**IEA**
**SOLAR R&D**

**INTERNATIONAL ENERGY AGENCY**
solar heating and
cooling programme

## task VIII
## passive and hybrid solar low energy buildings

# PERFORMANCE EVALUATION PROCEDURES

october 1988

Task VIII

# PASSIVE AND HYBRID SOLAR LOW ENERGY BUILDING

## Subtask A

## Performance Evaluation Procedures

October 1988

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## PREFACE

### INTRODUCTION TO THE INTERNATIONAL ENERGY AGENCY AND THE IEA SOLAR HEATING AND COOLING PROGRAM

International Energy Agency was formed in November 1974 to establish cooperation among a number of industrialized countries in the vital area of energy policy. It is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). Twenty-one countries are presently members, with the Commission of the European Communities also participating in the work of the IEA under a special arrangement.

One element of the IEA's programme involves cooperation in the research and development of alternative energy resources in order to reduce excessive dependence on oil. A number of new and improved energy technologies which have the potential of making significant contributions to global energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), supported by a small Secretariat staff is the focus of IEA RD&D activities. Four Working Parties (in Conservation, Fossil Fuels, Renewable Energy, and Fusion) are charged with identifying new areas for cooperation and advising the CRD on policy matters in their respective technology areas.

Solar Heating and Cooling was one of the technologies selected for joint activities. During 1976-77, specific projects were identified in key areas of this field and a formal Implementing Agreement drawn up. The Agreement covers the obligations and rights of the Participants and outlines the the scope of each project or "task" in annexes to the document. There are now eighteen signatories to the Agreement:

Australia
Austria
Belgium
Canada
Denmark
Commission of the European Communities
Federal Republic of Germany
Finland
Italy
Japan
Netherlands
New Zealand
Norway
Spain
Sweden
Switzerland
United Kingdom
United States

The overall programme is managed by an Executive Committee, while the management of the individual tasks is the responsibility of Operating Agents. The tasks of the IEA Solar Heating and Cooling Programme, their respective Operating Agents, and current status (ongoing or completed) are as follows:

| | |
|---|---|
| Task I | Investigation of the Performance of Solar Heating and Cooling Systems - Technical University of Denmark (Completed). |
| Task II | Coordination of Research and Development on Solar Heating and Cooling - Solar Research Laboratory - GIRIN, Japan (Completed). |
| Task III | Performance Testing of Solar Collectors - University College, Cardiff, U.K. |
| Task IV | Development of an Insolation Handbook and Instrument Package - U.S. Department of Energy (Completed). |
| Task V | Use of Existing Meteorological Information for Solar Energy Application  Swedish Meteorological and Hydrological Institute (Completed). |
| Task VI | Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors - U.S. Department of Energy (Ongoing). |

| | |
|---|---|
| Task VII | Central Solar Heating Plants with Seasonal Storage - Swedish Council for Building Research (Ongoing). |
| Task VIII | Passive and Hybrid Solar Low Energy Buildings - U.S. Department of Energy (Ongoing). |
| Task IX | Solar Radiation and Pyranometry Studies - Canadian Atmospheric Environment Service (Ongoing). |
| Task X | Materials Research & Testing - Solar Research Laboratory, GIRIN, Japan (Ongoing). |
| Task XI | Passive and Hybrid Solar Commercial Buildings - Swiss Federal Energy Office (Ongoing). |
| Task XII | Building Energy Analysis and Design Tools for Solar Applications - U.S. Department of Energy (Ongoing). |
| Task XIII | Advanced Solar Low Energy Buildings - The Royal Ministry of Petroleum and Energy. Norway (Ongoing). |

## TASK VIII - PASSIVE AND HYBRID SOLAR LOW ENERGY BUILDINGS

The Participants in Task VIII are involved in research to study the design integration issues associated with using passive and hybrid solar and energy conservation techniques in new residential buildings. The overall objective of Task VIII is to accelerate the development and use of passive and hybrid heated and cooled low energy buildings in the Participants' countries. The results will be an improved understanding of the design and performance of buildings using active and passive solar and energy conservation techniques, the interaction of these techniques, and their effective combination in various climatic regions and verification that passive and hybrid solar low energy buildings can substantially reduce the building load and consumption of none-renewable energy over that of conventional buildings while maintaining acceptable levels of year-round comfort. The subtasks of this project are:

0. Technology Baseline Definition
A. Performance Measurement and Analysis
B. Modeling and Simulation
C. Design Methods
D. Building Design, Construction and Evaluation

The Participants in this Task are: Austria, Belgium, Canada, Denmark, Federal Republic of Germany, Italy, The Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, United States amd United Kingdom.

This report documents work carried out under Subtask A of this task.

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Operating Agent (On behalf of the U.S. Department of Energy).

LIST OF CONTENTS

1 INTRODUCTION

# 1. INTRODUCTION

## 1.1 Background

Under Subtask D, Building Design, Construction and Evaluation of Task VIII of the IEA Solar Heating and Cooling Programme, passive and hybrid solar homes have been constructed in the member countries.

This report has been prepared to document the common monitoring and performance evaluation procedures used by the participant in assessing the performance of these dwellings.

