW heater over a given period of time and the totalized cubic feet of gas consumed during the same period of time.

The 19 units which are to be retrofitted with solar collectors and auxiliary storage tanks are now planned to be provided with additional fittings for installation of temperature sensors to measure the temperature of the water supplied by each of the 19 solar demonstration systems serving their respective existing DHW heaters. From readings of these temperature sensors one can obtain a measure of the heat consumed by the existing gas fired DHW storage units required to supplement the DHW heating demands not being met by the demonstration solar systems. To systematize data collection from the test installations, a data form was developed, for accumulating periodic readings to be taken from the various test instruments.

The efficiency of the solar collector determines the amount of the total incident solar energy which is captured by the collector and delivered as useful energy to the DHW system. To measure the solar input, a pyronometer calibrated to provide a signal proportional to incident solar radiation, i.e. directly in BTU/ft^2/hr is used. To measure the BTU output of the collector panel, sensors are provided to measure the entering and leaving solar collector water temperatures as well as the collector water flow rate.

After checks of efficiency of the existing DHW units are completed, a periodic record of gas consumption will be maintained for each gas meter. This record may be used to derive BTU consumption profiles for each of the representative dwelling units (see Figure 2.)

Due to budgetary constraints, the testing apparatus had to be held to that minimum necessary to validate system performance. The cost of all of the test equipment apparatus employed to achieve the test results described above has been estimated at $13,600.

Estimating the Performance of the Existing DHW Heaters

In order to establish the effectiveness of the demonstration solar heating system, one must first establish the efficiency of the existing DHW heaters. To this end, each of the 38 existing DHW heaters will be provided with a totalizing gas flowmeter and fittings into which a water flowmeter and a water temperature sensor for the DHW supply line which can be readily inserted. Returning to Figure 5, notice that these instruments, together with an integrating BTU meter, i.e. actuated by the water flow temperature sensors, should provide the totalized value of the BTU delivered by each of the existing DHW heaters versus the totalized cubic feet of gas consumed during the same period of time. The ratio of the two values permit us to approximate the efficiency of each test DHW heater which can be conveniently expressed as follows:

$$\%E = \frac{BTU \times 100}{N_t \times K} \qquad \text{Equation (1)}$$

The duration of each of the efficiency test runs does not appear to be critical but should extend for a minimum of two weeks. Several tests can be run simultaneously or the same test instruments can be used sequentially on each of the test DHW heaters.

Evaluating the Effectiveness of the Solar Demonstration System

The 19 units to be retrofitted are shown in Figure 4, and will be provided with additional fittings for installation of temperature sensors to measure the temperature of the water supplied by the collectors to the existing DHW heaters. The function of the various test instruments may be more clearly understood by referring to Figure 5.

Notice that the signal from Temperature Transmitter #1 (TT_1) is combined with the linearized flow signal from the water Flow Transmitter (FF) by computing relay (Y_1). The output of Y_1 is used to drive BTU Totalizing Meter Q_1, which accumulates the numerical value of BTU value delivered by the solar collector to its companion auxiliary storage tank. A similar BTU value is accumulated by Q_2, utilizing the FT and TT_2 signal through computing relay Y_2 to indicate the heat (in BTU) extracted from the existing DHW heater by the occupants. The difference between the readings of Q_1 and Q_2 amounts to a direct measure of the quantity of heat (in BTU) provided by the existing gas fired DHW heater in supplementing the DHW supply not directly heated by the solar demonstration system.

To systematize the data taking, the form illustrated in Figure 6 was prepared for use by client's personnel, accumulating the periodic information to be taken from the test instruments.

Determining the Solar Collector Efficiency

The efficiency of the solar collector in effect establishes that portion of the incident solar energy which is captured by the collector and delivered as useful energy to the existing DHW distribution system i.e. for each dwelling unit. To establish the overall solar demonstration system efficiency, one must compare the amount of solar energy delivered to the collector and integrated over a period of time with the total BTU delivered by the collector over the same period of time. The efficiency of the collector (E) can therefore be readily computed as follows:

$$\%E = \frac{BTU_{out} \times 100}{BTU_{in}} \qquad \text{Equation (2)}$$

To measure the solar input, a pyronometer, which has been calibrated to provide a signal proportional to the incident solar radiation in BTU/ft^2/hr is employed. The latter reading, multiplied by the net effective capture area of the solar collector provides a measure of solar energy input in BTU/hr. By recording the signal on a strip chart recorder, the area under the curve over a given time interval represents the integrated energy received by the collector during the interval.

To measure the BTU output of the solar collector, sensors are provided to measure the entering discharge water temperature from the solar collectors as well as the water flow rate through the collectors. The electronic measurement system previously described can provide an integrated reading respectively of input and output BTU's to the solar collector. The difference of these two readings taken over a given period of time, divided by the equivalent BTU of solar energy received by the collector over the same period of time, expressed by equation (2) above yields the efficiency of the solar collector directly.

The above procedure will permit our checking of the actual solar collector efficiency against published rated efficiencies. The procedure will also permit determining any degradation in performand of the solar collectors after they have been in operation for some time.

Long Term Monitoring

Concern for the possibility of vandalism dictated the need for a security fence to enclose the parapet of each test building with a further provision that no instrumentation be built in, only portable. After the initial startup of the solar demonstration system periodic recordings of gas consumption use are to be maintained for each test dwelling gas meter. From this record one can derive the BTU consumption profiles for each dwelling unit type, since the relationship of gas consumption to actual BTU delivered to the user may be computed from values of the natural gas heating value (in BTU/cu.ft.) and the computed efficiency of each of the various existing DHW heaters tested as described above. A gradual increase in the use of gas should alert the operator that the performance of a system is degrading. Any fall off in the performance of the individual solar demonstration systems will also be apparent when the gas consumption of the two groups of identical apartment units are compared. Final design of this solar demonstration system is now proceeding.

Nomenclature:

- BTU_t = Total BTU delivered by heater in time t.
- N_t = Total cubic feet of gas consumed by heater in time t.
- K = BTU per cubic foot of gas.
- E = Efficiency in percent.

References:

Milton Meckler, P.E., "Solar Retrofits for Multiple Dwellings." Solar Heating & Cooling, Nov/Dec 1976

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SENSOR SELECTION AND PLACEMENT

IN THE

NATIONAL SOLAR DATA PROGRAM

H. R. Berry and V. H. Johnson

International Business Machines Corporation
150 Sparkman Drive
Huntsville, Alabama 35805

ABSTRACT

The effective instrumentation of solar energy systems depends greatly on sensor selection and placement. Factors such as calibration, versatility, maintainability, and reliability also become important when the monitoring life exceeds five years. Commonality of sensors and clearly defined placement techniques provide the basis for an acceptable approach to data monitoring. This paper discusses the basic factors that influence sensor selection and placement, and presents the results of operational experience with sensor selection and placement gained thus far in the National Solar Data Program.

INTRODUCTION

An important goal of the National Solar Heating and Cooling Demonstration Program is to establish the performance characteristics of residential and commercial solar energy systems at selected demonstration sites, and to ensure the dissemination of this information to all interested parties.

To evaluate the performance of a solar energy system, performance evaluation factors must be computed from data collected during actual system operation. These factors are based on a system and subsystem energy balance concept that requires each system to be properly instrumented.

Since the comparison of performance across a wide variety of solar energy systems having a broad range of climatic conditions is a primary program goal, the process of collecting the data must be uniform to all systems and sites. Guidelines have therefore been established to ensure that the same types of sensors and placement techniques are used for all systems. Although specific placement requirements depend on the design characteristics of each system, these guidelines provide the basic methodology for determining the required measurements and their location so that performance calculations can be standardized.

SENSOR SELECTION

The sensors necessary for monitoring the thermal conversion processes of solar energy systems are divided into five types: pyranometers, temperature probes, flowmeters, wattmeters, and 'other'. The 'other' category contains those sensors that are unique to a given site. A study was conducted that established the extreme conditions expected based on the various geographic regions and variations in anticipated designs. Also included in this study were the recommendations of the Solar Heating and Cooling Performance evaluation Committee as published in the "Thermal Data Requirements and Performance Evaluation Procedures" for the National Solar Heating and Cooling Demonstration Program document. From this study of geographic locations and from the expected sizes and configurations of systems a definition of ranges was established. A trade study was conducted that considered cost effectiveness versus sensor accuracies available and acceptable for performance evaluation. These criteria were used with each sensor type to establish the sensor operating requirements of the National Solar Data Program.

A list of sensors approved for the National Solar Data Program is summarized in Table 1. In the process of selecting the best sensor, optimization of standard off-the-shelf hardware had to be made. The selection process must consider the calibration, versatility, maintainability, and reliability of sensors because, in this program, the monitoring life can exceed five years.

All sensors must have calibration curves or be capable of having their accuracy verified by an in-the-field calibration test. This is extremely important for investigation of system anomalies. For pyranometers and flowmeters, the calibration curves are used in determining actual values. The versatility of the sensor must be such that it can be adapted to various site configurations without compromising accuracy. Real time maintenance of equipment is precluded by remote monitoring of each site. Therefore each sensor must perform over extended periods without service interruption. The reliability of the sensors must be based on a high 'mean time to failure'. For this reason emphasis is placed on selecting sensors that have had long-term operation in the field. The minimum design parameters for primary performance sensors are given below.

Liquid flowmeters must have a selectable range of 0 to 5000 gallons per minute, and be adaptable to all ferrous and non-ferrous pipe sizes from 1/2" to 12". They must function over a selectable viscosity range of 1 to 1000 centistokes, and have an accuracy of $\pm 2\%$. Table 2 gives an example of liquid flowmeter selection criteria and a comparison of four specific types of flowmeters. Similar evaluations were performed on each sensor when comparative information was available.

Pyranometers must be capable of measuring incident solar radiation of approximately 428 British thermal units per square foot maximum over a tilt range of 0° to 90° (horizontal to vertical) with an accuracy of $\pm 3\%$.

Temperature probes must have a range of -75°F to +500°F, and must be adaptable to all ferrous and non-ferrous pipe materials including both large and small tanks. They must have an accuracy of $\pm .5\%$ at 32°F and a repeatability of $\pm .1\%$.

Wattmeters must be capable of measuring electrical power from .1 Killowatts up to 1.2 Megawatts, with an accuracy of $\pm 2\%$, for all multiphase and multiwire configurations.

Air velocity sensors must have a selectable range of 1 to 6000 feet per minute and be adaptable to all standard duct sizes with an accuracy of $\pm 3\%$.

TABLE 1. LIST OF APPROVED SENSORS*

DATA REQUIREMENT	NAME	SPECIFIC SENSOR TYPE
Total radiation	Pyranometer	Thermopile
Diffuse radiation	Pyranometer w/shadow band	Thermopile
Ambient outside air temperature/ with radiation shield	Resistance Temperature Detector	Platinum Resistance Thermomery
Temperature (air)	Resistance Temperature Detectors	Platinum Resistance Thermomery
Temperature (liquid)	Resistance Temperature Detectors	Platinum Resistance Thermomery
Surface temperature	Resistance Temperature Detectors	Platinum Resistance Thermomery
Flow rate (air)	Anemometer	Hot wire
(natural gas)	Gas Meter	Diaphram
Flow rate (liquid)	Flowmeter	Impact
(Totalizing)	Flowmeter	Nutating Disc
(Fuel oil)	Flowmeter	Nutating Disc
Electrical power	Watt transducer	Hall Effect
Relative humidity	RH probe	Capacitance

*Condensed from "Instrumentation Installation Guidelines" (November 1, 1977) published by the Department of Energy.

TABLE 2. LIQUID FLOWMETER SELECTION CRITERIA AND COMPARISONS*

REQUIREMENT	IMPACT TYPE	TURBINE (INDUSTRIAL)	VORTEX SHEDDING	PITOT TUBE
	FLOWMETER TYPE			
RANGE 0-5000 GPM	1	2	4	3
SIZES (1/2" TO 12")	1	2	4	3
LOW PRESSURE DROP	2	4	3	1
TEMPERATURE RANGE (-55 TO 300°F)	1	3	2	4
ACCURACY	2	1	3	4
OPERATING LIFE (ALL CONDITIONS)	1	4	3	2
VISCOSITY RANGE (<1 TO 100 CST)	1	2	N/A	3
ELECTRICAL INPUT (5 OR 15 VDC)	1	2	N/A	3
OUTPUT (0-100 MV, 0-5V)	1	3	4	2
POWER (<20 MA AT 5VDC)	1	2	N/A	3
MEDIA COMPATIBLE (CONTAMINATION)	2	4	2	3
WEIGHT - (50 LB. MAXIMUM FOR 12" SIZE)	1	4	3	2
INSTALLATION COMPATIBLE	1	4	2	3
MAINTENANCE (FIELD CAL. VER.)	1	4	3	2
COST	2	3	4	1
INSTALLATION COST	1	4	3	2

*The numbers in the Table are a relative rating with 1 defined as "most suitable" and 4 as "least suitable".

Before instrumentation, a systematic analysis of the requirements of each demonstration site is made which incorporates the criteria discussed here. The purpose is to select an optimum combination of sensors for each site to meet the overall program objectives.

SENSOR PLACEMENT

The spectrum of solar energy systems participating in the National Data Program encompasses a wide range of technical expertise, from the novice to the professional engineer. To arrive at a set of applicable guidelines for sensor placement, the "Instrumentation Installation Guidelines" has been published by the Department of Energy (November 1, 1977). It describes the site monitoring concept, defines responsibilities, and established acceptable installation methods for sensors. Placement guidelines for each of the five previously mentioned sensor types are presented below, with the exception of sensors of the 'other' type; being site-unique, they will not be included in this discussion.

Liquid flowmeters are preceded by at least ten pipe diameters upstream and six downstream of uninterrupted flow for pipes less than two inches in diameter, and twenty pipe diameters upstream and ten downstream of uninterrupted flow for pipes two and one-quarter inches or larger. It is realized that with today's space limitations, architectural designs do not always allow long pipe runs and consequently the desired upstream and downstream straight run length cannot be met. When this condition is identified, careful selection of the proper locations can result in an acceptable sensor installation. When possible, these meters are placed in a horizontal section of pipe near an absolute temperature probe. It is good practice to place the flowmeter on the low temperature side of the circuit to minimize temperature influence on the measurement.

Watt transducers should be placed in an Underwriter's Laboratories approved enclosure as required by local codes. Low power transducers require the conducting lines to be connected directly to the transducer. However, on large-current conducting lines a current transformer is used around the conductor. Only the output of the current transformer and voltage sense lines are connected to the transducer. Ideally, placement of the watt transducers is provided in the planning for the site. This approach allows the transducers to be installed with minimal impact on existing wiring. To reduce the number of watt transducers required, selective grouping of circuits is recommended (e.g., all power used in the collector loop). This provides economy without sacrificing accuracy.

Although specific placement requirements depend on the particular measurement involved, these guidelines provide the necessary standardization for comparing data between sites.

Pyranometers are mounted on a fixture supplied by the site contractor in the same plane as the collector array. The installation should prevent the pyranometer from casting a shadow on any collector absorber surface and neither should the collectors shade the pyranometer. Care is taken to minimize reflected energy from surrounding surfaces. Being a precision instrument, the pyranometer should not be subjected to mechanical shock or vibration due to system operation.

Temperature probes are installed at each energy monitoring location in a manner that will allow the average temperature to be determined. A monitoring location is defined as: an inside ambient temperature, outside ambient temperature, or inlet temperature and outlet temperature across each functional subsystem including pipes, tubes, tanks, ducts, and rock bed storage. Where possible, stagnant heat collection areas and high heat producing equipment environments are avoided. These conditions create erroneous data when the system is not operating and errors in the data during initial operation until stabilization occurs. In order to reduce constraints on the system due to instrumentation, temperature sensors are placed in thermowells. Also due to the extreme environmental conditions weather heads are used to protect the electrical connections.

OPERATIONAL EXPERIENCE

Many system operational anomalies have been identified during sensor verification in the National Solar Data Program. Identification and solution to these anomalies are discussed with the designer or contractor and instrumentation engineer. This paper will address a few examples of the type operational experiences gained relating to sensors. It has been found that the impact of measurement errors on the monitoring of a solar energy system depends on the system's operational characteristics. For example, a temperature measurement that is 0.5 degrees off might have a minor impact on the performance monitoring of a system with a very high temperature difference across the collector, but it could have a major impact when the temperature difference across the collector is low. However, if the temperature probes involved have repeatability and are calibrated in the field with a very accurate reference probe, then correspondingly accurate measurements can be realized during system operation by incorporating correction factors into the data collection software.

Exact placement of sensors has been and will continue to be a problem due to variations in the interpretation of instrumention schematics, and due to inadequate documentation of recommended sensor placements. An example of this is in the placement of temperature sensors. A schematic will show a monitoring location at the outlet of the collector array at the top of the collector with the control sensor for the system near the lower part toward the inlet port to the collector. As the solar radiation heats the collector absorber, the heat transport media is heated and thermally migrates to the top of the collector raising the temperature of the fluid and temperature sensor resulting in a high differential temperature. When the control sensor starts the system, the monitored data will indicate a high energy collection condition until stabilization is obtained. By proper location of the sensor this condition can be minimized and more realistic data can be obtained. This type problem is presently being experienced today on many solar demonstration sites.

An example of the benefit of improved communication for possible operational problems is the system that has been designed with a low pressure head pump where installing an intrusive flowmeter would reduce the system performance. However, if identified before installation the flowmeter target size can be reduced to minimize the effect on the system. The Instrumentation Installation Guidelines document contains a table defining the pressure drop for a given pipe size and flow range. It has been found that if the instrumentation engineer is involved during the design reviews before sensor installation, this problem is minimized through the resulting improvement in communications.

The key to avoiding problems with sensor placement is to keep designers and installers informed of the sensor types and aware of sensor purpose in the system and then to identify potential problems before sensor installation.