The overall objectives of Task VIII for this evaluation were to assess the reduction in building heating and cooling load and in consumption of non-renewable energy compared to conventional buildings, and to assess the year round comfort conditions within the dwellings.

## 1.2 General schematic outline of field measurement projects

The discussion in this section is mainly based on the IEA-report, Guiding Principles Concerning Design of Experiments, Instrumentation, and Measuring Techniques (1) and a Norwegian report on Energy Monitoring in Buildings (2). Parts of the discussion are not strictly related to the IEA Task VIII work but should be of general interest and useful for any monitoring project.

Clearly defined objectives and careful planning are prerequisites for a successful monitoring project. The essential components of a monitoring project are outlined in the following list. Each component is expanded on in the different chapters of this report (the points of correspondence are indicated in the list).

1. The aim of the project should be clearly specified. (Chapter 2).

2. Based on this aim, a clearly defined objective should be formulated. Uncertainties in problem formulation should be identified. (Chapter 2).

3. The system has to be defined:
   - system boundaries
   - energy and mass flow across system boundaries
   - energy generated by internal sources

   Within what system boundaries are you going to measure? And, how will you eliminate as many of the uncertainties as possible within the system? (Chapter 3).

4. When the system has been defined, an experimental design and reference model have to be chosen:
   - describe the system with a mathematical model in order to know which factors have to be measured
   - estimate the magnitude of all energy flows
   - eliminate (differences in) factors that cannot be controlled (climate, occupants, etc.)
   - decide at what level of accuracy and detail the data is needed (cost and time have to be considered)
   - describe reference system

   (Note that just energy consumption has been considered here. If it is the intention to use the data for a comfort evaluation or for validating a simulation program, this has to be considered. See also chapter 2).

5. Based on 3 and 4 above, a monitoring plan has to be prepared. The monitoring plan serves as an checklist of what has to be done at the monitoring site, before, during and after the monitoring period (Chapter 4).

6. Based on the stated objectives and the analyses performed under 2, 3 and 4 above, the detailed instrumentation plan can be prepared. This covers quantities to be measured, sampling frequency, equipment (sensors and data acquisition system) and monitoring period (Chapter 5).

7. After the monitoring equipment is installed, and monitoring is going to start, the following have to be carried out:
   - calibration of sensors

- verify that both monitoring system and monitored system work as designed - test by manual instruments
- during the measurement campaign, the data collected have to be followed up carefully, keywords here are graphic output and/or output of easily tested parameters.
- control by manual instruments
- test for unpredicted changes in use and running of the building/system

8. First step of the data reduction and analysis process is to reject bad data in the data collection, stemming from undetected malfunctions in the monitoring system.

9. The results of the measurements can be presented as graphs and equations as well as tables and statistical data (Chapter 6), and also be related to chosen reference cases (chapter 3).

## 1.3 Monitoring checklist

A successful monitoring project takes careful planning and undertaking. The following checklist covers the main steps of this process.

I. Define monitoring objectives
II. Define monitoring restrictions and requirements
III. Make an agreement with the occupants
IV. Decide upon necessary one-time measurements and calculations
V. Plan the continuous measurements
VI. Document the site and monitoring program
VII. Instrument the building
VIII. Check the monitoring system before use
IX. Continuously check the monitoring system during use
X. Continuously evaluate heat balances for the building
XI. Evaluate the performance and document the findings

## REFERENCES

1. IEA-report, G.V. Fracastoro, M.D. Lyberg:
   Guiding Principles Concerning Design of Experiments, Instrumentation and Measuring Techniques, ISBN 91-540-3955-X
   Stockholm, 1983

2. NTNF-report, Energimålinger i Bygninger, Anvisninger for måling og rapportering (in Norwegian, Energy Monitoring in Buildings, Instructions for monitoring and reporting)
   Oslo 1983/1984

3. CEC-report, R. Ferraro, R. Godoy, D. Turrent:
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5. Palmiter, L., B. Hamilton, and M. Holtz, "Low-Cost Performance Evaluation of Passive Solar Buildings," Solar Energy Research Institute, SERI/RR-63-223, Golden, Colorado USA, 1977.

6. Frey, D., M. McKinstry, and J. Swisher, "Installation Manual for the SERI Class B Passive Solar Data Acquisition System," Solar Energy Research Institute, SERI/TR-254-1671, Golden, CO USA, 1982.

# 2 MONITORING OBJECTIVES

There are two principal objectives for monitoring solar heating systems /3/:

I. to understand how they work;

- energy consumption and energy balance
- the amount of energy from solar system and other applied techniques
- usability of house and solar system with regard to comfort, maintenance and function
- evaluation of component performance

II. to assist in the validation of simulation models

The objectives of the monitoring programme of the Task VIII building projects are stated in the introduction (Chapter 1).

## 2.1 Choice of measurement level - general remarks on different approaches

When specifying what to measure in a solar test house, different approaches are available. The most common approach is to divide the specifications into different levels or classes. Each class is supplied with lists of (minimum number of) values to be measured. This approach may lead to an unnecessary amount of data, if the data collection is not seen in connection with its use for later analysis.