Hot water usage on several instrumented sites has proven to be a large part of the total load. Short term usage for periods less than five minutes has been found to result in large errors in the energy balance computations. These errors are caused by the short term usage being non-coincident with flowmeter sampling, and therefore going undetected; and also due to heat losses in the pipes causing the differential temperature to be low across the tank being monitored. Originally, it was felt that a statistical average could be applied to the hot water system measurement samples, but based on the established sample frequency this method required a large sample of data to obtain the desired accuracy. Therefore improved monitoring methods were evaluated and both the sensor and the sensor placement were subsequently changed. A totalizing type flow sensor with a continuous ramped output that totalized the hot water usage over a pre-established volume was installed, and the temperature sensor was placed in the outlet port of the tank so it could not be influenced by the ambient temperature. In this configuration, the sensor is basically monitoring a constant differential temperature during short term usage. An illustration of this approach is shown in Figure 1.

SUMMARY

Very thorough analyses and cost trade studies were made for the purpose of selecting the most effective sensor hardware available. These results were used to create an approved sensor list from which the sensor hardware is selected for each individual site. This list is continually being expanded as the needs are identified for additional sensors due to operational experiences and program changes.

The sensor selection or instrumentation process for an individual site involves a systematic analysis of the requirements of each site for the purpose of identifiying the total number, types, sizes and expected ranges of sensors. A preliminary instrumentation process can be performed by the designers or contractors using the guidelines listed in the Instrumentation Installation Guidelines document; however, final approval of sensor selection is contingent on type data to be collected that will be sufficient to complete the performance evaluation factors for each system.

The problems encountered to date on the placement of sensors for performance evaluation are similar to those experienced by other groups such as control and process engineers. In an effort to eliminate these problems more emphasis is being placed on following the Instrumentation Installation Guidelines for placement of sensors, on requesting and preparing better documentation, on identifying possible environmental effects on sensors, and on verifying the sensor locations during the data collection system checkout. All of these activities are being accomplished through a better understanding and working relationship between the instrumentation engineer and the contractor and/or designer.

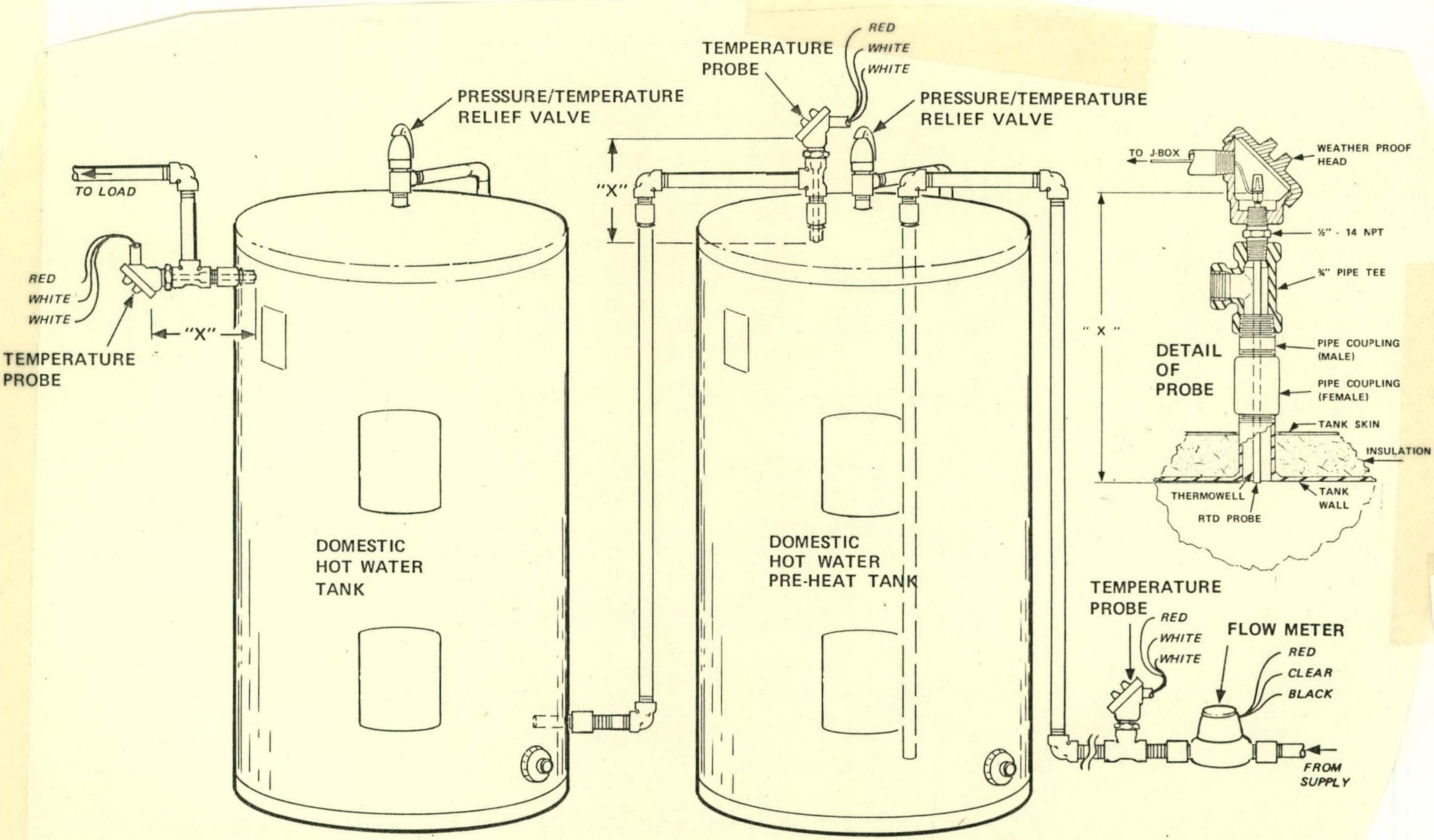

Figure 1. Sensor Placement for Domestic Hot Water Tank with Pre-Heat Tank.

FLOW RATE CALIBRATION FOR SOLAR HEATING AND COOLING SYSTEM EVALUATION

G. E. Mattingly
Fluid Engineering Division
National Bureau of Standards
Washington, D. C. 20234

Abstract

A description is given of the flow metering calibration facilities at the National Bureau of Standards that pertain to solar collectors and the instrumentaiton required to evaluate their performance. Alternative methods are also briefly described for obtaining the quantified assurance that the pertinent flow measurements are as good as they are quoted to be. Flow metering problem areas are also discussed with suggestions for preventative or remedial action.

Introduction

Fluid flow rate is a major parameter that is essential in the evaluation of solar heating and cooling systems. Whether the fluid is liquid or gas, the energy transport through, and the efficiency of the solar collector system, cannot be characterized without confident measurements of the mass rate of flow. To quantify solar system performance, it is imperative that the flow rate instrumentation be properly selected and installed according to recommended practice as described below. In addition this instrumentation must be calibrated and maintained in order to assure continuously accurate measurements.

Selection and Installation of Flow Rate Instrumentation

The initial selection of flow meters should be based upon the particular criteria and constraints imposed by the fluid and flow parameters as well as the accuracies desired. To do this, manufacturer's specifications and the data base that might be available in the metering literature should be used for particular meter performance. The selected meter should then be installed in the solar collector system according to recommended practice [1,2]* and then evaluated by an appropriate method, for example by direct conventional calibrations such as those offered by the National Bureau of Standards (NBS), by other calibration facilities that are themselves traceable to NBS, or indirectly by the use of suitable transfer standards [3,4,5].

Flow Calibration Services Offered by NBS

At NBS, conventional calibration services are offered for a wide range of flow rates and pipeline sizes in both gaseous and liquid media. Both volumetric and gravimetric primary standards are maintained by NBS for flow determinations.

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*Bracketed numbers refer to references given below.

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In gases, NBS maintains volumetric standards for calibrating meters using dry air (i.e., relative humidity less than five percent) as a surrogate fluid. The range of flow offered extends up to 85 m^3/min (3000 SCFM) at a maximum pressure of 861 kilopascals gauge (kPg) (125 psig) at ambient temperatures of 20°C (68°F) in the Bureau's largest air flow facility. Using bell-type provers and mercury sealed piston displacement facilities, air calibrations are offered which extend to 1.5 m3/min (50 SCFM) at a maximum pressure of 3448 kPg (500 psig) at ambient temperatures of 20°C (68°F). In some cases, transfer standards in the form of critical nozzles are used for air flow rate calibrations. Although calibrations are performed at elevated pressure, the results, in terms of volume rates of flow, are furnished with respective meter response in terms of laboratory temperature and pressure.

For liquid flows, NBS maintains gravimetrically based systems for calibrating meters using water and hydrocarbon fluids. In water, the flow rate range offered extends to 625 kg/sec (10000 GPM) and a maximum pressure of 517 kPg (75 psig) at ambient temperatures of 20°C. Smaller facilities are also maintained in which the calibrating fluid can be changed from the routinely used water to one containing antifreezing additives such as glycol that are pertinent to water based solar collection systems. In these, the flow rate ranges up to 2.5 kg/sec (40 GPM) and a maximum pressure of 345 kPg (50 psig) at 20° ambient temperatures. In performing liquid flow calibrations with fluids other than the normal working ones, provision of the fluid, any relevant density and viscosity characteristics, and the removal of the fluid from the calibration facility must be included in the contract.

Using hydrocarbon fluids, i.e., MIL-C-7024B-TYPE II which has properties that approximate those of jet fuel or MIL-H-5606B which is a hydraulic oil, the normal liquids used, the flow range offered extends to 100 kg/sec (2000 GPM) at 348 kPg (50 psig) and ambient temperature (20°C). In a smaller hydrocarbon facility, the flow range reaches 10 kg/sec (200 GPM) at 207 kPg (30 psig) and ambient temperature (20°C). In these two facilities the kinematic viscosity of the normal fluids ranges between 1.1 and 20 centistokes in the temperature ranges available.

A tabulated summary of the NBS flow calibration facilities for gas and liquid metering in closed conduits is presented in Table 1.I. The uncertainties quoted refer to the determination of flow rate using primary standards.

The calibrations described above are provided on a fee-paid basis designed to cover the costs required to perform the actual calibration. Maintaining the various calibration facilities at the quoted uncertainty levels is a service that has been provided through the NBS budget. Calibration fees change from time-to-time and the current fee schedule is given in the current issue of NBS Special Publication 250 [6]. For the quoted fees, the normal calibration consists of installing the meter, together with sufficient lengths of adjacent piping and pipeline elements such as elbows, filters, etc., in the appropriate NBS facility and determining the flow rate and meter response at each of five (5) flows spaced evenly or as per special requests across the range of interest. At each of these flows the flow rate is determined together with the corresponding meter response five (5) times. On another day, a complete repeat of this procedure is performed. The meter assembly is then returned to its owner with a report of calibration which describes the entire process and gives the calibration results in terms of averages and pertinent statistics. The addition of extra flow rates or the performing associated services are also done, where possible, on an "at cost" basis. It is suggested that only high quality flow meters or metering systems such as those described in [5] be used as a transfer standard between NBS and systems which evaluate the performance of solar collector units. The conditions under which the calibration is conducted should duplicate as closely as is feasible those prevailing when the flowmeter is operating in practice. In this manner the flow accuracy levels called for in ASHRAE 93-77 [7] can be established and maintained.

As an alternative to NBS flow meter calibrations, it is pertinent here to mention that it may be expedient for owners or operators of flow meters or flow transfer standards for solar collector evaluation systems to obtain calibrations at flow labs other than NBS. These may be owned or suggested by the particular meter manufacturer. In these laboratories, the level of traceability to national standards should be clearly specified, the uncertainty level for determining flow rate adequately quantified, and a flow transfer standard ought to be available and used to check against flow anomalies in the lab's piping system. For example, if a gravimetric flow determination scheme is used, are the weights used to check the weighing system of the proper class and traceable to NBS? Is the timing scheme used traceable to NBS? Is the transfer standard calibrated at NBS across the flow range of interest? Given that these conditions are satisfied, the flow calibrations obtained via such a laboratory should be dynamically traceable to NBS and, given appropriate uncertainty levels, adequate to the ± 1 percent accuracy levels specified in ASHRAE 93-77.

NBS Calibration Services for Wind Flow Instrumentation

At NBS, calibration services are also offered for wind flow sensors as might be used in the evaluation of solar collector systems in "open air" conditions. These services are described in NBS Special Publication [5] and are performed in one or more of the multipurpose wind tunnel facilities maintained by NBS. In these facilities, wind flows range between 4.5 cm/sec to 82 m/sec. In addition, NBS maintains a unique facility in which gusting wind conditions can be produced [8]. Again fees are arranged on an "at cost" basis for performing the specific calibration. A tabulated summary of the available facilities and their characteristics are presented in Table 1.II.

Flowmetering In Solar System Operation and Evaluation

Because of the wide variety of configurations, conditions, and components that are involved in solar system operation and evaluation, some general considerations will be given here that are intended to enhance the flow measurement assurance in these systems. To properly evaluate the solar collector performance, it is imperative that the instruments and methods used in the evaluation system be considerably more precise than those mailing 3/7

installed in the collector itself. Accordingly, the instrumentation selection and installation features for the components in the evaluation system ought to be done so as to enable the desired precision and accuracy levels to be achieved. Whether the desired levels have been achieved or not can be determined via careful calibration procedures as offered by NBS as described above and proper analysis of the data obtained. In the event these levels are not achieved, the alternatives are to modify the system in some appropriate manner or change components, or both. Since flowmeter performance can be affected in many ways, it seems pertinent to consider several of these and the remedial actions.

Owing to the fact that solar collector units and the associated evaluation equipment are generally designed to be spatially compact, it is envisioned that flow meter installations are, of necessity, to be done with minimal lengths of straight constant diameter piping adjacent to flowmeters. This can lead to potential problems with the typical types of flowmeters used, such as orifice plates, nozzles, target meters, and turbines.

All flowmeters are affected to some extent by anomalies in the linear velocity distribution in the flow entering the meter (for example, see [9,10]). This can occur in spite of the fact that the meter is installed according to manufacturer's specifications and/or recommended procedures. Remedial action in this event might be to move the meter so that longer lengths of straight, constant diameter piping separate it from upstream elbows or other elements which affect profile. Should this fail, a flow conditioner should be provided in the straight piping upstream of the meter. This would have the intended purpose of mixing the energy in the flow across the cross-sectional area of the conduit, thereby reducing anomalous effects.

Swirling flows also affect meter performance, see [11,12]. This is especially true for turbine meters which, because of their high resolution characteristics and pulsed output, are readily adapted to solar systems. Remedial action would be to move the flowmeter so that longer straight lengths of constant diameter piping separated it from elbows or other elements which might put swirl into the flow. Should this fail, a suitable flow straightener should be installed [13].

Particulate matter in the flowing fluid will, if it is not properly filtered, ultimately deposit on critical meter components and degrade flowmeter performance. This is a severe problem for the critical bearings in turbine meters and less so for differential type and target type meters [11,12]. For these reasons, considerable effort should be taken to insure that the interior of the flow conduit and the fluid are clean, and that proper filtration is used in the system.

The accurate measurement of mass flow rate using volumetric-type meters can depend critically on the associated measurement of temperature [14] and the characterization of fluid density in liquid and especially in gaseous systems. As well, the performance of several types of meters, particularly turbines, depend critically upon the temperature dependent fluid viscosity [12].

Besides the associated measurement of temperature, fluid flow measurements in liquids can be affected by pressure levels in that incipient cavitation effects can radically impair meter performance and longevity, particularly turbine meters [12]. For these reasons, pressure levels in the flowing liquid should be maintained well above the liquid vapor pressure level and monitored in the vicinity downstream of flowmeters to insure that cavitation effects are not present in the flow meter.

Given that due consideration is given such factors as mentioned above, and given that installed flowmeters receive proper and timely calibrations after appropriate intervals, flow meter performance and the assurance that the flow measurements are as good as they should ought to be satisfactorily quantified.

Summary

The NBS flow calibration facilities pertinent to the operation and evaluation of solar collection systems have been briefly described together with the calibration services offered. Possible problem areas in making satisfactory fluid flow measurements have been discussed, together with suggested solutions.

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TABLE 1. NBS FLOW CALIBRATION FACILITIES WITH PERFORMANCE CHARACTERISTICS RELATING TO SOLAR COLLECTOR TESTING

I CALIBRATION FACILITIES FOR GAS AND LIQUID METERING IN CLOSED CONDUITS

	FACILITY	CAPABILITIES	FLOW DETERMINATION SYSTEM
1.	LOW AIR FLOW	1.5 m^3/min (50 SCFM) max. 3448 kPg (500 psig) max. AMBIENT TEMP. (20°C) ± 0.25 % uncertainty	BELL-TYPE PROVERS, MERCURY SEALED PISTON DEVICES, AND CRITICAL NOZZLES
2.	HIGH AIR FLOW	85 m^3/min (3000 SCFM) max. 861 kPg (125 psig) max. AMBIENT TEMP. (20°C) ± 0.25 % uncertainty	CONSTANT VOLUME COLLECTION TANK, AND CRITICAL NOZZLES
3.	LOW WATER FLOW*	2.5 kg/sec (40 GPM) max. 345 kPg (50 psig) max. AMBIENT TEMP. (20°C) ± 0.13 % uncertainty	DYNAMIC WEIGHING PROCEDURE
4.	HIGH WATER FLOW	625 kg/sec (10,000 GPM) max. 517 kPg (75 psig) max. AMBIENT TEMP. (20°) ± 0.13 % uncertainty	STATIC WEIGHING PROCEDURE
5.	LOW LIQUID HYDROCARBON FLOW	10 kg/sec (200 GPM) max. 207 kPg (30 psig) max. AMBIENT TEMP. (20°C) ± 0.13 % uncertainty	DYNAMIC WEIGHING PROCEDURE
6.	HIGH LIQUID HYDROCARBON FLOW	100 kg/sec (2000 GPM) max. 348 kPg (50 psig) max. AMBIENT TEMP. (20°C) ± 0.13 % uncertainty	STATIC WEIGHING PROCEDURE

*WATER CAN BE CHANGED TO INCORPORATE ANTIFREEZING ADDITIVES.

II CALIBRATION FACILITIES FOR WIND SENSORS

	FACILITY	CAPABILITIES	SPECIAL FEATURES
1.	WIND TUNNEL	0.9m x 0.9m test section 4.5 cm/sec to 9 m/sec ± 1.0 % uncertainty	VELOCITIES MEASURED USING LASER VELOCIMETRY AND HOT-WIRE ANEMOMETRY
2.	WIND TUNNEL (dual test section)	1.5m x 2.1m test section 46 m/sec max. vel. ± 0.3 % uncertainty	LOW STREAM TURBULENCE. ADJUSTABLE PRESSURE GRADIENT. VELOCITIES MEASURED USING HOT-WIRE ANEMOMETRY AND PITOT TUBE.
		1.2m x 1.5m test section 82 m/sec max. vel. ± 0.3 % uncertainty	LOW STREAM TURBULENCE. VELOCITIES MEASURED USING HOT-WIRE ANEMOMETRY AND PITOT TUBE.
3.	WIND TUNNEL	1.4m x 1.4m test section 27 m/sec max. steady vel.	CAN BE OPERATED IN STEADY OR FLUCTUATING MODE. GUSTS RANGE FROM 0.1 to 25 Hz; AMPLITUDES RANGE TO 50 % OF MEAN FLOW.

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TEMPERATURE CALIBRATION FOR SOLAR HEATING AND COOLING SYSTEM EVALUATION

J. F. Schooley
Temperature Section
National Bureau of Standards

ABSTRACT

Problems associated with the calibration of temperature instrumentation for performance monitoring of solar systems are briefly discussed. A short outline is presented of thermometer calibration services and associated programs available at the National Bureau of Standards.

Introduction

Temperature is one of the major parameters in the evaluation of solar heating and cooling systems. It enters every phase of such systems, from the solar collector through the fluid handling system to the thermal energy storage components and any subsequent heat exchange and distribution equipment. Unless these temperatures are measured accurately, there can be no confidence in any calculations of system efficiency. For these reasons, it is essential to solar system performance evaluation that the temperature instrumentation be selected for the particular application and that the calibration of such equipment be maintained within carefully specified accuracy limits.

The International Practical Temperature Scale of 1968[1] is the basis for all thermometer calibration services performed by the National Bureau of Standards. In the temperature range which is of interest to solar system studies, the standard instrument for temperature measurement is the Standard Platinum Resistance Thermometer (SPRT). Its construction, characteristics, and use in precision thermometry are described in considerable detail in the NBS Monograph 126[2]. Three of the temperature reference points which define the IPTS-68 between 0 °C and 300 °C (roughly speaking, the range of interest for solar systems) are the triple point of water (0.01 °C) and the freezing points of tin (231.968 °C) and zinc (419.58 °C).

NBS Temperature Calibrations and Associated Services

The NBS thermometry calibration group maintains these and other temperature fixed point devices, temperature baths, and a number of SPRT's. The use of this equipment enables the NBS to offer calibrations depending upon the thermometer to be tested, which can accurately represent the IPTS-68 within one millidegree Celsius over the range of present interest. Some 1500 individual temperature calibrations are performed by the NBS for U. S. industrial, medical, academic, and governmental laboratories in an average year. Relatively few of these 1500 calibrations are performed on the high-accuracy SPRT's, however. Over two-thirds of the thermometers submitted to the NBS for calibration are the liquid-in-glass type, for which the accuracy limit is 0.02 °C to 0.03 °C. In addition, we test many industrial-type resistance thermometers, thermistors, and thermocouple thermometers of both noble-metal and base-metal construction; the accuracy of these thermometers varies according to their type and the temperature range. Calibrations by comparison with standard thermometers may be performed in liquid baths at temperatures from -110 °C to 500 °C or in furnaces over the range 0 °C to 2100 °C.

These calibrations are provided on a fee-paid basis, which is designed so as to recover the costs of maintaining this service. Most of the calibration requests are for routine tests which are described in the NBS Special Publication 250[3]. There are many requests, however, for thermometry testing of an unusual nature; whenever possible, consistent with the availability of the requisite time, materials, and equipment, the NBS temperature calibration group provides such services as cannot reasonably be obtained elsewhere.

The thermometers which are submitted for these lower-accuracy calibrations fill many important roles in U. S. technical activities. For example, medical patient care and testing, pharmaceutical manufacturing, routine weather monitoring, thermostat fabrication, heating and refrigeration equipment manufacture, and temperature processing of many kinds all require a definite tie to the IPTS-68, but they do not require the highest levels of measurement accuracy.

Thus too with temperature instrumentation for the performance monitoring of solar systems, in our view. The calculations to be made on the basis of these measurements are thermodynamic in nature, and thus they require a clear relationship to the IPTS-68. Yet fully useful results can be obtained with sensors at accuracy levels of 0.1 °C.

In addition to its direct calibration program, the NBS offers two other services which are important in the context of solar system performance analysis. One of these is a Precision Thermometry Seminar which is held twice each year. In this week-long seminar, personnel whose duties involve thermometer calibration in government, academic, or private laboratories receive instruction in precision thermometry. Three sensor types are discussed individually; SPRT's, thermocouples, and liquid-in-glass thermometers. The three phases of instruction are complementary, and each participant receives "hands-on" experience with the NBS precision thermometry equipment. By participating in this seminar, a person can quickly obtain an appreciation of the concepts, equipment, and procedures that are involved in making precise and accurate temperature measurements. Such an appreciation is essential in the design of adequate thermal analysis methods and equipment for solar system evaluation.

A final NBS temperature calibration group service which is relevant to the evaluation of solar systems is its Measurement Assurance Program. In this program, the direct calibration service is supplemented by a thermometer measurement data exchange which is designed to provide the participant with an overall evaluation of his thermometry capability, including the reliability of any temperature reference point devices, temperature baths, thermometer measurement equipment, and operational and analytical calculation procedures. In general, the user of this service is enabled to maintain a continuous analysis of his temperature measurements so that he can verify, both for himself and others, the level of performance of each component of his thermometry operation.

Calibrations for Solar System Evaluation

Thermal systems based on solar energy collection already are numerous both in component configurations and in types of application, and the variety of such systems is likely to increase with time. In order to provide guidance to the manufacturers of these systems, it is important to evaluate their efficiencies; this Conference is providing a valuable service in that respect.

The basis for performance evaluation is, of course, measurement. The evaluation phase of system development clearly demands substantially more measurement instrumentation than is needed for monitoring and control of the system in actual use, and the evaluation instrumentation generally must be capable of higher precision as well. Proper placement of carefully selected sensors and satisfactory measurement schedules and data analysis requires careful engineering calculation and design. Careful attention should be devoted to obtaining accurate data, as well, by specifically considering calibration needs in the selection and placement of temperature instrumentation.

There appears to be no "average" number or type of temperature sensor for monitoring solar system performance at the present time. The ASHRAE Standard 93-77, for example, specifies a minimum of three temperature sensor locations in the closed-loop testing of solar collectors[4]. On the other hand, a mobile solar equipment evaluation laboratory which was recently examined by the NBS temperature calibration group utilized some thirty temperature sensors. The NBS Solar Townhouse installation[5] employs a similar number of temperature sensors.

Temperatures which will be measured in performance monitoring of solar systems typically include some or all of the following: outdoor air temperature; structural support, wall, or roof temperatures; indoor air temperature distribution; solar collector inlet fluid and outlet fluid temperatures, and the direct temperature difference; thermal storage inlet and outlet temperatures and temperature differences and fluid temperature distribution; heat exchanger inlet and outlet temperatures; and passive collector temperature distributions. A discussion of the basic requirements which dictate thermometer placement and measurement precision and accuracy requirements can be found in reference (4), and its references, in NBSIR 76-1137[6], in NBSIR 77-1305[7], and in many of the other contributions to this Conference. The specifications for solar collector performance monitoring, for example, call for temperature difference measurements within an accuracy of ±0.1 °C; the maximum inaccuracy permitted is ±0.5 °C[4].

The different temperature sensors which are likely to be employed in these measurements are Type T thermocouple thermometers[8,9] or thermopiles, resistance thermometers, liquid-in-glass thermometers, and thermistors. In the case of differential temperature measurements, the precision can in principle be enhanced by locating the "hot" and "cold" junctions of thermocouple or thermopile thermometers in the two positions for which the temperature difference is required. Alternatively, two resistance thermometers which are so mounted can be placed in adjacent legs of a resistance bridge.

Such methods as the foregoing would seem to satisfy the necessity for accurate thermometry required by the performance evaluation calculations. However, the nature of solar systems themselves compels us to beware of unusual measurement problems. In our opinion, the most troublesome of these are the following:

1) Much of the equipment must operate in outdoor conditions. This implies, for example, that extension wires of differential-temperature thermocouple or thermopile thermometers may be exposed to direct radiation from the sun, or to snow, ice, or rain; these wires will thus be subjected to temperatures considerably different from the two temperatures whose difference is to be measured. This situation can lead to measurement errors well outside of those specified;

2) The solar system equipment may be subjected to substantial variation in operating conditions, particularly fluid flow rates; the level to which temperature equilibrium is realized within critically important measurement zones must therefore be carefully examined;

3) The time interval over which performance data must be obtained will in general be of the order of months. Given the cyclic conditions to which the temperature instrumentation will be exposed over that period of time, periodic *in situ* calibration checks will almost certainly be necessary in order to maintain the desired accuracy levels.

In order to circumvent these measurement problems which one can anticipate, we propose that performance monitoring equipment be designed and utilized so as to overcome their effects. This can be done by:

1) Providing, at each critical temperature location, a port for a removable calibrated thermometer of relatively high accuracy. This "check thermometer", with its own measurement apparatus, can then be used periodically to determine the state of calibration of the particularly important performance monitoring thermometers;

2) Performing tests on the actual parts which contain the most critical temperature probes, in order to determine the spatial temperature variability in the probe region under conditions which simulate actual use. These tests should include positioning, flow-rate, and fluid type variations which are to be expected in the field.

3) Making an effort, both in design and installation of the equipment, to avoid unnecessary exposure of thermocouple extension wires, probe headers, and other sensitive instrumentation to the full range of ambient conditions.

Coupled with a careful initial selection of working temperature sensors and adequate initial laboratory calibrations, we believe that the procedures discussed above can be expected to provide scientifically valid temperature data for solar system performance calculations.

Summary

In this contribution, we have briefly discussed the NBS temperature calibration service, and we have noted the existence both of formal thermometry instruction and of individual Measurement Assurance consultative services within the same group. Finally, we have attempted to call attention to problem areas in solar system thermometry and to suggest solutions which can, in our opinion, help to alleviate these problems.

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COMPARISON OF SOLAR RADIATION SENSORS FROM VARIOUS MANUFACTURERS

Edwin Flowers
NOAA/ERL, R32X2
Solar Radiation Facility
Boulder, Colorado 80302

ABSTRACT

Laboratory tests and outdoor comparisons have been made on pyranometers from a variety of manufacturers. Laboratory tests showed that the Eppley PSP, Spectro Lab, Lambda, Matrix and Schenk pyranometers were not affected by operating the instrument on angles tilted from the horizontal, whereas Kahl, Hy-Cal, Eppley 8-48, and Lintronic, gave errors up to ten percent depending on the instrument and tilt angle. Continuous outdoor exposure of the instrument has shown small variation between sensors on a monthly basis but relatively larger differences on daily and hourly time scales. Laboratory temperature tests of the sensors are presented along with approximate instrument costs.

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HEAT FLOW INSTRUMENTATION IN COLORADO STATE UNIVERSITY SOLAR HOUSES

T.M. Conway
Solar Energy Applications Laboratory
Colorado State University
Fort Collins, Colorado 80523

ABSTRACT

The most important data in solar space heating and cooling systems research are the solar energy incident on the collector surface and the thermal energy delivered to storage and the various loads, including space heating or cooling and domestic hot water heating. The heat flow quantities are functions of the fundamental parameters; temperature, pressure, and flow, which can be measured directly with highly reliable and stable transducers. The transducer signals can be continuously processed and combined to produce an analog signal proportional to the heat flow. This heat flux transducer signal can be integrated or accumulated and read by a data logger at regular intervals. Alternatively, the individual transducer signals can be read at regular intervals and recorded and the heat flow quantities can be calculated and numerically integrated when the data is processed.

Accuracy, reliability, stability and expense are critical factors involved in all instrumentation problems. The latter approach appears to provide the greatest reliability and stability at the least expense. Accuracy is a function of the rate of change in the fundamental parameters and the sampling rate or data logger scan interval. Accuracy must also be weighed against the amount of data to be processed and computer time. With the availability of minicomputer-based digital data acquisition systems with real time data processing capabilities, the amount of data that must be stored and analyzed can be reduced and accuracy can be improved.

The heat flux transducer approach has not been employed at Colorado State University but is presently being explored. Fourteen companies have been found that list heat flux transducers in their product line. Approximately thirty additional companies have been contacted for information on mass flowmeters. If a suitably accurate, reliable, stable and economic heat flux transducer can be found or assembled, it may be implemented in order to free the minicomputer for additional real time data processing and analyzing.

The purpose of this paper is to present a description of the evolution of the instrumentation system and data processing strategies at CSU Solar House I and, in particular, to present an analysis of heat flow instrumentation employed in the system. A discussion of proposed methods and equipment for improving the system is also presented...

INTRODUCTION

In 1973 the Solar Energy Applications Laboratory at Colorado State University received a grant from the National Science Foundation to design, build and test a practical residential solar heating and cooling system. The primary purpose ot the project was to design an effective and economical solar system for heating, cooling and domestic hot water heating in a single family residence which would be typical in appearance, size, construction and energy requirements. The system employs a liquid flat-plate collector which was designed, built and installed by members of the laboratory staff, graduate students and university shop personnel. Solar heat energy is transferred from an anti-freeze solution in the collector through a heat exchanger to the hot water storage tank. The delivery of heat from the storage tank to the three loads is illustrated in Figure 1. A forced air heating and cooling distribution system is employed using radiator coils through which is circulated hot water from storage or cold water from a hot water fired Arkla Industries lithium bromide absorption chiller.*

INSTRUMENTATION AND DATA PROCESSING

The original instrumentation system was composed of a pyranometer, thermocouples, a multi-point strip chart recorder, water meters, gas meters, and kilowatt-hour meters. The data processing system was a desk calculator and a hard working graduate student who hand recorded the meter readings every hour, hand integrated the temperature and solar insolation recordings, and calculated the performance.

The instrumentation system has gradually evolved into the present automatic data acquisition and analysis system shown schematically in Figure 2. The solar system has also become considerably more complex. An evacuated tube collector system mounted on a test stand adjacent to the house is connected to the house load and the flat-plate collector system is connected to an identical real-time computer simulated load. The data collected for this duel system are listed in Table 1 and the quantities calculated from this data are listed in Table 2. The instrument system components are listed in Table 3.

The data points are scanned by the data logger once every 10 minutes. The data is stored on magnetic tape and are also transmitted to the minicomputer for limited processing. Hourly average values of the starred items in Tables 1 and 2 are printed every hour along with solar and instrumentation error flags enabling the operator to check for proper operation of the systems every hour. At the end of each day hourly average values of all the items in Tables 1 and 2 are printed.

The data processing system for the 10 minute scan data on the magnetic tapes has also gone through an evolutionary process. It has recently been converted to the on line, iteractive CYBER system. The data variables and channel assignments, hourly and daily calculated quantities, printout and data base formats and variables, and the processing equations are all entered as data into the general processing program. A time-code recognition algorithm, which inspects time code sequences and intervals for validity was developed to properly handle irregular scan times, locate and flag data gaps, and allow starting and stopping the processing at any time desired. These features allow modifications to be made to the data processing information at any time. This is required when channel assignments are changed or when sensors are recalibrated or replaced. The program contains several data checks and bad or missing data are identified with coded flags. The data is processed monthly. Summaries of hourly, daily and monthly values of selected temperatures, volumetric flows and heat flows are generated.

*Prior to 1977 an Arkla air cooling unit instead of the later model water chiller was used. This unit was a standard natural gas fired unit that was modified to operate with hot water.

Comments on missing or bad data are read in and listed on the hourly print out. The presence of the processing information as data within the program allows it to be stored in the data base at the beginning of the month and each time any changes are made. This provides a continuous record of the data processing information and allows the program to be reset to its original form at any point in time by reading the proper file in the data base. The monthly summary program prints out daily and monthly quantities in formats suitable for direct inclusion into Solar House I reports. The monthly summary program also allows manual flagging of days which should be excluded from the summaries due to missing or bad data. A feature allowing for corrections of individual data quantities is also included. The final daily values, along with the flags and comments, are then included in the data base.

HEAT FLOW INSTRUMENTATION

The thermal energy delivered to a load or storage device is a function of the fundamental parameters of mass flow, heat capacity of the heat transfer media, and temperature change in the media and is given by the expression:

$$Q = \iint \dot{m}\, CpdTdt.$$

Heat Flow Transducers - Several companies list heat flow transducers or Btu meters in their product lines[1,2] and many have been contacted for information. Unfortunately no instruments have yet been located that appear directly applicable for heat flow instrumentation in solar research. Most of the Btu meters listed do not have sufficient resolution, have very poor accuracy for temperature differences less than 5°C, and/or are very expensive. Most of these instruments cannot accommodate temperature dependent density or heat capacity. Efforts to locate sources of heat flow transducers are continuing. At least one company, Signet Scientific*, is presently developing such a device. This company already produces an inexpensive positive displacement flow meter and a temperature transducer so the product should soon be available. The best approach along these lines appears to be to utilize commercially available components and assemble your own heat flow transducer. For liquids such as water where the change in the product of heat capacity and density is only 0.63% from 20°C to 100°C, temperature dependence of ρCp may be neglected and the procedure is straightforward.