Another approach is shown below. In this approach the main point is to choose values to be measured and level of detail according to the goals and intentions in the project. Although the IEA-project has recommended a minimum number of performance factors for this approach, ideally it would be considered as a method for planning the whole monitoring project.

The following four subsections expand the four principal headings (labelled A-D) in the diagram on the following page.

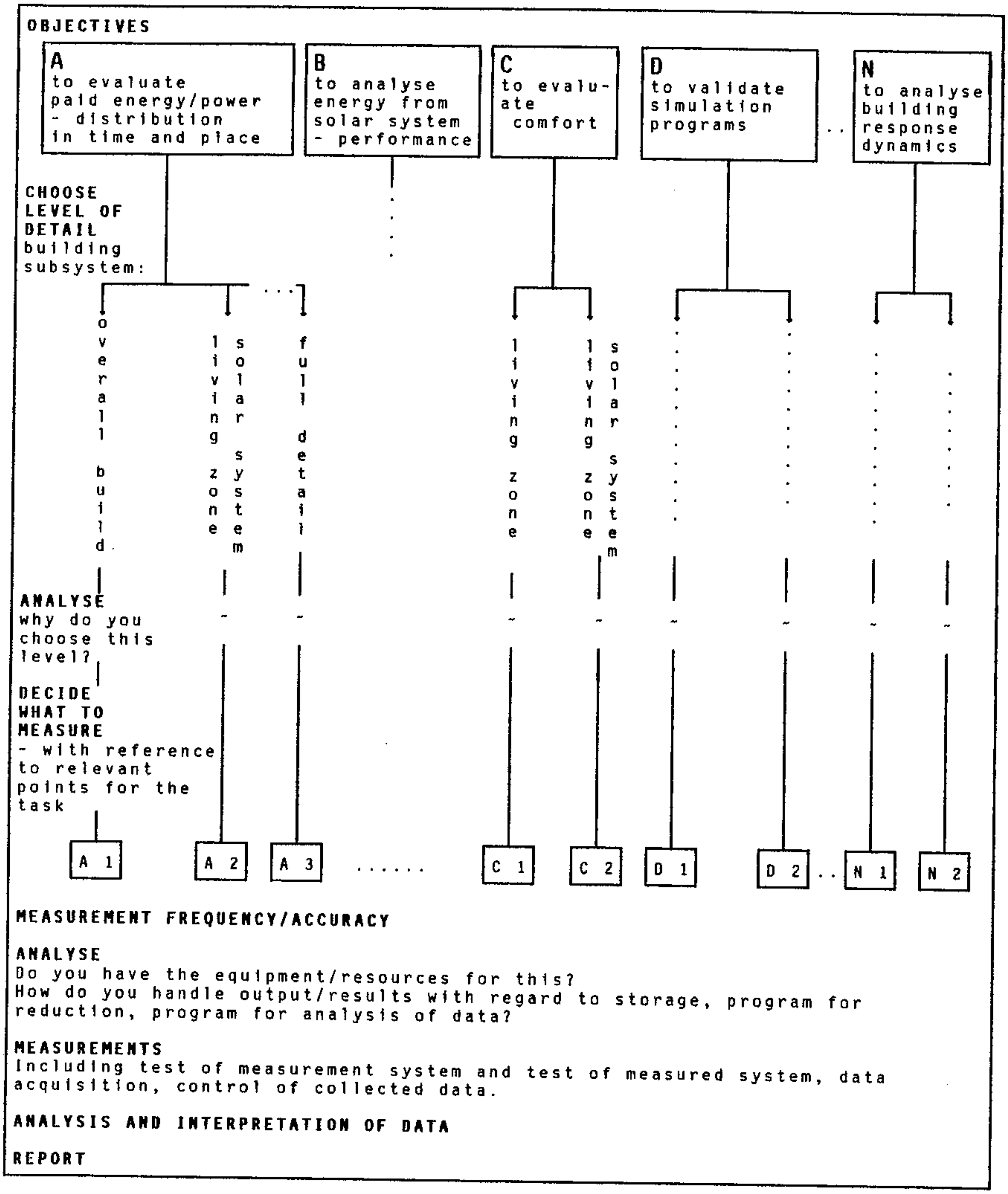

Figure 2.1

How to choose measurement level:

- o What do you want (goals)?
- o Not necessarily the same level of measurement detail for all objectives.

Each numbered box contains a list of measuring values to be used in the (mathematical) evaluation of the task. The box should, in this context, be filled out by the user according to the actual system. A great deal of overlapping will occur between the different boxes.

## 2.2 Energy and power consumption (A)

Often, when monitoring solar buildings, the aim is to see how big the net contribution from the solar heating system is. This is of importance for understanding the energy and power consumption of the building and to determine the cost effectiveness of the solar house/system.