Mass flow rate transducers are available[2,3], but they are generally quite expensive and/or require frequent calibration and adjustment. In ethylene glycol and water solutions the heat capacity increases with temperature and the density decreases so there is no advantage in using a mass flow meter. This is not the case in air. For systems using water storage, such as CSU Solar House I, the heat flow transducer should be located on the water side of the heat exchanger as indicated in Figure 1, and a simple device with an output linearly proportional to the product of the volumetric flow rate and the temperature difference can be used with acceptable accuracy. For air systems, the effects of humidity and pressure must also be accounted for.

Data Processor Method - The alternative to the heat flow transducer approach is to sample the volumetric flow rate and the inlet and outlet

*Signet Scientific, P.O. Box 5570, El Monte, California 91734/ (213) 571-2770 temperatures (and the pressure and humidity for air systems) at a rate that insures that the change in these parameters between scans is very small. The heat transferred can then be determined by calculating the instantaneous heat flow and numerically integrating these values. With microprocessor based data acquisition systems, this approach appears to provide the best combination of accuracy, reliability and cost effectiveness.

The CSU Solar House I system has employed this general approach since 1974. A two minute scan interval was originally used. This was the shortest interval that could be used with the original data logger (Doric 210) with one hundred channels of microvolt level signals. Comparison of results based on every fifth scan indicated that little accuracy would be scrificed and substantial computer time would be saved by using a ten minute scan interval. It was obvious that serious errors would result in individual values of the heat flow quantities when a pump turned on or off between scans but these errors were random and cancelled during the month.

The instantaneous flow rate was determined from the measured pressure differential across a calibrated orifice and the temperature difference was obtained from copper-constantan thermocouples. The heat delivered to the heat exchanger by the collector anti-freeze solution was measured. The heat capacity and density effects were calculated from the temperature integral of the product of first order curve fit equations based on the known temperature dependence of these parameters. Serious zero drift problems were encountered in the differential pressure strain guage bridge circuits that were built in the CSU instrument shop. These errors were eliminated by converting to turbine flow meters (Cox Instrument Series 21) and shortly afterward the accuracy of the data was improved by adding pulse accumulators (AGM Electronics, Inc.) to give totalized flow volumes during the scan interval.

The latest improvement has been the installation of a faster and more accurate data logger (Doric 220) in which any selected channels can be randomly accessed by a minicomputer (Wang 2200T). The inlet and outlet temperatures and accumulated flow will be scanned every thirty seconds and the heat flow quantities will be accumulated. Hourly totals will then be printed on the hourly summary printout. The next proposed improvements are to utilize an accurate differential temperature transmitter and to put the magnetic tape drive on the output of the minicomputer so that ten minute values of the accumulated heat flow values can be written on the tape.

With a custom multiprogrammed, minicomputer based, real time data acquisition system with interrupt capability, such as a CAMAC system or a Dynatech 6200 series system, excellent quality solar system performance data can be obtained with very little or no additional data processing. This type of system appears to cost less than is invested in the present Solar House I system. With such a system interrupts would be generated by important status changes such as the collector pump turning on. An executive program having the highest priority would interrogate the interrupts and determine the sensors to be scanned and the scan rate requirements for the desired measurement. Scanning programs would be assigned the next priority level. For example, the heat exchanger pump turning on would initiate the scanning of the heat exchanger flow rate sensor and the storage inlet and outlet temperature sensors. When the pump turned off, scanning would halt. Scanning of less critical data points and the performing of logging tasks would be assigned to the next lower priority levels. The remaining priority levels would be assigned to program maintenance and other less significant tasks.

Effects of Solar System Characteristics on the Instrumentation System - With a large thermal mass collector system such as the Owens-Illinois collector system on Solar House III a relatively long scan interval can be used to measure the heat flow from the collector after the collector turn on transients have disippated. For a low thermal mass, fast response collectors such as the Corning evacuated tube collector system, a much shorter scan interval is required. Each heat transfer system, such as the auxiliary heater, the cooling system and the domestic hot water system should be analyzed to determine the proper scan interval. This, of course, applies to every instrumentation parameter. If the transducer involved has a linear output an integrator or accumulator can be used to reduce the sampling rate required. For example, the output of a pyranometer can vary quite rapidly in partly cloudy weather. For a pyranometer whose output is temperature dependent, such as the Kipp pyranometer, an integrator can also be used provided that both the integrator and the temperature are read at a rate that insures that the temperature variation between readings is small. For an air system dampers frequently leak and it is desirable to take heat flow readings in all parts of the system when a blower is running. The sensitivity of the flow monitoring device should be sufficient to detect significant leakage. This may also be desirable in liquid systems to detect malfunctioning automatic values.

The solar and auxiliary systems as well as the mechanical and control systems can interact with the instrumentation system. Sensors must be properly located to obtain good data. For example, turbine flow meters should not be located near the inlet to centrifugal pumps that induce a vortex in the line. Conversely, some types of instrumentation sensors or sensor installations may modify the behavior of the solar system by introducing pressure drops or providing heat leaks. Every component and every modification or addition to the thermal, mechanical, control and instrumentation systems should be carefully analyzed to insure proper performance of these systems.

SENSORS

Flow Sensors - Orifice differential pressure flow meters are apparently the choice of the chemical process industry for the best combination of reliability and accuracy. Rugged, stable, temeprature compensated differential pressure orifice flow meters with integral square root extractor circuits are available in the $1000-$1500 price range. Tubbine flow meters may be a little more accurate but are subject to bearing wear and fouling due to scale deposits. The calibration should be periodically checked. It is desirable to have back up units to minimize down time. These units are in the $250 to $800 price range without electronics. The accumulators used for turbine flow meter signals at CSU cost the same ($170) as integrators that would be used for the orifice flow meter signals. However, instantaneous flow rates can be read directly as dc voltages for the orifice flow meters while the turbine flow meters require a frequency counter. The paddle-wheel flow meter made by Signet Scientific Company has not been used at CSU but appears quite attractive. It also produces a frequency output but is quite inexpensive ($140) and the $90 paddle wheel sensor and transducer unit can be removed without disassembling the plumbing. The sensor-transducer units are interchangeable for 1/2 inch through 12 inch pipe sizes so that only the sensor unit is needed for backup and backup units are not needed for each size. The paddle wheel rotates at a lower speed than a turbine flow meter and thus should be less susceptible to bearing wear and it appears to be much easier to clean.

Target, vortex, ultrasonic and magnetic flow meters have not been used at the CSU solar houses primarily because the other types were recommended by the CSU hydraulics people.

Flow measurements in air systems are much more difficult. The most important criteria for accurate air flow measurements is to provide sufficiently long straight duct sections to insure uniform flow through the measuring device which may be a pitot array device, such as those used in CSU Solar House II, a venturi device, or a thermal device. The first two devices are differential pressure type flow meters and require a very sensitive and expensive differential pressure transducer. A thermal device has the advantage of being sensitive to very low flows. It is also very important that very little pressure drop be induced by the device. Increasing the blower power to allow for a large pressure drop will modify the entire system performance because of increased air leaks. Sealing the system makes it an untypical system that would not be found in residential applications and thus would perform differently. Thermal type sensors have not been fully analyzed for application at CSU as yet. They may or may not be sufficiently stable and reliable and the cost of the system required is another unknown.

Temperature Sensors - For critical differential temperature measurements using thermocouples, the thermocouples should be individually calibrated and closely matched. Calibration tests have shown that accurancies of ±0.1°C can be obtained using the data logger and its linearization circuitry to measure absolute inlet and outlet temperatures and taking the difference. The absolute temperatures may be accurate to only ±1.5°C but this is not a significant source of error. For a temperature difference of 5°C the accuracy is only 2%. For high volume flow measurements such as the 95ℓ/m (25 gpm) flow on the storage side of the collector heat exchanger significant error can result because temperature differences as low as 2°C are frequently encountered.

This can be improved by using multijunction thermopile to measure the temperature difference as is done in the Solar House II air systems. However, this requires extensive additional data processing to obtain the temperature difference.

Very accurate ΔT transmitters with linear outputs are available using thermopiles or platinum elements for $300 to $700.

CONCLUSIONS

Heat flow measurement accuracies on the order of 1% are very difficult to obtain and maintain because they depend on the accuracies of the measurements of two or more parameters. Complete analysis of this accuracy for daily or monthly values has not been performed. The effort required for this analysis would be considerable and may not be practical.

REFERENCES

[1]Guide to Scientific Instruments, Science Vol. 197, No. 4309A, 20 Sept. 1977.
[2]Chilton's Control Equipment Master, '77-'78, published by Chilton Co., Chilton Way, Radner, PA.
[3]Measurements and Control, Vol. 11, No. 4, July-August 1977.

Temperature Range	
Collector	30-100°C
DHW	10-60°C
Load	30-100°C
Cooling	4-25°C
ΔT Range	0-20°C

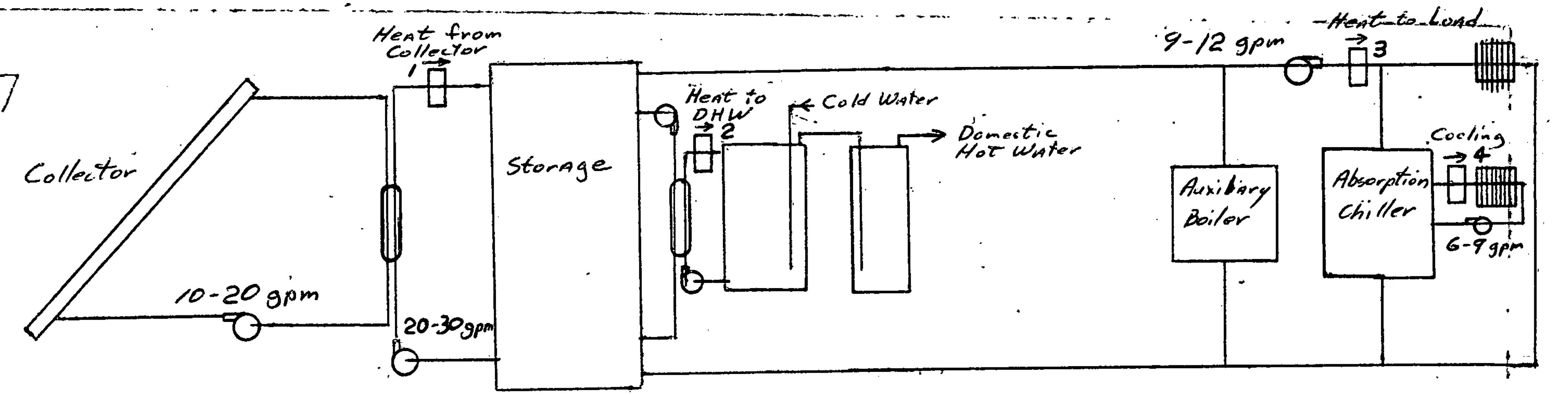

Figure 1. Liquid System

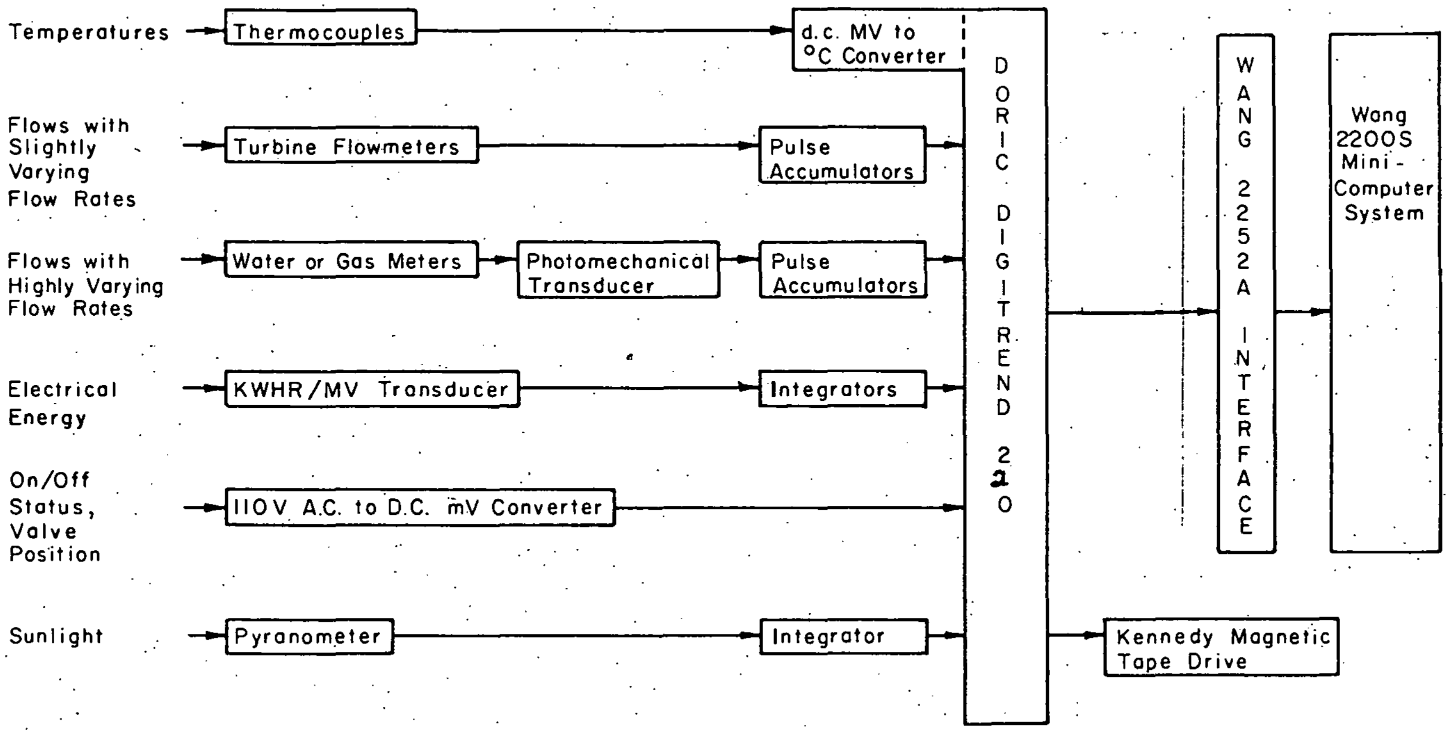

Figure 2. CSU Solar House I Instrumentation System

Table 1

Data Collected

Acronym	Description	Acronym	Description
TBFP	Temperature behind flat plate collector	TWT	Temperature of warm storage tank
		TCT	Temperature of cool storage tank
TRTFP	Tank room temperature (flat plate)	TFAC	Temperature from alternate coil
TUSTFP	Temperature under flat plate storage tank	TTAC	Temperature to alternate coil
		TRA	Temperature of return air
TTCFPB	Basement temperature to flat plate collector	TSA	Temperature of supply air
		TFCT	Temperature from cooling tower
TTCFPA	Attic temperature to flat plate collector	TTCT	Temperature to cooling tower
		TSHW	Service hot water temperature
TFCFPB	Basement temperature from flat plate collector	TP	Temperature of preheat tank
		THW	House dew point temperature
TFCFPA	Attic temperature from flat plate collector	THD	House air temperature
		TOD	Outdoor air temperature
STBFP	Bottom flat plate storage tank temperature	SYST	Collector supply house load
		M2IND	Mode 2 Indicator
STMFP	Middle flat plate storage tank temperature	V2IND	Solar/Auxiliary Indicator
		V3IND	Normal/Alternate Mode Indicator
STTFP	Top flat plate storage tank temperature	P7IND	Pump 7 on/off indicator
		P6IND	Pump 6 on/off indicator
TFHR	Temperature from heat rejector	IP3OT	P3 on time
TTHR	Temperature to heat rejector	IWIND	Wind run (integrated)
TTM3	Temperature to Module 3 (west)	IFAC	Integrated alternative coil flow rate
TTM2	Temperature to Module 2 (middle)		
TTM1	Temperature to Module 1 (east)	IFCT	Integrated flow of cooling tower
TFM3	Temperature from Module 3	IFCH	Integrated flow of chiller
TFM2	Temperature from Module 2	IFPEL	Integrated flat plate electric
TFM1	Temperature from Module 1	IP1EL	Load pump (P1) integrated electricity
TBTB	Temperature behind test bed		
TTA1	Temperature to Array 1	ISEL	Integrated solar electric power
TTA2	Temperature to Array 2	IHWGAS	Integrated hot water gas consumption
TTA3	Temperature to Array 3		
TFA1	Temperature from Array 1	IBGAS	Integrated boiler gas consumption
TFA2	Temperature from Array 2	IFHW	Integrated hot water flow
TFA3	Temperature from Array 3	IFHR	Integrated heat rejector flow
TRT	Tank room temperature	IFL	Integrated load flow rate
TUST	Temperature under storage tank	IFCFP	Integrated flat plate collector flow
TTC	Basement temperature to test bed collector		
		IFA3	Integrated flow - Array 3
TFC	Basement temperature from test bed collector	IFA2	Integrated flow - Array 2
		IFA1	Integrated flow - Array 1
STB	Storage tank bottom temperature	IFC	Integrated collector - flow rate
STM	Storage tank middle temperature	ISS	Integrated solar spectral radiation
STT	Storage tank top temperature	ISHO	Integrated horizontal insolation
TFL	Temperature from load	IS45	Test bed integrated 45° insolation
TTL	Temperature to load	IS45FP	Flat plate integrated 45° insolation
TTCHG	Temperature to chiller generator		

Table 2

Items Calculated from the Scanned Data

Acronym	Description	Acronym	Description
CDEGDA	Cooling degree days	QBG *	Total heat content of the gas burned in the boiler
CLDDD	Cooling load calculated from degree day data	QCOOL*	Actual cooling accomplished
CLDM	Changed to QAIR	QCOOLS*	Cooling actually accomplished by solar
COP	Coefficient of performance of the LiBr chiller	QCTR*	Energy removed by the cooling tower
COT	Collector on time in seconds. It is calculated from the collector flow assuming an average mass flow rate	QHCG	Heat delivered to the primary and alternate coil by gas
DELQST	Change in energy in storage during the day	QHWG*	Total heat content of gas burned to heat the service hot water tank
EFFO	Collector efficiency while collector is on	QLOAD*	Heating or cooling energy actually supplied to the house (does not include inadvertent energy supplied via storage)
EFFT	Collector efficiency for entire day	QPCS	Heat energy delivered to the primary coil by solar
ELECS	Electricity used to run solar equipment	QSHB	Total solar supplied energy as calculated from an energy balance
HDEGDA	Heating degree days	QSHWS*	Energy supplied to the preheat tank by solar
HLDDD	Heating load calculated from degree day data	QSOLAR	Summation of measured solar energy supplied
HLDM	Heating load measured	QSTOR*	Energy available in storage above 20°C
HOURFR	Fraction of time which collector is operating	QU *	Useful energy gain from collectors
HOURO	Hours of operation for collector during the day	S45*	Integrated insolation at 45°
HWGAL*	Hot water usage in liters	S450*	Integrated insolation at 45° while collector is on
MCLD	Measured cooling load	SOLCOL	Percent of actual cooling accomplished by solar
PCTARCS	Percent of energy delivered to the chiller which is solar supplied	TODO*	Outdoor temperature while collector is on
PCTHTS	Percent of heating energy which is solar supplied	TSTOR*	Average storage tank temperature (STT + STM + STB)/3
PCTSHWS	Percent of energy to service hot water which is solar supplied	TSTORO*	Average storage tank temperature while the collector is on
QAIR	(Solar + gas) Energy to the chiller (formerly CLDM)	WIND*	Average wind speed in kilometers/hour
QAIRCG	Gas supplied energy to the chiller	WINDO	Average wind speed while collector is operating
QAIRCS	Solar supplied energy to the collector	XLOAD	Energy to either heating or cooling load (similar to QLOAD)
QAUX *	Auxiliary energy supplied for either heating or cooling, but not service hot water	QHR	Energy to simulated load

Temperatures in degrees Celsius
Gas flows are in cubic meters

Other flows are in liters
Energy units are Megajoules

Table 3

CSU Solar House I Instrumentation System Components

A. Data Logger

Doric Scientific Digitrand 220
- 100 channels
- Type T thermocouple and dc voltage inputs
- 0.1°C and 1.0 μV resolution

B. Recorder

Kennedy Company 1600/5
- 7 track, 556 BPI

C. Minicomputer System

Wang 2200 T, 32 K byte CPU
- 2200 Console-CRT/Keyboard/Cassette
- 2201 Output Writer
- 2272-1 Digital Plotter
- 2270-2 Dual Diskette Drive, 500 K byte

D. Signal Conditioning

1. AGM Electronics Model EA 4052-2 Pulse Accumulator
2. AGM Electronics Model EA 4011-5 Integrator

E. Sensors

1. Thermo Electric type T thermocouples
2. Cox Instrument turbine flow meters
3. F.W. Bell PX-2202 B watt transducers
4. Weathermeasure Scientific - W164B Contact Anemometer
5. Eppley Laboratories Model PSP Pyranometer
6. EG & G Model 992 Dew Point Hygrometer

F. Power Conditioning

Deltec DSU 710 Uninterruptible Power Supply
Deltec RP 710 One Hour 700 VA Battery Pack

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AN INEXPENSIVE MULTIPLEXER TEMPERATURE MEASURING SYSTEM FOR MONITORING AND EVALUATION OF SOLAR COLLECTORS

Dr. Ronald D. Evans, P.E.
Department of Mechanical Engineering
and Aerospace Sciences
Florida Technological University
Orlando, Florida

Mr. Dennis Greeley, Engineer
Martin Marietta Aerospace
Orlando, Florida

Mr. Robert Martin, Engineering Manager
Fourdee Division Emerson Electric Company
Casselberry, Florida

ABSTRACT

The design of an inexpensive multichannel temperature acquisition system for use in the performance testing of solar collectors is presented. The basic sensing elements of the system which are used to measure temperature consist of a series of matched semiconductor silicon diodes. The advantages of selecting silicon diodes as a temperature sensor over conventional sensors such as thermocouples, resistance therometers and thermistors are discussed.

The basic diode circuit and its integration into a multiplexed temperature measuring system is presented. The system is designed with the capability of preselecting the sampling rate depending upon the application. Data recording can be accomplished using a single channel strip chart recorder. The system can be calibrated to record temperatures directly in °C or °F to an accuracy of ± 0.5%.

Introduction

To evaluate the thermal performance of any solar collector it is necessary to have accurate information on temperatures at various points on the collector or associated collection system. With this data, an accurate assessment of the collector's performance can be determined.

A temperature sensing method that is used widely is the thermocouple. Thermocouples are, under proper conditions, consistent and reliable. The principle of operation is based upon the Seebeck effect (1). The Seebeck effect is the generation of a voltage by maintaining two dissimilar metal junctions at different temperatures. Good accuracy can be obtained due to the variation of junction voltage as it varies linearly with temperature. The major disadvantage of the thermocouple is that the voltage is very small, a maximum of 60 microvolts per degree Celsium, thus making the thermocouple very susceptible to sensing extraneous voltages from the environment. Also, distorted readings may result if the thermocouple circuit receives radio signals from a nearby transmitter. An additional problem, when using a thermocouple is that high quality, carefully calibrated instrumentation must be used due to the size of the signal. This introduces the problem of maintaining calibration at increased costs. Also, care must be exercised when working with a thermocouple to insure proper materials are selected which are compatible for introduction into the measurement system. Since the system operates on the principle of dissimilar materials generating a voltage, error signals can be introduced by incompatible materials. Another disadvantage is that a reference junction is necessary for the utilization of a thermocouple as a temperature sensing device, thus adding to the complexity, the cost of the system, and difficulty of using them on a solar collector which would tend to act as an antenna for extraneous signals.

Resistance thermometers are another common means of making temperature measurements. Their principle of operation is based upon the linear variation of electrical resistance with temperature. Like the thermocouple, resistance thermometers under the proper conditions provide good reliable temperature measurements. However, these devices necessitate either special equipment for reading out the temperatures or a bridge circuit to determine the resistance. This is a major disadvantage since this type of special equipment is expensive and the bridge circuit requires a reference calibration curve. Since the lead wire resistance varies with temperature one must keep the lead wires short in order to avoid erroneous measurements (1).

Another sensor that uses the idea of resistance varying with temperature is the Thermistor. The Thermistor is generally used in temperature compensating circuits. Unlike the conductor type sensors, this semi-conductor's resistance is inversely related to its temperature. The major disadvantage of the Thermistor is its nonlinearity which makes it difficult to use with data recording equipment. Another disadvantage is that care must be taken when selecting a Thermistor to insure it has been properly aged, since the device's response will vary with age (1).

After considering each of the previous temperature sensing devices one must turn to other sensors if simplicity and cost are major considerations. A temperature sensitive semi-conductor that has a linear variation with temperature is the common silicon diode. The operation of the diode as a temperature sensor is based upon the fact that its reverse saturation current varies linearily with temperature over a wide range. The main advantage of a silicon diode is associated with the size of its output voltage and the significant change with temperature which it represents. As a result, the system is resistant to extraneous signals and can have a long lead wire between the diode circuit and the sensor probe. In addition, due to its large voltage output, less sensitive and less expensive equipment can be used to record the data. Finally, the circuit is simple to design and the components are inexpensive.

Basic Diode Circuit Design

The basis for practical operation of the diode is that the diode voltage is related to the reverse saturation current which varies with temperature. For the temperature range of interest in many solar collector applications, -50° to +175° Celsius, the variation is linear and the sensitivity is comparable to a thermocouple. The relation for a silicon diode is given by (2).

$$V_D = \frac{NkT}{q} \ln \left[\frac{I_D}{I_r(T)} - 1 \right] \quad \text{volts} \qquad (1)$$

In Equation 1, V_D = diode voltage, I_D = diode current, k = Boltzman's constant, T = temperature, °K, q = electron charge in coulombs, N = geometrical constant of the junction ($1 \leq N \leq 2$ for silicon).

For a typical diode the variation of voltage for a change in temperature is -2.97 mv/°C. This compares to only 60 μv/°C for a thermocouple.

If one examines Equation 1 there are two unknowns, N and I_{ro}, that must be found in order to use a diode as a thermometer. Since there are two unknowns, the simultaneous solution of two equations is required to determine their values. The required equations are found by selecting two different operating points substituting into Equation 1 and solving for N and I_{ro}. The results are:

$$N = \frac{q(V_{D1}-V_{D2})}{kT \ln(I_{D1}/I_{D2})} \qquad (2)$$

$$I_r\ (25°C) = I_D \exp\left(\frac{-V_D q}{NkT}\right) \qquad (3)$$

Using Equation 3, a calibration curve can be constructed by supplying the diode with a constant current and varying its temperature over the desired operating range. A typical calibration curve is shown in Figure 1.

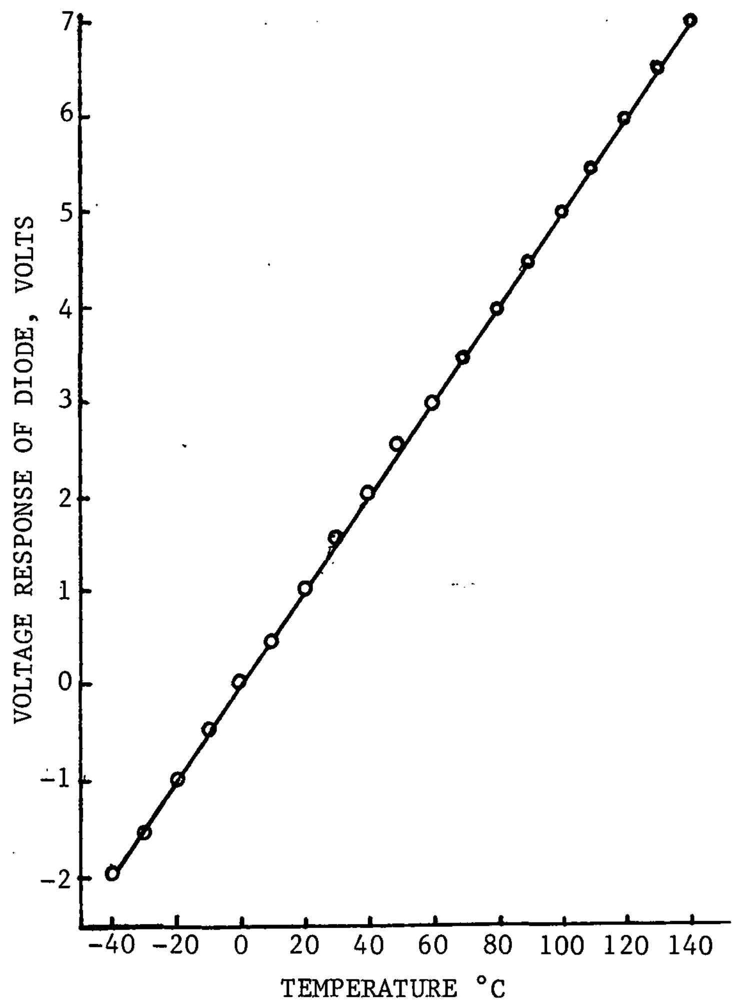


FIGURE 1. CALIBRATION CURVE FOR DIODE TEMPERATURE SENSOR

Integration of Diode Circuits and Multiplexer

In order to make the diode voltage signal easier to work with, a preamplifier is used. Such a preamplifier should have an offset voltage of less than two millivolts in order to maintain a minimum of one degree Celsius accuracy. A low cost operational amplifier, such as an LM741CN, can deliver a gain of 11 and usually has a one millivolt offset. Figure 2 shows a practical circuit, including resistor R1 which acts as the current source.

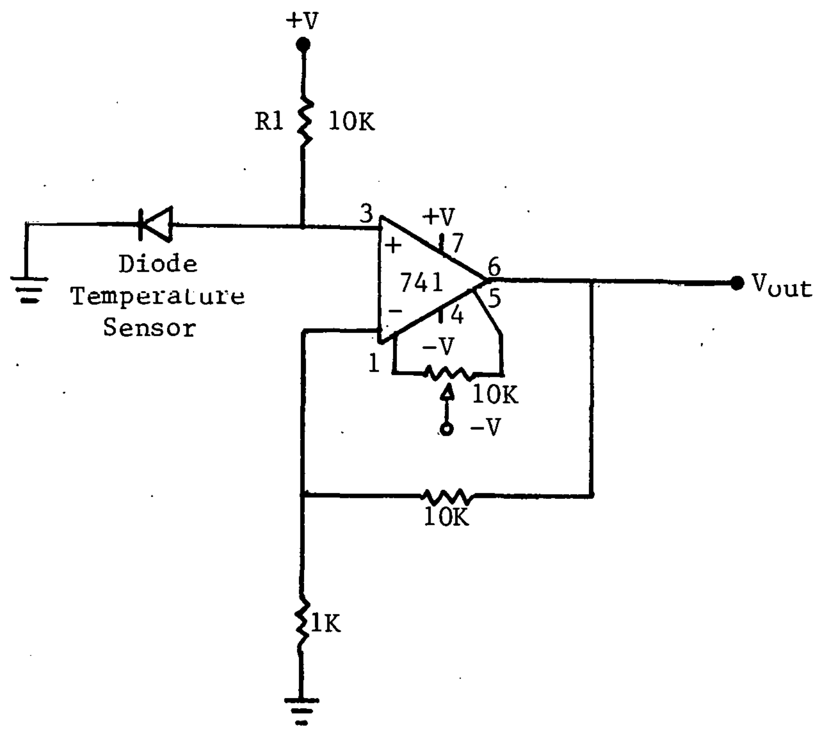
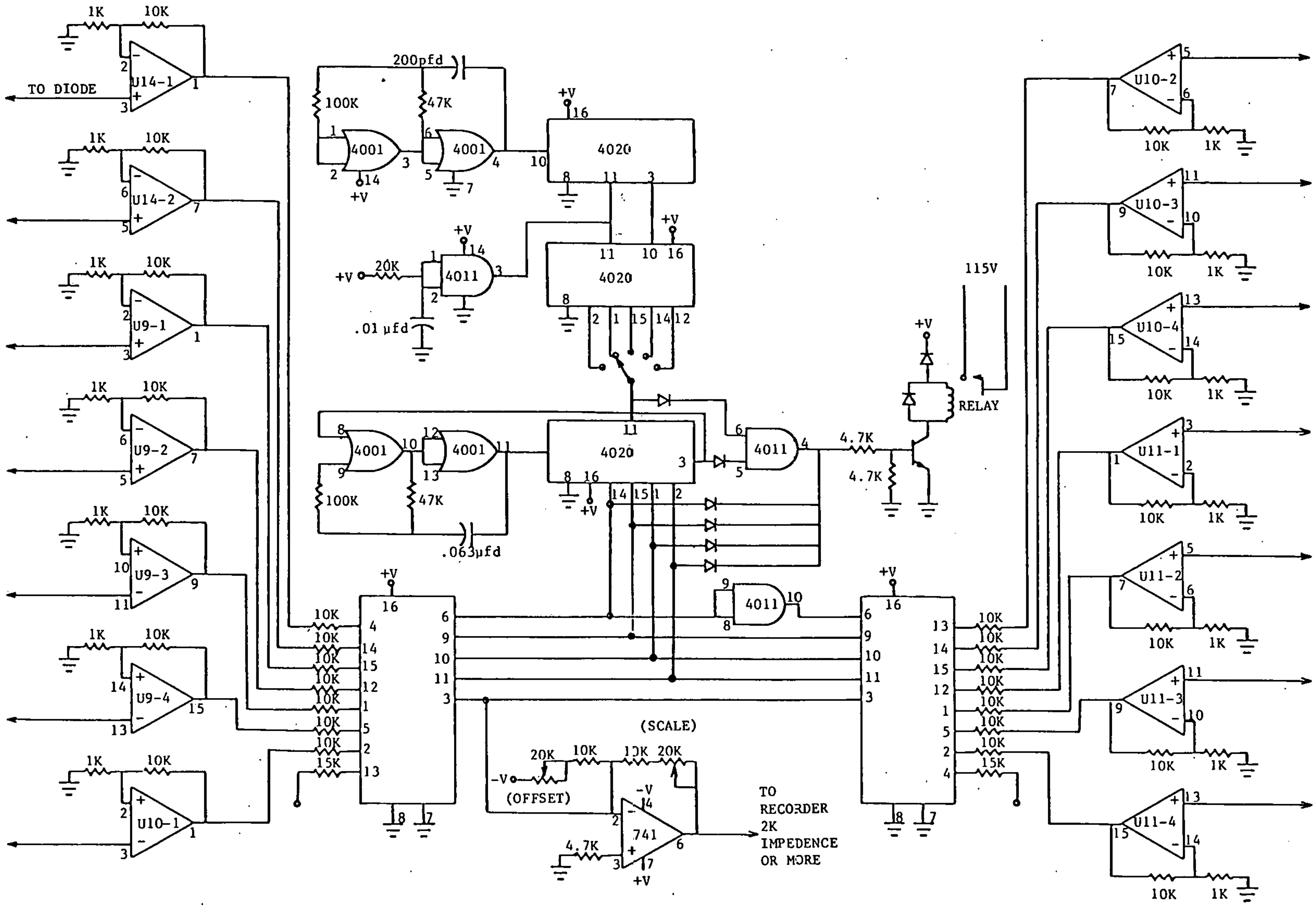


FIGURE 2. SINGLE DIODE CIRCUIT

In many applications it is necessary to record temperature readings from several points in the solar collector system. Therefore, it is desirable if these temperatures can be recorded in a single device. In order to accomplish this task a Complimentary Metal-Oxide Semiconductor, CMOS, transmission gate was used to multiplex the various signals on to a single line. One simple and inexpensive CMOS unit is a 4051PC, which contains the circuitry to decode an instruction signal and choose any of eight channels and place it on an output line. Two of these units were used together to obtain sixteen multiplexed channels. Two of these channels can be used for reference signals and still have the ability to take fourteen different readings. A timing circuit was used to generate the addressing signal needed to control the multiplexers and to set the sample period. The timers selected consisted of an RC circuit and one or two CD4020AE fourteen bit counters. A second timer was used to set the sample period. As an added benefit, this second timer was also used to control the data recording device. In the design shown in Figure 3, untrimmed quad amplifiers (SN721044) were used. These units have the benefit of an offset voltage small enough that it need not be trimmed and each unit conveniently contained four amplifiers. These fed into the multiplexers and into a second amplifier, a LM741CN, which is capable of delivering ten milliamperes to a



+ and - 15 volt regulated power supply required

FIGURE 3. CIRCUIT DIAGRAM OF MULTIPLEXER TEMPERATURE ACQUISITION SYSTEM

1000 ohm resistor.