## 2.3 Performance of solar system (B)

Since hybrid and passive solar heating systems form an integral part of the building, hybrid/passive components will contribute to the building energy losses as well as the energy gain. Solar heating is beneficial only when the gains more than compensate for the losses. One approach to calculation of the useful solar contribution defines the energy balance of the passive system. This approach considers the energy benefits of the solar system on its own. However, a second approach is available. If the solar components are not there, other conventional elements would have to be inserted in their place. These components would also have contributed to the load. The alternative definition for useful solar energy is thus the difference in the energy balances of the passive component and of the alternative conventional element. (3)

Also because of the integration of these systems into the buildings, measurements of the energy savings resulting from passive/hybrid solar heating in occupied houses are very difficult. The problem is particularly extreme in purely passive systems. In these, the amount of solar energy transferred into the heated space is very difficult to identify. Furthermore, the proportion of this energy transferred during a period of demand (therefore replacing conventional heating) cannot be measured directly. This is due to the difficulty in estimating the amount of solar energy potentially contributing to overheating, and therefore being vented. (3)

Two approaches to resolving this difficulty are available also. Both are likely to give a satisfactory level of accuracy:

- the subtractive method:
  In this method the total energy losses from the building are calculated from measurements of temperature differentials and one-time measurements of the building heat loss coefficient. All energy inputs to the building other than solar energy are measured or calculated, so that useful solar contribution can be calculated by subtraction from the total losses. Uncertainties: Variation in heat loss factor due to window venting, useful contribution from free heat gains. (8)

- the regression analysis method:
  Apart from the occupants, the two main factors affecting the auxiliary heating consumption of a building are the internal-ambient temperature difference and the total solar radiation incident on the elevations. These two variables and auxiliary heating can all be measured fairly accurately at, for instance, weekly intervals. Each set of measurements can then be plotted on a three dimensional graph (see figure 2.). Using regression analysis, a mathematical surface can then be fitted to all experimental points. The regression coefficients of the surface will give the building heat loss coefficient, the "solar usefulness coefficient" and the effective free heat gains, whilst useful solar contribution will come from the surface. A problem with the method is the need for 3-4 years of data for the correlation. (See also ref. (3)).

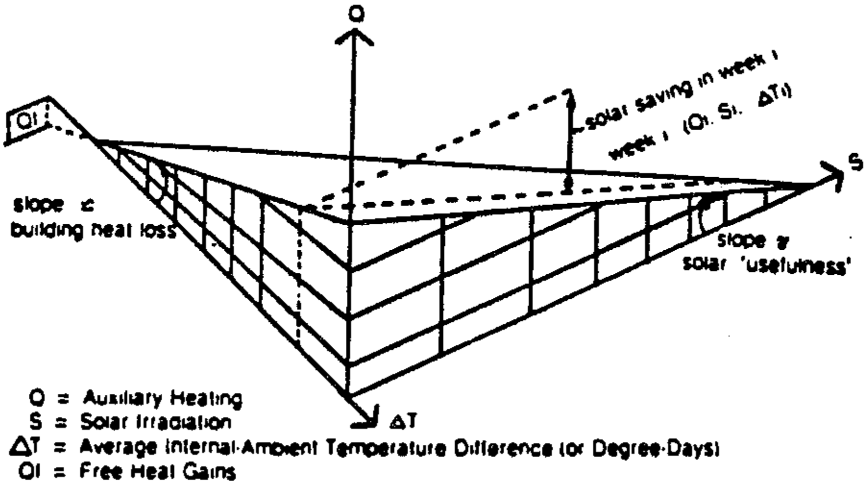

Figure 2.2. The "regression analysis" approach, from (3).

## 2.4 Level of comfort (C):

When evaluating solar buildings, an important consideration is the level of comfort in the building (and in sunspaces). If a system performs excellently with regard to energy, but is not within reasonable comfort limits, the system cannot be regarded as satisfactory. The building has to be occupied when comfort levels are to be measured. This is due to the important effect the occupants have on the indoor climate by adjusting it to their needs. This is in contradiction to energy evaluations. The influence the occupants have on the energy balance is very hard to account for.

The main task for comfort evaluation in solar houses would be to examine thermal comfort. The composition of the air must be considered: content of dust, odours, vapours, micro-organisms, etc. However, other factors are of importance.

For thermal comfort, the most important environmental variables are: air temperature, mean radiant temperature, (relative) air velocity, water vapor pressure in ambient air. In addition, solar irradiation (unshaded spaces) and asymmetric radiant fields (spaces with large areas cold and warm surfaces) can be important for more special cases. These are factors to be used in the Comfort Equation (see (5)).

One way of presenting the measured comfort level could be as a cumulative PMV distribution function (PMV - predicted mean vote) (5) for representative positions, where the activity level is set to "sedentary" and clothing to "light"/"medium" (see figure 3).

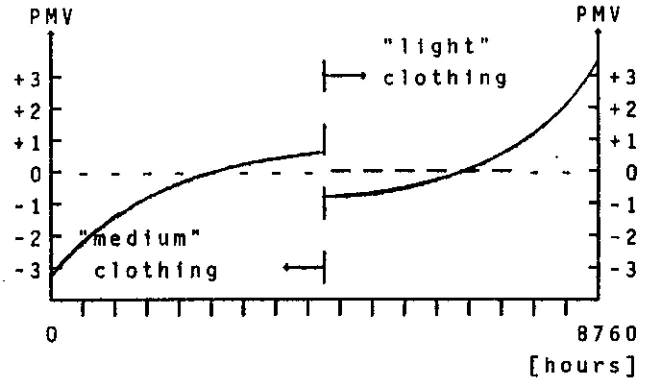

Figure 2.3. A cumulative PMV distribution function for a sunspace. The PMV function is defined in (5). For the right part of the curve "light" clothing is used, for the left part is "medium" clothing used.