Even though the silicon diode is relatively consistent, there is an offset voltage factor which must be considered. The offset voltages can be eliminated by matching the voltage response of a large number of diodes at a constant temperature. Matched diodes that were used with the prototype system were found by grouping the diodes into their similar voltage response categories.

Before placing the sytem into operation, temperature measurements were taken and compared to measurements taken with an accurate mercury thermometer. The diode sensors and integrated multiplexer recording system were found to agree within acceptable limits of the reference device. The system was installed in a solar collector system for two months of nearly continuous operation and has proven to be completely reliable obtaining consistent temperature measurements with an accuracy of ± 0.5°C. In addition, the system was exposed to a nearby radio transmitter and there were no indications of erroneous readings even when long lead wires were used between the diode sensors and multiplexer. Experimental results utilizing this measurement system have been reported at other conferences and are given in references 3 and 4. A photograph of the multiplexer temperature measuring system is shown in Figure 4.

While the system has proven to be very satisfactory, there are improvements that would enhance the accuracy of the unit and make it more convenient to use. Greater accuracy can be obtained by supplying the diode with a more stable current supply by use of a feedback circuit. Also, a probe of three diodes in series would result in greater accuracy. Preliminary experiments have shown that an accuracy of ± 0.1% can be obtained by this method (2). Accuracy can also be improved, and the need to match the diodes eliminated, by trimming the preamplifiers offset voltage to zero by using a viable resistor as shown in Figure 2. Other improvements can be achieved and these are discussed in detail in reference 2.

Conclusions

The application of silicon diodes as the temperature sensors for use in the monitoring and evaluation of solar collectors has proven to be reliable, accurate and economical. Integration of the sensor probes into a multichannel multiplexer system provided a simple, inexpensive, fully automated data acquisition system. Total cost of the materials, components and miscellaneous supplies to build the prototype multiplexer temperature measuring system was less than fifty dollars. Such an inexpensive automatic data acquisition system appears to be useful for small solar industries which cannot afford the more sophisticated temperature sensing and monitoring equipment.

Acknowledgement

The authors wish to acknowledge the Florida Solar Energy Center for their financial support of this project.

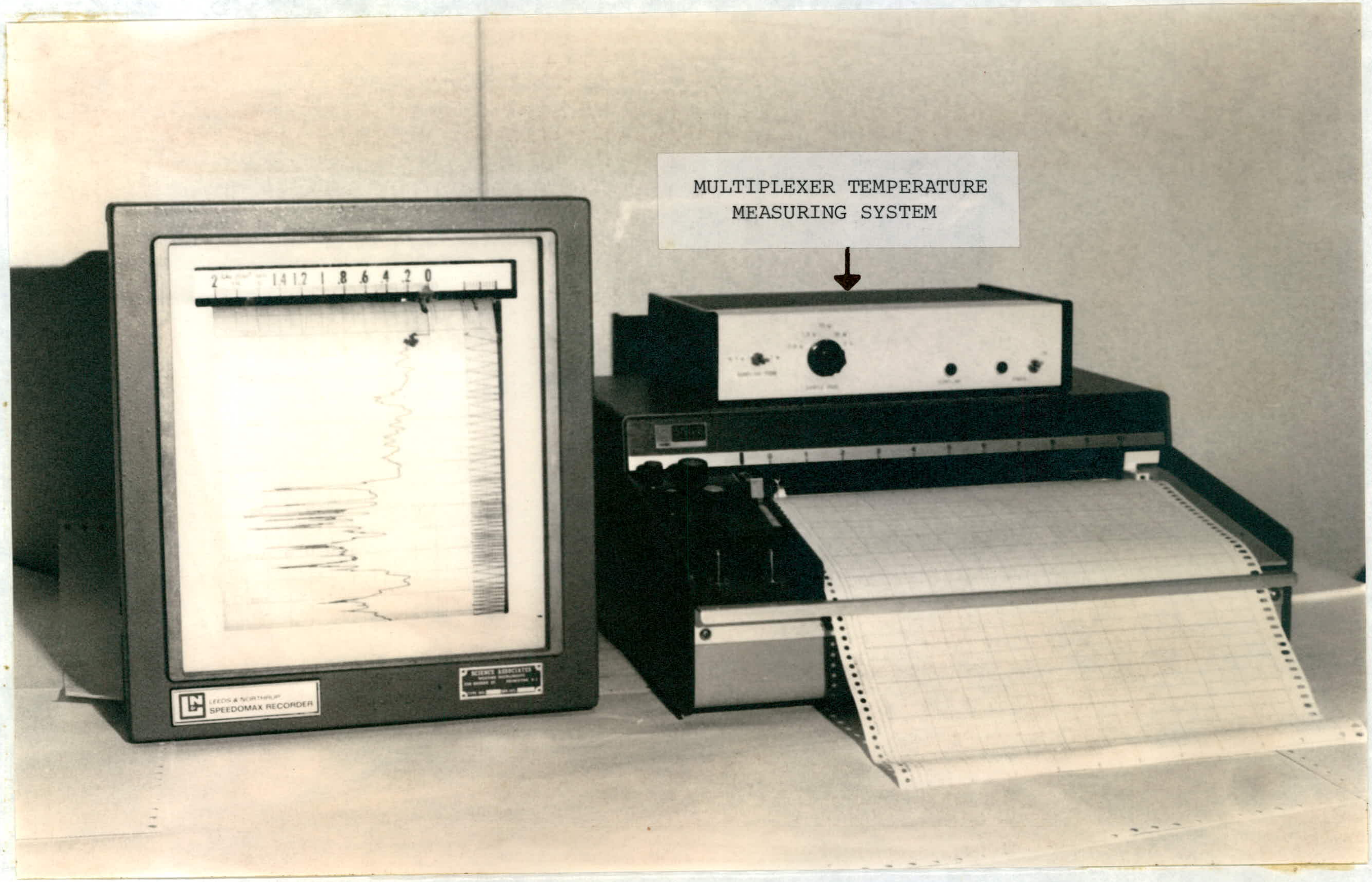


FIGURE 4. PHOTOGRAPH OF MULTIPLEXER TEMPERATURE ACQUISITION SYSTEM

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Approaches to Some Common Sensor Problems*

by
S. R. Swanson, R. F. Boehm, R. L. Lux, J. E. Moore
University of Utah
and
S. K. Evans
Utah Power and Light Company
Salt Lake City, Utah

Abstract: Several data acquisition problems that relate primarily to sensor selection and use are touched upon. Low cost approaches to temperature and air velocity sensors are discussed. The feasibility of a technique for measuring water temperatures without cutting into pipe lines is evaluated. In addition, a design of a module for evaluating sensible heat flows in systems using digital pulsed recorders is also outlined.

Introduction: Monitoring of solar heating systems can be an extremely complex and expensive endeavor, particularly if energy flows are desired to be known in detail. Depending upon the particular system and the information desired, it may be required that two to four fluid flows be monitored as well as recording five to over twenty temperatures. Cost considerations on sensors arise from both initial purchase price as well as installation. Another factor, that of the supplementary conditioning equipment required, may also be important, but this will not be touched upon here in detail for purposes of brevity.

Temperature Sensors: Generally when a recordable signal is required, temperatures are monitored by thermocouples or some type of resistance elements. Thermocouples have the requirement that a reference junction be used and the output is a millivolt signal, which may have to be amplified. Resistance devices commonly used are thermistors or platinum resistance thermometer elements. These are then used with a resistance bridge and can yield a signal determined by the excitation voltage used.

Reasonably priced platinum resistance thermometers (PRT's) can be purchased for unit costs ranging from $13 to $44 depending upon the service and the configuration.(1) PRT's are unrivalled for situations that demand extremely high accuracy and stability. Depending upon the design a PRT may have a resistance around 100 ohms and will vary in resistance like 0.1 ohm /^{o}C.

Thermistors range in cost from a few dollars up to nearly a hundred dollars apiece depending upon the configuration chosen. (1) A more typical range of costs for the purposes of this discussion is three to ten dollars. Their resistance at room temperature is typically on the order of kilo ohms and their change of resistance with temperature (the more important variable) can range from 10 to 10^5 ohms/^{o}C. An additional desirable characteristic of these devices, like the PRT's, is the ability to purchase them in lots with essentially the same resistance characteristics.

We have used relatively ordinary transistors as a low cost alter-

* This work is supported in part by Utah Power and Light Company.

native to the temperature resistance elements noted above. A typical configuration used is a 2N2484 and a representative configuration is shown in Figure 1. Like the other temperature indicating devices based on resistance changes, the transistor has a linear variation of resistance with temperature. However, while the slope of the curve is essentially the same between different units with the same model, the offset (or intercept) can vary as much as 10%. Of the 24 units we used on monitoring of two homes, the unit cost was approximately \$1 (available from almost any local electronic supplier), their room temperature resistance is on the order of kilo ohms and their resistance change with temperature is on the order of 10 ohms/^{o}C.

Non Invasive Pipe Temperature Measurements: In the two houses we are currently monitoring it was deemed desirable not to cut into existing water pipes. Although it is generally thought that accurate fluid temperature measurements could not be accomplished with a sensor mounted on the outside of the pipe, we were willing to evaluate the probable errors resulting from that approach. We were concerned both with transient and steady-state errors.

Copper "saddles" were designed for holding the transistors in contact with the copper tubing. The specific dimensions used for a 5/8 inch outside diameter tube are shown in Figure 2. In an actual installation fiberglass insulation is wrapped around the pipe and saddle to decrease heat loss (or gain) in the assembly.

A test configuration shown in Figure 3 was used for evaluation of the saddle concept. Water of controllable temperatures was circulated from a constant temperature bath. Two thermocouples were immersed in the flow through pipe penetrations as shown. Results of the steady state tests are shown in Figure 4, while the transient response is shown in Figure 5. A maximum error of less than two percent was demonstrated on the steady state evaluation. Transient response tests for the design shown demonstrated a time constant of 22 seconds.

Low Cost Approach to Air Flow Sensors: An investigation of commercially available sensors for measuring low velocity air flows indicated that virtually all devices were expensive (several hundred dollars). Further, the design requirements for a suitable transducer are difficult to meet. Air flow rate in a duct may be on the order of 700 ft/min. Thus stagnation pressure increase, which is a common method for measuring air flows, is low and difficult to measure accurately in this case. In general some type of averaging across the duct is desirable.

To meet these requirements we designed, constructed, tested and installed a device which is basically a model airplane propeller that is rotated by the air flow. A diagram of the instrument is shown in Figure 6. The line of sight between the light emitting diode phototransistor pair is broken by the turning blades of the propeller. A pulsed signal is particularly appropriate for the Digital Pulsed Recorders we are using, but with signal conditioning a variable voltage output could result. The propeller consists of two Cox 5D3P model airplane propellers glued together to form a symmetrical configuration that has the same response characteristics to air flowing in either direction - a requirement for this installation because the air direction reversed when charging storage compared to when depleting storage.

The air flow meters were calibrated by measuring the frequency output as a function of different air flows. In a single test two meters are placed at different locations within a duct which is representative of the actual installation. A reducer is mounted on the end of the duct bringing the flow to four inch diameter at the exit. Measurements of the flow velocity were made at that point with a hand-held anemometer. In this case an Air Flow Developments LTD AM5000 model was used. The calibration curve for two of these meters is shown in Figure 7. Obvious from the calibrations shown, and in keeping with what one would hope, is the nearly identical output characteristics of the two meters.

For our application, an in-place calibration was also performed. After the meters were installed, the velocity profile (at a given location in the duct) was mapped using a wand-type hot wire anemometer. Measured volumetric flows were then correlated with the propeller sensor outputs.

Q-Meters: As was mentioned above, the data recording in our systems is accomplished by Digital Pulsed Recorders (DPR's). The physical arrangement of these DPR's is such that they accumulate data internally for a 15 minute period and then punch the accumulated values for each channel. Problems arise when detailed information is required about quantities that vary considerably during the 15 minute period. Depending upon the heating system design and duty cycle, this problem can be quite acute in the measurement of sensible energy flows. Consider the relationship:

$$\dot{q} = \dot{W} (T_i - T_j)$$

where $\dot{W}$ is the product of the specific heat and the mass flow rate. In a given system all quantities on the right hand side of this equation could demonstrate unique time variations with periods much less than 15 minutes. Hence, using accumulated values for $\dot{W}$, T_i, and T_j to calculate the energy flow can lead to serious errors.

To improve accuracy in this aspect, a processing circuit was designed to calculate the energy quantity electrically. A block diagram of the circuit used to accomplish this is shown in Figure 8. Note that, as before, recording is accomplished by a Digital Pulsed Recorder, so the output of the circuit is compatible with that of data logging.

Discussion: The instrumentation system design problems posed by solar system evaluation are not unique, but in fact have a number of features in common with other temperature and flow measurements. Thus the transducer designs given here represent only particular approaches to these measurement problems. However it seems to the authors that solar system evaluation does in fact contain some inherent characteristics in a systems sense that do relate to transducer and measurement system design. For example, the evaluation of solar systems requires integration of energy flow data over time, and the time scale of interest ranges from a few minutes to a season.

For example, the bottom line of solar system evaluation is seasonal (or longer) performance. In general more detail is required to assess the performance of individual components and to relate the measured performance to environmental data. Thus, not only are data required in the form of a yearly integrated value, but also integrated over a much shorter time span, down to a few minutes. It appears that these requirements should be incorporated into the measurement system planning as much as possible. For example, the sensible energy flow measurement devices (Q meters) discussed above are a step in that direction, and recognize the inherently transient nature of solar systems. It is likely that further specialized systems of this kind can be developed and will prove to be useful.

Summary: Several approaches to sensor-related problems have been discussed. Improvements in cost and/or accuracy of techniques for the measurement temperature, flow and energy are outlined.

Reference: 1. "1978 Temperature Measurement Handbook," Omega Engineering, inc., P. O. Box 4047, Stanford, CT., 06907.

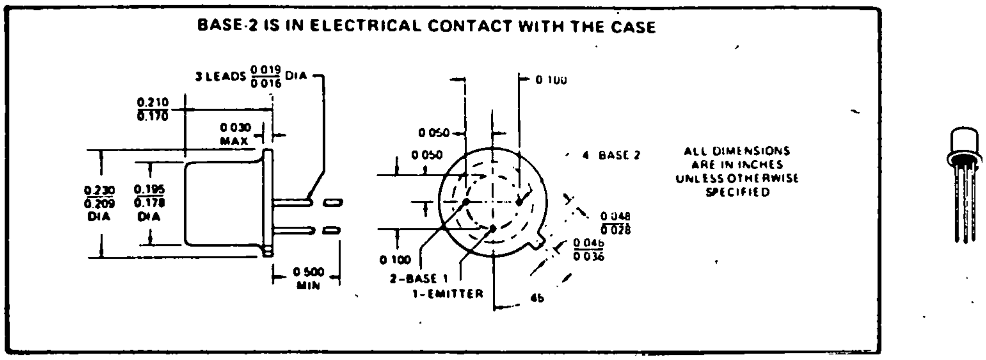

Figure 1. Detail of Temperature Sensors.

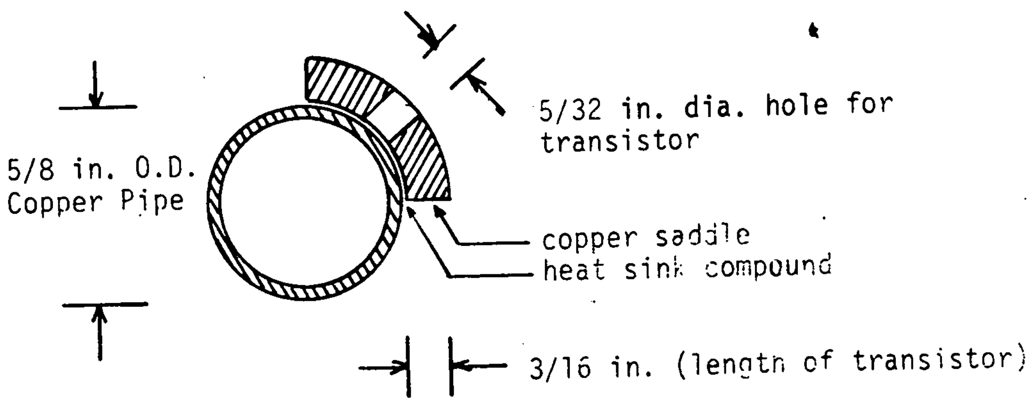

Figure 2. Detail of Copper Saddle Mounting on Copper Pipe.

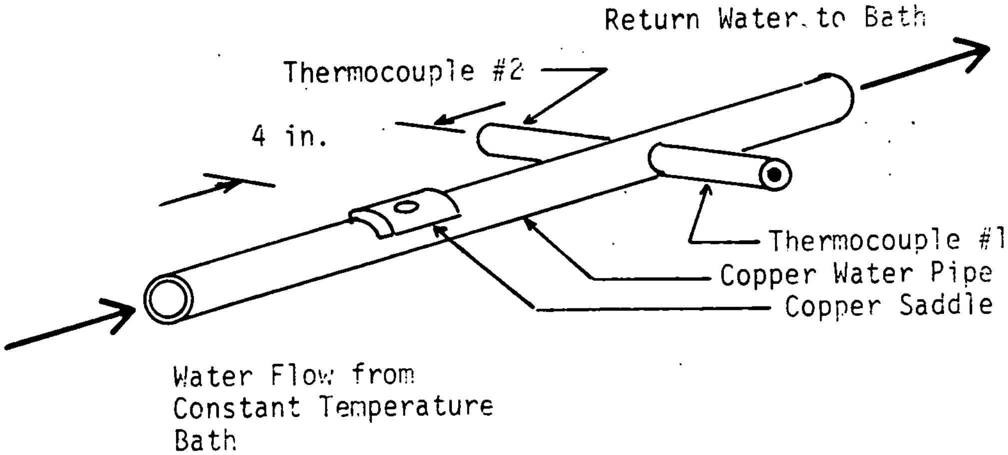

Figure 3. Schematic of Test Stand for Copper Saddle

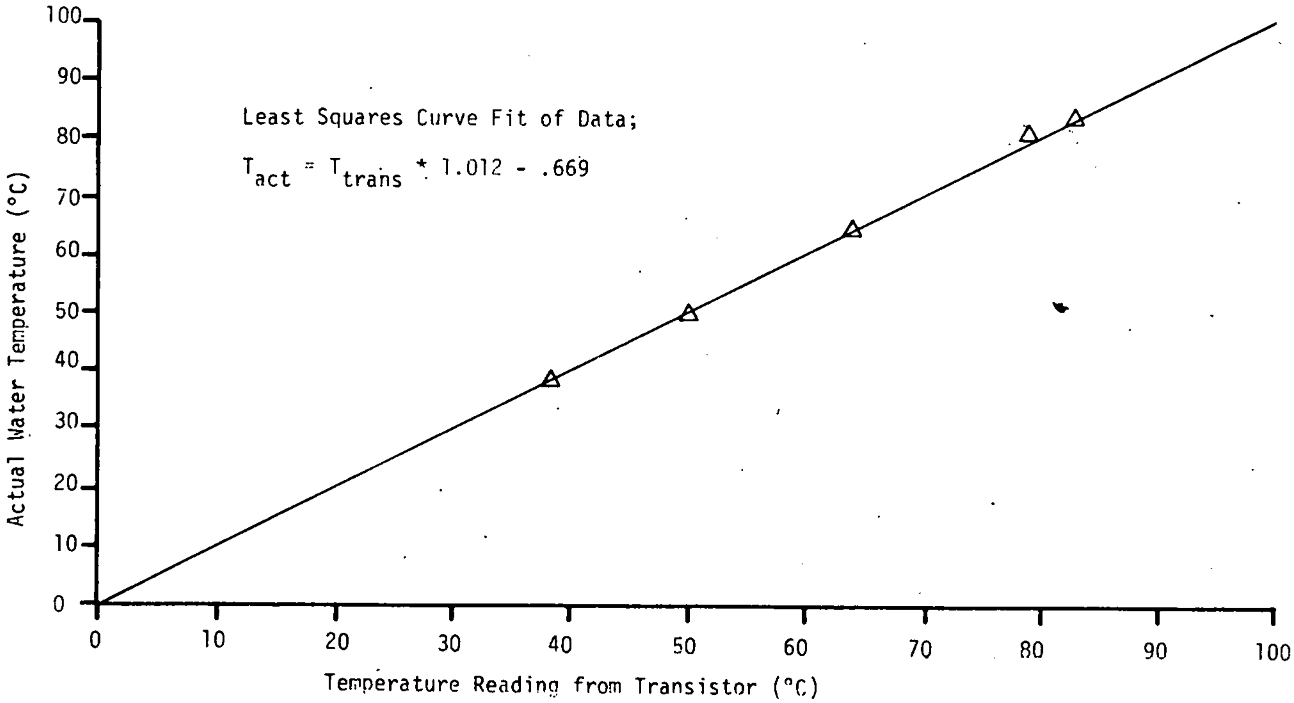

Figure 4. Graph of Temperature Accuracy Test.

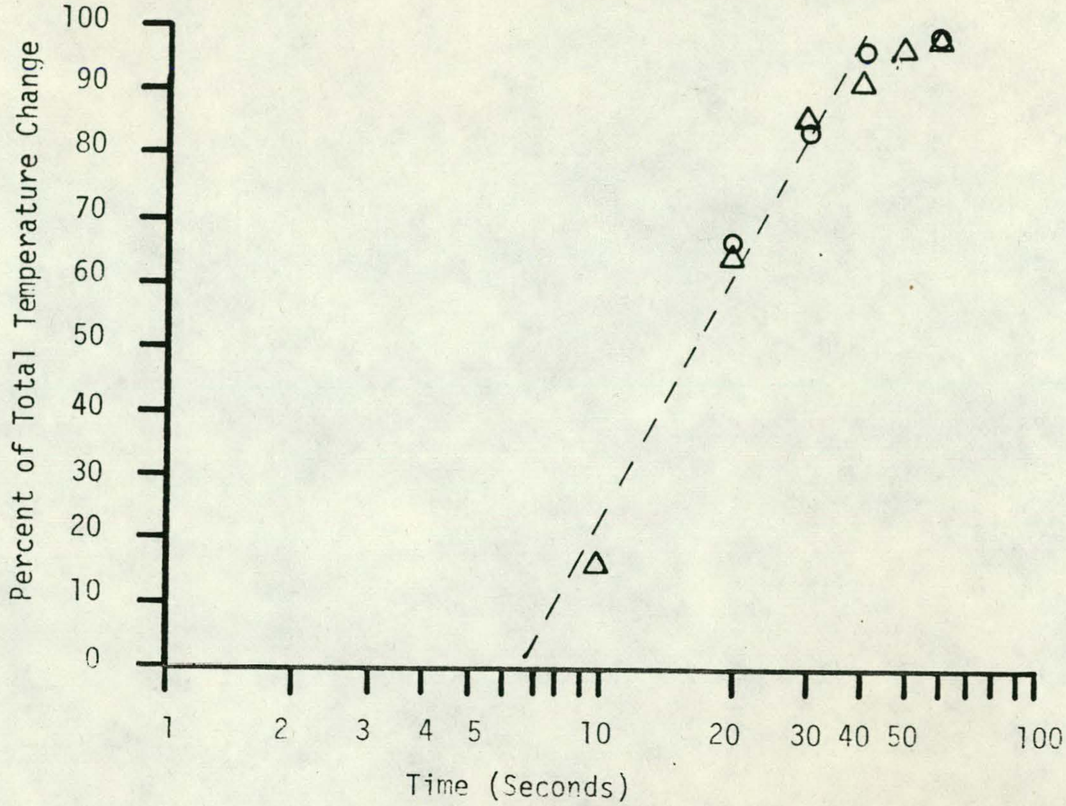

Figure 5. Graph of Transient Response of Copper Saddle For Two Different Initial Temperatures and Essentially the Same Final Temperature.

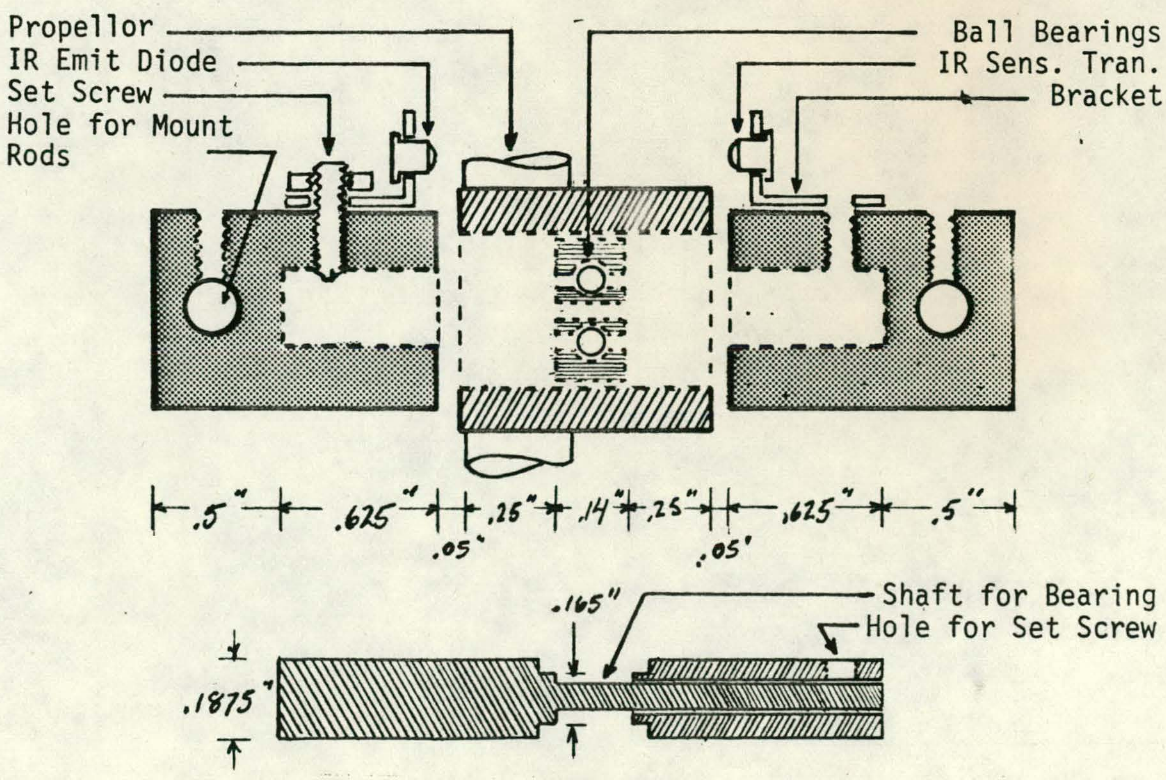

Figure 6. Section Through Air Flow Meter.

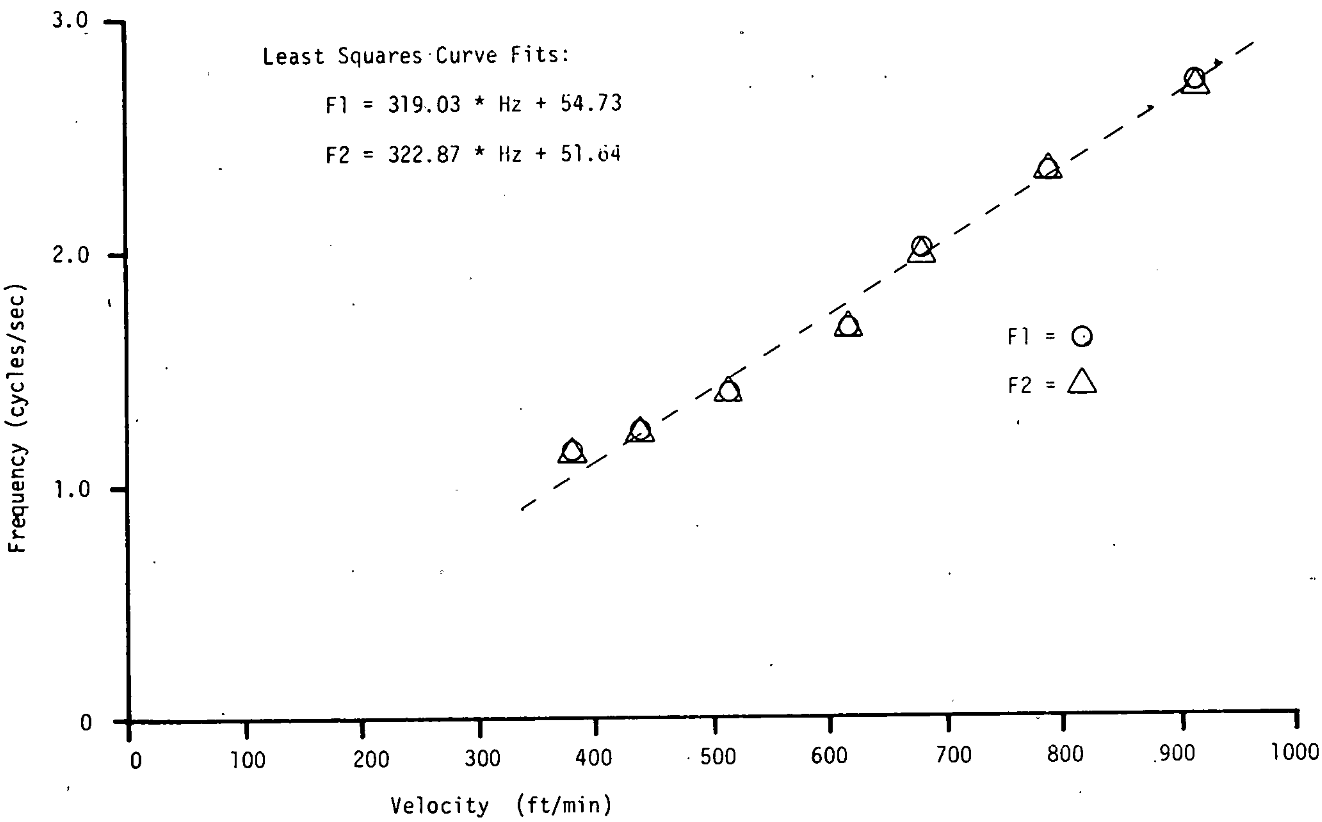

Figure 7. Calibration Chart for Air Flow Meters F1 and F2.

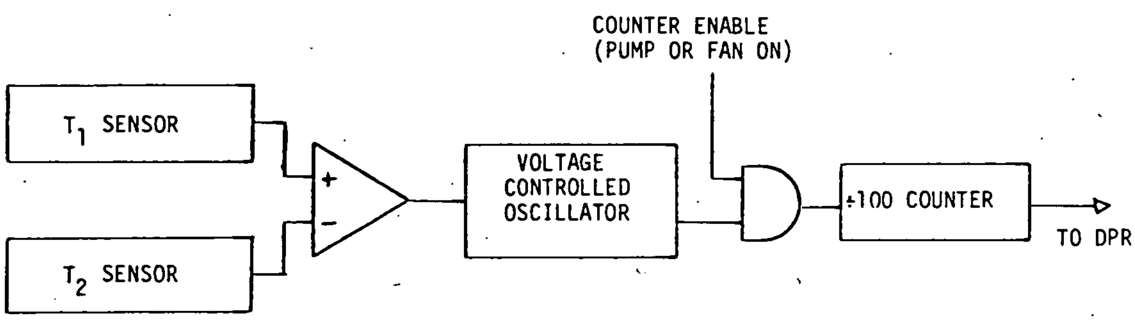

Figure 8. Q Meter Block Diagram.

TURBINE FLOWMETERS FOR MONITORING SOLAR SYSTEMS

by

James W. Baughn
Associate Professor
University of California
Davis, CA 95616

James B. Bergquam
Professor
California State University
Sacramento, CA 96819

ABSTRACT

This paper briefly reviews the characteristics of turbine flowmeters with emphasis on their use in the monitoring and evaluation of solar heating and cooling systems. The turbine flowmeter is commonly used in process measurements and can provide accurate and repeatable measurements of both flow rate and total (integrated) flow over a broad range with a linear output. It provides digital information (when used with a counter), has high reliability, fast response rate, and has a relatively small pressure drop (when used near the lower end of its linear range). It's disadvantages include sometimes higher costs and the need for a pulse counter or frequency to voltage converter. It has been adopted for measurements of water and water/glycol flow in solar collectors in a number of solar monitoring and testing programs.

INTRODUCTION

A turbine flowmeter measuring system is illustrated in figure 1. The sensor consists of a tube section within which a turbine with multiple blades is mounted. A flow straightener is generally mounted upstream of the turbine. The turbine blades operate at a rotational speed which is a function of the flow rate and as each blade rotates past a coil magnetic pickup an electrical pulse is generated. Since the rotational speed is linear with flow rate over a broad range the pulses can be counted to obtain the total flow and/or the frequency may be measured to obtain the flow rates.

TURBINE FLOWMETER CHARACTERISTICS

Theory

A dimensional analysis[1] (Buckingham π theorem) of the fluid flow in a turbine flowmeter (neglecting friction and compressibility) shows that the relationship of the variables is

$$\frac{Q}{nD^3} = f\left(\frac{nD^2}{\nu}\right) \tag{1}$$

where Q is the volumetric flow rate, n is the rotor angular velocity, D is the meter bore diameter, and ν is the fluid kinematic viscosity. Note that nD is proportional to the velocity of turbine blades, and that $\frac{nD^2}{\nu}$ is in effect a blade Reynolds number. When measurements of $\frac{Q}{nD^3}$ are made as a function of $\frac{nD^2}{\nu}$ a curve such as figure 2 is obtained.

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At lower values of $\frac{nD^2}{\nu}$ (where viscous effects are significant) a strong dependence of $\frac{Q}{nD^3}$ on $\frac{nD^2}{\nu}$ is observed. However, over a broad range of higher values of $\frac{nD^2}{\nu}$ it is found that $\frac{Q}{nD^3}$ is nearly constant, i.e. a linear range where

$$Q = kn \quad , \quad k = \text{calibration constant} \tag{2}$$

This linear relationship makes the turbine flowmeter particularly useful for measurements of total flow, which can be especially valuable in solar monitoring applications.

Accuracy and Repeatability

The accuracy of a flowmeter is determined primarily by its calibration and repeatability. The repeatability (i.e. the ability of a given instrument to repeat its calibration) of turbine flowmeters has been demonstrated[2] to be typically within .025%. This high repeatability essentially limits the accuracy to that of the calibration. Typical calibration accuracies of 0.25% have been demonstrated when traceable to the National Bureau of Standards. For most solar applications the accuracy and repeatability of turbine flowmeters is not limiting and is determined solely by the calibration.

Range and Linearity

The linear range[3] of turbine flowmeters is usually between 10:1 and 20:1 (i.e. from 1/10 or 1/20 of full range to full range). Some military and aerospace meters extend this to greater than 100:1. Within this range the calibration constant, k, may remain constant within ± 0.5%. The meter bore diameters available range from 1/4 inch to 24 inches and result in liquid flow ranges from 0.1 to 50,000 gpm for most solar application meters in size from 3/16" to 1½" would be used. These have full scale ranges of 0.1 gpm to 175 gpm and are sometimes available used or surplus.