## 2.5 Validation of simulation program (D)

What to measure, and how often, depend on the level of detail in the program that is to be validated and on the validation level selected.

There are many levels of validation. These levels depend on the degree of control over the possible sources of error in a simulation. The following sources of errors can be listed:

- o differences between the actual weather around the building and the weather data used with the program
- o differences between the occupant's actual behavior and those effects assumed by the program user
- o user error in deriving building input files for the program
- o differences between actual physical properties of the building and those input by the user
- o differences between the actual thermal transfer mechanisms operative in individual components and the algoritmic representation of those mechanisms in the program
- o differences between heat transfer mechanisms describing interactions between components and their representation in the program
- o coding errors (6).

At the most basic validation level, the actual long-term energy usage of a building is compared to that calculated by the computer program with no attempt to eliminate sources of discrepancy. It is difficult to interpret the results of this kind of exercise because all possible error sources are operating simultaneously. Even if good agreement is obtained between measured and calculated performance, the possibility of mutually compensating errors prevents drawing conclusions about the accuracy of the method. More informative levels of validation are achieved by controlling or eliminating various combinations of error types. At the most detailed level, all known sources of error are controlled in order to identify and quantify unknown error sources (6).

In other words, one has to be careful using just one or two buildings for a validation exercise; whether it is of complex computer programs or of simple design and calculation tools. A better validation method would be a comparative approach with more rigorously validated simulation models.

For a detailed validation, only short periods (i.e. one week) of data are needed. This means well instrumented occupied houses can be used as monitoring objects if the occupants can be moved out during the periods of measurement.

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When deciding the aims one should consider carefully whether the monitoring objectives will give the required answer. For occupied houses there are limits to the detail and accuracy with which it is possible to measure. Some objectives may be beyond the reasonable scope of the project.

## REFERENCES

1. IEA-report, G.V. Fracastoro, M.D. Lyberg:
   Guiding Principles Concerning Design of Experiments, Instrumentation and Measuring Techniques, ISBN 91-540-3955-X
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2. NTNF-report, Energimålinger i Bygninger, Anvisninger for måling og rapportering (in Norwegian, Energy Monitoring in Buildings, Instructions for monitoring and reporting)
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7. Holtz, M.J, Hamilton, B., "Program Area Plan: Performance Evaluation of Passive/Hybrid Solar Buildings", Solar Energy Research Institute Report, SERI/PR-721-788, October 1980.

8. Palmiter, L, Hamilton, B and Holtz, M.J., "Low Cost Performance Evaluation of Passive Solar Buildings", Solar Energy Research Institute Report, SERI/RR-63-223, October 1979.

# 3 PERFORMANCE EVALUATION METHODOLOGY

## 3.1 Introduction

An essential activity in developing a building energy performance evaluation methodology is to define the basis of comparison between the monitored building and some reference case. This comparison is important because it allows qualitative conclusions to be drawn from the quantitative performance results. As outlined in Chapter 1 and 2, the analyst must determine in advance what kinds of comparisons and interpretations will be performed in order to properly define the scope of the analysis. This, in turn, dictates the range of measurements required.

Once we have determined the quantitative result, such as auxiliary energy use, on an absolute scale through performance monitoring, we need to decide whether that value represents good or poor performance relative to some standard. In Task VIII each participating country had previously defined a reference building to be used for these comparisons (1). The reference building describes the design and construction characteristics, including thermal features such as envelope insulation levels, glazing type, area and distribution, air infiltration rate, and mechanical system efficiency, typical of conventional homes in each participating country. The performance of the reference building should be determined analytically, using selected input values that are as consistent as possible with the monitored solar building. That is, building geometry, area and volume should be based on the monitored solar building; however, all thermal design features such as wall, floor and ceiling insulation, glazing type, area and distribution, air infiltration rate and mechanical system efficiency, should be based on the reference building. The energy performance of the monitored solar building and the reference building should then be compared on the basis of overall building energy use. Energy savings in the solar building must be distinguished between solar savings and building envelope savings. An optional enhancement of the method will allow direct calculation of solar component savings, which will be particularly interesting for hybrid designs.

To ensure the relative accuracy of the energy savings comparison between the monitored solar building and the calculated reference building, the monitored solar building performance should be compared to predicted solar building performance using measured values of weather, internal heat gain, air infiltration, and so on in the simulations.

Figure 3.1 shows a flow chart of the monitoring and analysis activities. The reference building evaluation is an integral part of the methodology, and the comparison to the monitored passive/hybrid solar building is the basic product. As stated before, this comparison is the process by which the quantitative results become qualitative conclusions from which decisions can be made regarding design, financing, policy, and so on.