Pressure Drop

The pressure drop is approximately proportionally to the square of the flow rate (i.e. the loss coefficient does not vary significantly) over the linear range. i.e.

$$\Delta p = k_p Q^2$$

where k_p is characteristic of the design and size of a particular meter. For example, a typical 1" diameter meter with a maximum linear flow of 40 gpm might well have a k_p of 1×10^{-3} psi/(gpm)^2 giving a pressure drop of approximately 1.6 psia at full flow. However, if this same meter had a linear range of 10:1 and was operated at 4 gpm, the pressure drop would be approximately .016 psi (i.e. $p = 4^2 \times 10^{-3}$). These numbers are only approximate since in fact the loss coefficient does vary with flow rate. However when pressure drop is of concern, operating at the lower end of the linear range is desirable. This was necessary for the solar natural circulation experiment described below.

APPLICATION TO SOLAR SYSTEMS MONITORING

Turbine flowmeters are currently in use in a number of monitoring and testing installations. For example the Florida Solar Energy Test Center uses ½ inch meters for their performance tests. They are individually calibrated to within 0.1% of the particular flow rates used in their testing.

The first author of this paper has used these meters in a study of a natural circulation (thermosyphon) hot water system[5]. A diagram of this system is shown in figure 3. For natural circulation systems a minimum pressure drop is needed and therefore a 1 inch diameter meter was selected (used Waugh Model #FL-165B) and operated at the lower end of its linear range. A digital-analog converter was used to transform the frequency to a DC voltage which was recorded with the pyranometer and thermocouples, thereby obtaining a continuous record of the time-dependent flow rate. A calibration coefficient, k, of approximately .11 gpm/Hz was measured for this sensor. For the range of 0.5 to 2.0 gallons per minute, this resulted in a frequency of 4.5 to 18 Hz.

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3. W. G. Anchew, *Applied Instrumentation in the Process Industries*, Volume 1, A Survey, Gulf Publishing Co. pp. 76-80, 1974.

4. Telephone conversation with Thomas Tiedemann of the Florida Solar Energy Test Center.

5. J. W. Baughn and D. A. Dougherty, "Experimental Investigation and Computer Modeling of a Solar Natural Circulation System", *Proc. Int. Solar Energy World Conference*, June 1977.

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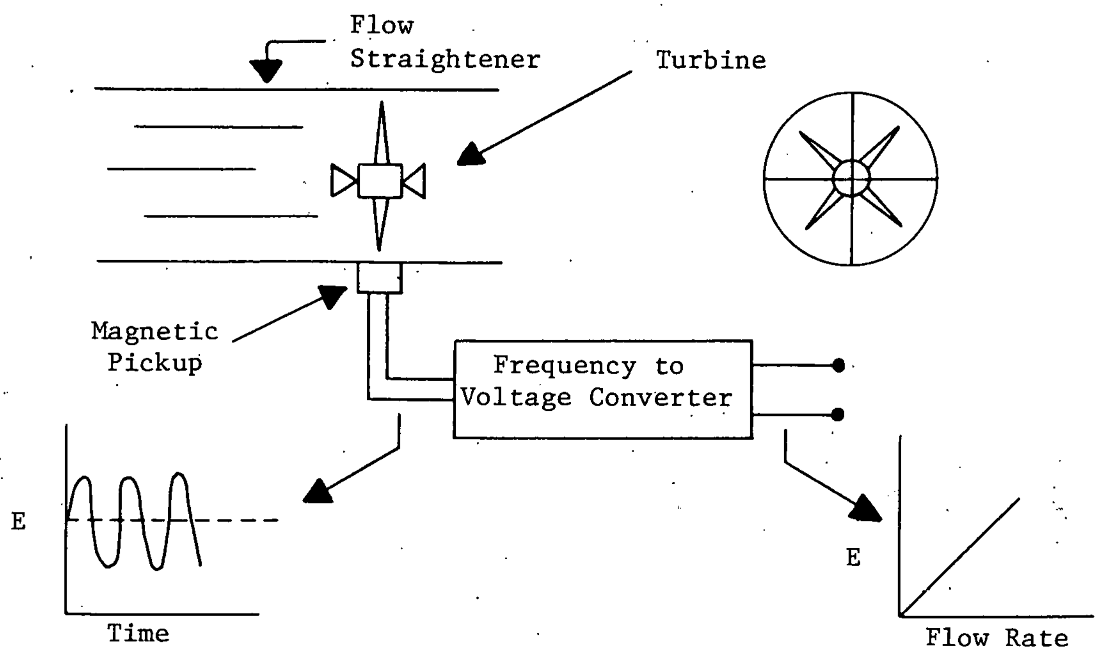

Figure 1. Diagram of Turbine Flowmeter Measuring System

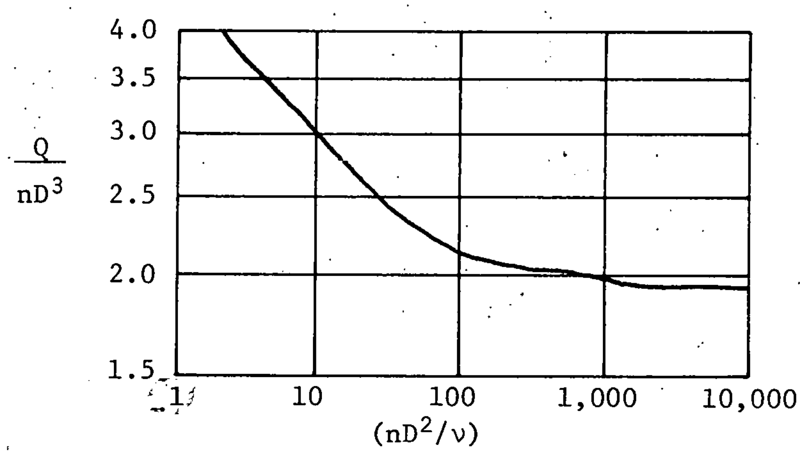

Figure 2 Turbine Flowmeter Characteristics (from Ref. 1)

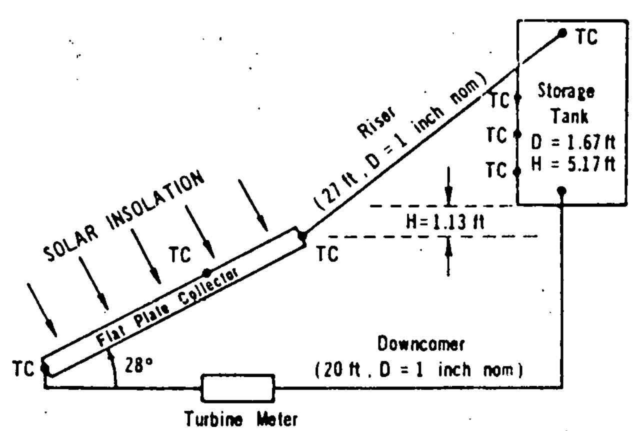

Figure 3 Diagram of Thermosyphon System

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LOW-COST INSOLATION RECORDING SYSTEM*

O. Dayle Sittler and Mercedes M. Agogino
Physics Dept., Eastern New Mexico Univ.
Portales, New Mexico 88130

ABSTRACT: Accurate insolation measurements usually entail large investments in precision pyranometric instruments. A detailed comparison of data from an inexpensive pyranograph with data from a higher precision station shows that values for total daily insolation lying within 10% of pyranometer station values can be derived from pyranograph records with minimal time and effort through the use of careful calibration and data management techniques.

One important factor in evaluation of performance of a solar system is the amount of solar energy actually available for capture. Daily integrated insolation on a horizontal surface is probably the most useful information of this type, especially for evaluating flat-plate collectors. The cost of a complete station, with precision pyranometer and instruments for recording insolation data, is around $2000. A somewhat simpler, lower precision device for recording insolation is the mechanical pyranograph (Fig.1). Such an instrument, costing only about $400, has advantages of requiring no electrical power for operation and including its own chart recorder. It is often assumed, however, that pyranograph data have such poor accuracy as to make the instrument almost worthless except for rough approximations.

Figure 1.
Mechanical Pyranograph (Weather Measure Model R401)
Bimetallic strips of sensing element couple directly to recording pen.

A pyranograph was put in operation at Eastern New Mexico University in 1972 to provide some approximate insolation data for evaluating the solar heating and cooling system used by lizards (1). Since December, 1976, this instrument has been tended fairly meticulously by Physics Dept. personnel to build up as accurate a data base as possible on insolation in this area. It is hoped that this information will help predict operating characteristics of solar heating systems for humans as well as those for lizards. A typical one-week record from this pyranograph is shown in Fig. 2.

After installation of an Eppley PSP Pyranometer and integrating chart recorder at the same site in 1977, it has become possible to

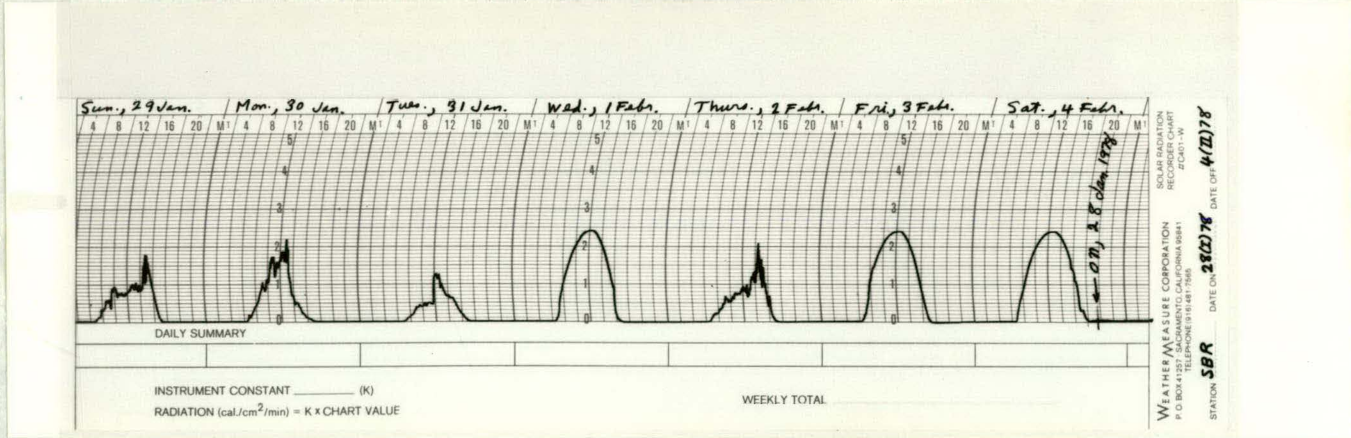

Figure 2. Typical Pyranograph Record
Actual size of ruled chart area is 3 inches by 11½ inches.

compare data from the pyranograph with that from the more accurate pyranometer. The pyranograph had not been recalibrated since 1972; therefore, it is not too surprising that the pyranograph calibration factor is about 11% low as compared to the pyranometer. However, as the scatter diagram of pyranometer data vs. integrated pyranograph data (Fig. 3) shows, the pyranograph does give a remarkably accurate estimate of the insolation indicated by the pyranometer. The graph represents data from 80 days between 17 October 1977 and 19 January 1978. (Gaps in data were due to failure of one of the instruments to record data.) The correlation coefficient between the two instruments'

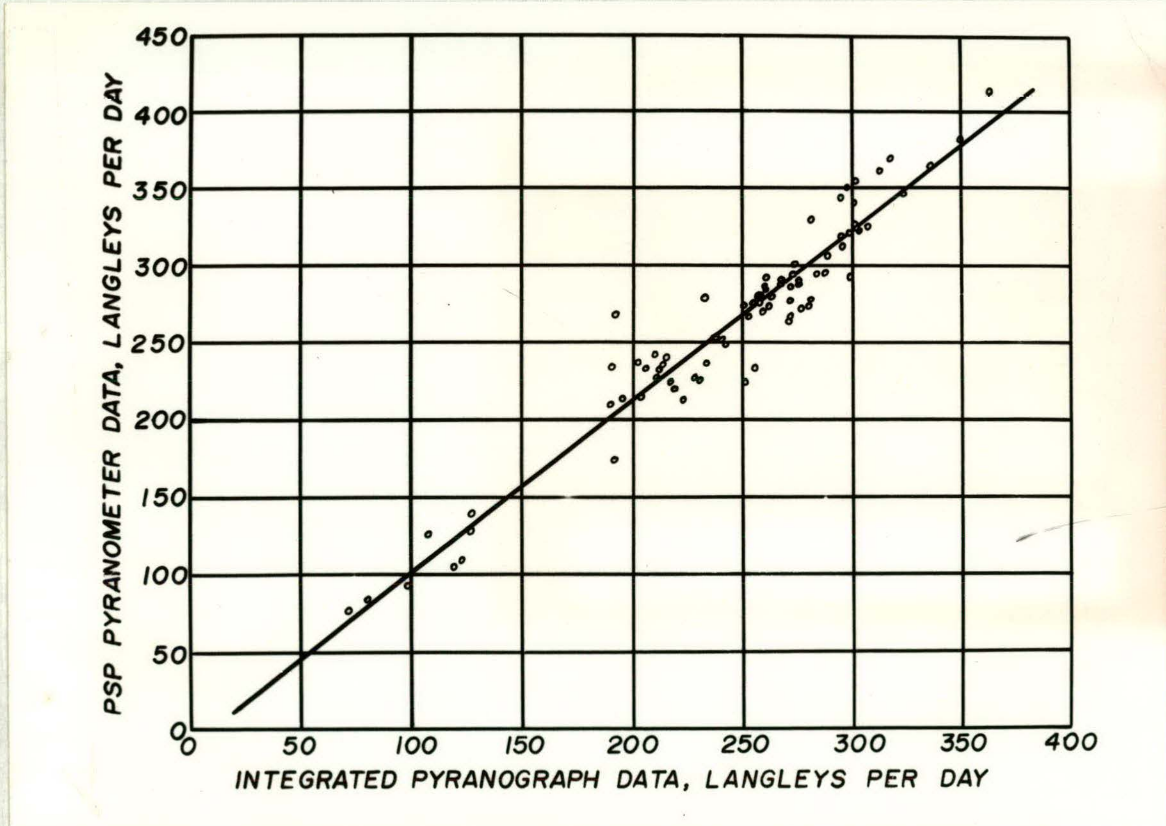

Figure 3. Integrated PSP Pyranometer Data vs. Pyranograph Data
Data from 80 days, 17 Oct.'77 - 19 Jan.'78. Straight line through scatter-diagram is linear least-squares fit; PSP Pyranom. value = -9.5 + 1.11 x Pyranograph value. Standard error of estimate = 18 Langleys. Correlation coefficient is 0.96

insolation values is 0.96. The standard error of the estimate (i.e., standard deviation of insolation from the indicated least squares linear fit value) is about 18 Langleys per day, which implies that, by using such a linear fit for calibration purposes, one can obtain values for total daily insolation which are within 20 or 30 Langleys of what a precision pyranometer would indicate.

The usual procedure for analyzing pyranograph charts involves either using a planimeter to determine areas under insolation curves, or summing ordinates at hourly intervals to give what is essentially an integration by the trapezoidal rule. Either of these procedures is rather tedious, and the trapezoidal rule in particular is not very accurate for areas bounded by curves. For these reasons, we have adopted a procedure which is both simpler and more accurate for analyzing the pyranograph data. The times (hr:min) of beginning and end of each day's insolation are read from the chart. These times can be estimated to within about 10 minutes. Then, the ordinates at each even-numbered hour between these two times is read. The arbitrary units from the chart are used directly, and no attempt is made to estimate fractions of the smallest chart division. These raw numerical data are then entered directly into IBM cards. There is no preliminary attempt to adjust data for instrument scale factor nor for actual times of sunrise or sunset; these are more easily entered into the computer programs for data reduction as they are needed. The resulting numerical data from the chart for each day consist of 5 to 7 two-digit numbers (range: 0.1 to 3.5) plus the two times. We have found that a week's data can be read from the charts in about 20 minutes, and punching data cards for a month requires only an hour of a student helper's time.

Our Fortran program for integrating pyranograph data uses Simpson's rule to integrate the central portion of each day's record. The program first locates the even-numbered hour following the beginning of the day's insolation and applies the trapezoidal rule to the triangular-shaped part of the record from beginning time to that even-numbered hour. Simpson's rule is then used to integrate the next 4 or 6 two-hour intervals, and the trapezoidal rule is again applied to continue the integration to the end of the day's insolation. Since the pyranograph record on a typical clear day resembles a parabolic curve, the use of Simpson's rule for the central, more curved portions of the record gives more accurate estimates for the integral than would the trapezoidal rule. On records for cloudy days, Simpson's rule approximates the jagged-looking record by parabolic arcs passing through the two-hour ordinate values. This is probably at least as good as using the straight lines of the trapezoidal approximation for calculating the integral. Finally, use of accurately known points for beginning and end of an insolation period improves the accuracy of the integration over the simple "summation of ordinates" procedure by giving proper weights to the ordinates near each end of the period.

Using the instrument's arbitrary chart units directly in the data analysis program simplifies maintenance of accuracy. There is some indication that the pyranograph's response is somewhat nonlinear, and this may lead to apparent variations in its calibration from one season to the next. As such changes in instrument calibration are discovered, data recorded between calibrations can be re-evaluated by simply including a new scale factor in the computer program. If a definite nonlinear response is established, then the resulting systematic errors in insolation data can be reduced by including a scale factor correction function in the program.

The effort involved in tending the instrument is minimal. We have found that the weekly chore of winding the clock spring and changing charts takes only 15 minutes. Thus, it appears that inexpensive pyranographs can provide highly accurate insolation data for evaluations of solar collector performance if careful calibration and data management techniques are employed.

(1.) Gennaro, A. L. 1974. Growth, Size, and Age at Sexual Maturity of the Lesser Earless Lizard, Holbrookia maculata maculata, in Eastern New Mexico. Herpetologica 30: 85-90.

Since lizards hybernate, their winter solar heating system designs are simpler than those for humans. The lizards remain underground during adverse climatic conditions.

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