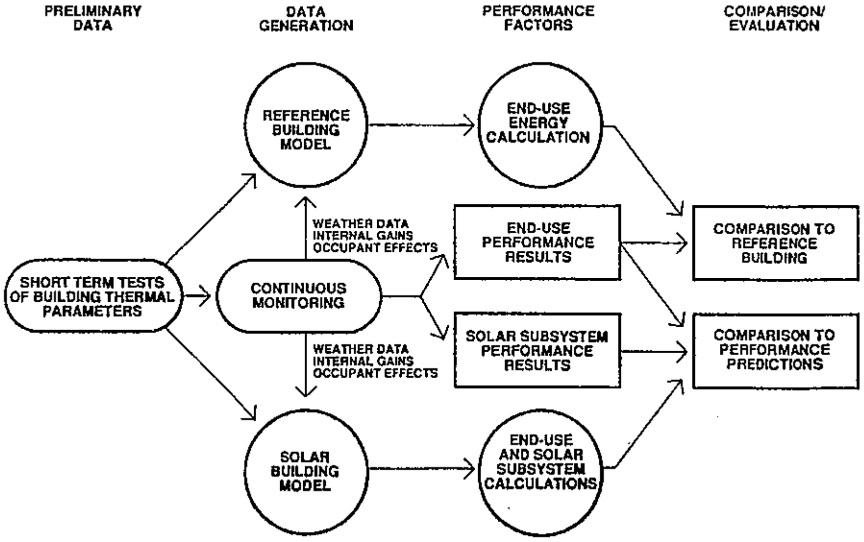


Figure 3.1: Performance Monitoring/Evaluation Methodology

The first step in the IEA Task VIII performance evaluation methodology is the measurement of building thermal parameters and other constants to be used in later steps. These values range from simple geometric quantities such as conditioned (heated/cooled) floor area to thermal parameters such as the building load coefficient.

The next step involves the long-term monitoring of the solar building. In addition to determining the thermal performance results, this process generates internal heat gain and weather data that can be used as inputs to simulation models of the reference building or the solar building.

The short-term measurements and data from the continuous monitoring are used to normalize the reference building and solar building models to obtain a consistent comparison with results from the actual solar building. For the purposes of IEA Task VIII, this was considered the basic mandatory level of performance evaluation. However, further detailed results can be derived from the passive or hybrid subsystem, depending on the level of monitoring detail, as shown in Table 3.1. An additional option is to compare the subsystem performance to that calculated from a model of the solar building, again using measured inputs to the extent possible. This generally requires more detailed monitoring than that required to determine basic system performance.

Table 3.1. Levels of Monitoring and Analysis Detail

1. BASIC MANDATORY LEVEL

    - Subtractive Energy Balance Approach
    - Acceptable for Simple Passive Systems

2. ENHANCED SUBSYSTEM EVALUATION

    - Additive Energy Balance with Measured Passive Gains
    - Necessary for Most Hybrid Systems
    - Optional for Simple Passive Systems

3. ENHANCED SIMULATION MODEL COMPARISON

    - Detailed Measurements of System Parameters
    - Optional

## 3.2 Basic Passive and Hybrid Solar System Types

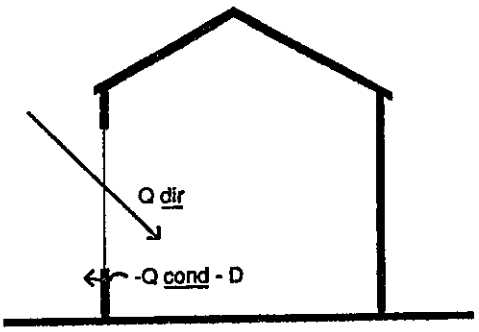
Figure 3.2 illustrates the basic solar energy system types to be considered. The collection strategies include direct gain, indirect gain (such as a Trombe Wall), isolated gain (such as a sunspace), and air-cooled collector panels. Thermal storage components can be charged by passive or active means. Building structural elements, such as walls and floors, can be used for actively-charged thermal storage by incorporating hollow core concrete products or a rockbed. Figure 3.2 shows the basic thermal energy flows, including conduction, convection, and radiation, for each system. These processes will be described in more detail under "Defining Equations", Tables 3.3, 3.4, 3.5, and 3.6.

## 3.3 Building Energy Balance Definitions

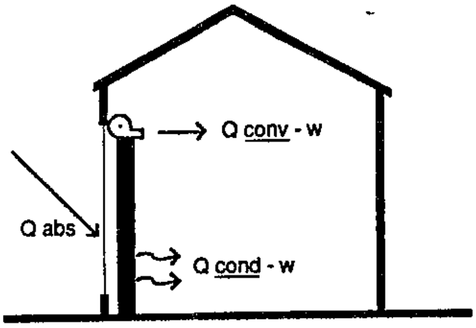
Figure 3.3 illustrates the basic heating season energy balance approach. Overall building thermal performance is calculated from a monthly energy balance, based on a single control-volume that includes the air of the heated space. The energy terms include the sum of the delivered solar energy terms, auxiliary heating, and internal gains, which are balanced by the envelope heat loss and the energy that is vented to prevent overheating. Energy storage terms are important in dynamic analysis, but changes in stored energy are small over longer time spans.

Equation 1 can be simplified by integrating the heat loss and solar gain terms such that they only include the heat necessary to maintain the indoor temperature set-point. This removes the venting term from the equation, leaving Equation 2, where the gross solar gain is replaced by the net solar gain, and the gross heat loss is corrected to exclude losses from overheated indoor air. Equation 3 is a further simplification of Equation 2, with the internal gains subtracted from both sides of the equation, leaving the net heat load balanced by the net solar gain and the auxiliary heat delivered. This type of energy balance is often used in solar savings calculations.

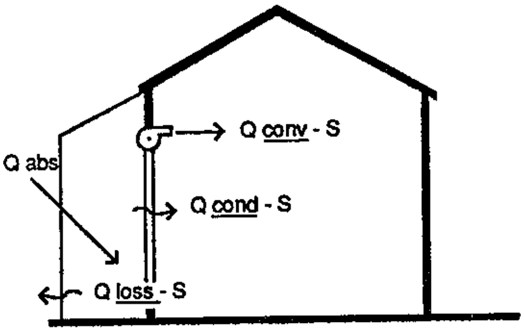
Figure 3.2. Sample System Types



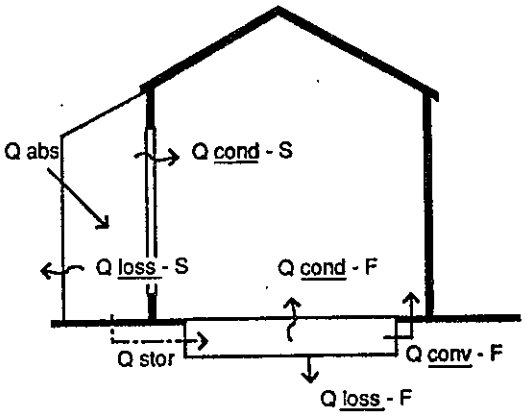
DIRECT GAIN



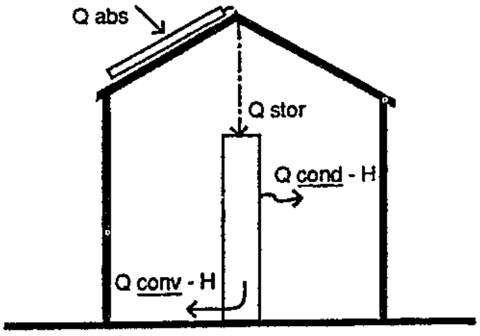
INDIRECT GAIN



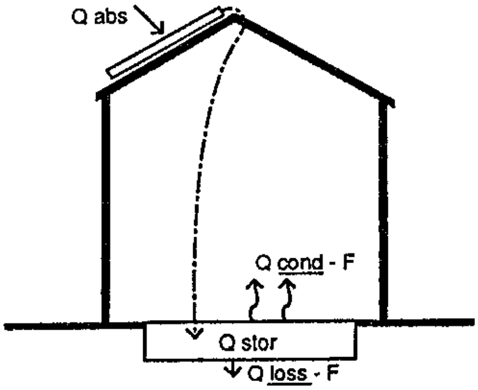
ISOLATED GAIN



ISOLATED GAIN WITH RADIANT SLAB

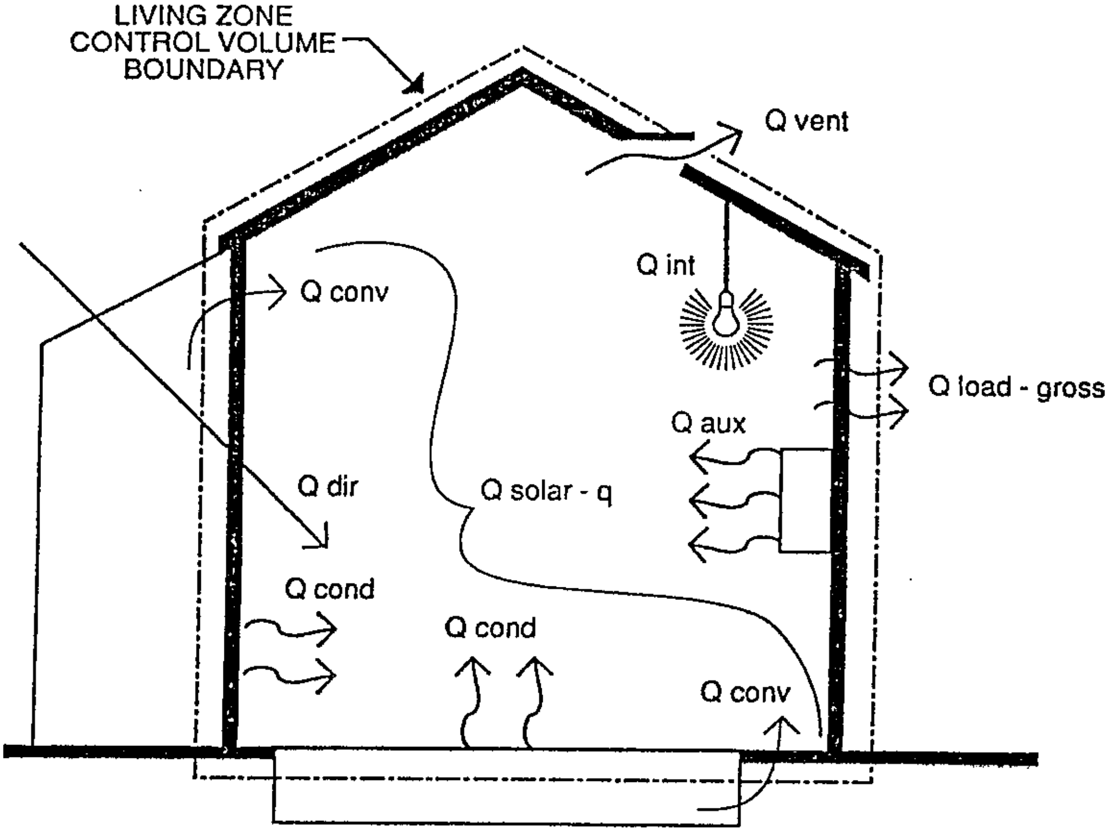


ACTIVE CHARGE WITH RADIANT WALL



ACTIVE CHARGE WITH RADIANT SLAB

Figure 3.3. Building Energy Balance



$$L(T_{in} - T_{amb}) = Q_{load\text{-}gross} = Q_{solar\text{-}g} + Q_{aux} + Q_{int} + Q_{vent} \qquad \text{eq. 1}$$

$$L(T_{set} - T_{amb}) = Q_{load\text{-}corr} = Q_{solar\text{-}n} + Q_{aux} + Q_{int} \qquad \text{eq. 2}$$

$$Q_{load\text{-}net} = Q_{solar\text{-}n} + Q_{aux} = Q_{load\text{-}corr} - Q_{int} \qquad \text{eq. 3}$$

WHERE:

$L$ = building heat loss coefficient

$Q_{solar\text{-}g}$ = gross solar gain

$Q_{solar\text{-}n}$ = net solar gain

$Q_{vent}$ = winter ventilation to prevent overheating

## 3.4 Thermal Analysis Approach

The analysis procedure will vary depending on whether the solar design is a simple passive heating system or a more complex hybrid system. Also, the extent to which the performance comparison requires subsystem data will influence the analysis procedure. For simple passive systems, the basic analysis will closely follow the subtractive methodology developed for the Solar Energy Research Institute´s Class B Passive Solar Performance Monitoring Program. (See References 2, 3 and 4).

SERI´s approach uses Equation 2 as the basic energy performance measure. Measured auxiliary and internal heating are subtracted from the corrected heating load, as defined above, to determine the passive heating contribution. Separating the passive heating in this way allows the analyst to determine how much of the building´s energy savings, relative to the reference case, are due to passive solar gains and how much are due to envelope efficiency. However, it is important to note that the passive solar term can include the effect of many passive heat gains and losses in addition to the solar gain through the primary passive component. Other passive energy flows include solar gains through east and west windows, solar absorption by walls and roofs, thermal buffering by sunspaces, and additional infiltration caused by the occupants. Direct measurement of all these energy flows would be difficult and probably beyond the scope of most monitoring plans.

A more advanced approach will be necessary for determining the solar performance for hybrid heating systems. The simple subtractive approach is not capable of separating the heat delivered by the hybrid subsystem from the other passive energy flows. Thus, an additive calculation of solar subsystem performance must be performed, summing the individual solar gain terms shown in Figure 3.3 for the hybrid system. If there are significant gains from passive components, they can be calculated in two ways: 1) subtractively, adding the hybrid heat delivery to the right side of Equation 2; or 2) additively, measuring the direct, indirect, and convective gains from all glazing apertures. This additive approach can optionally be used for more rigorous analyses of simple passive systems as well. The details of the measurement and calculation steps for this additive procedure are presented under "Defining Equations", Tables 3.3, 3.4, 3.5, and 3.6.

In addition to the heating season energy performance, it is important to evaluate the thermal comfort and cooling season performance in the monitored building. Obviously, if the passive solar strategy leads to serious overheating problems, it is not successful regardless of how much heating energy it saves. Because most of the buildings to be monitored in Task VIII are in northern climates where heating loads are dominant, the cooling season analysis will focus on the building´s tendencies to overheat, rather than looking specifically at passive cooling strategies. In these climates, a well designed solar building should not require significant mechanical cooling to maintain thermal comfort in the summer. To determine if this is the case, cooling energy use and thermal comfort conditions will be monitored. The thermal comfort analysis will also be useful during the heating season in detecting excessive indoor temperature swings.

For comfort evaluation, we suggest to use the "effective temperature" method developed by Joe Carroll, who simplified the Fanger comfort equations (3). The primary performance factor is the difference between the effective temperature, which is a function of dry bulb and mean radiant temperatures and humidity ratio, and the preferred temperature, which is a function of the ambient temperature and the time of day. Appendix 1 includes a complete description of "effective temperature" and how it can be used as an indicator of thermal comfort.

## 3.5 Performance Factors

Performance factors are the quantitative performance measures that can be used to compare a building´s performance to another building or to some standard. To make such comparisons valid, the performance factors must be reduced to simple and consistent terms. Important driving forces for building performance must be equal or normalized in some manner. For example, two buildings with substantially different floor areas and internal gains could not be meaningfully compared unless these factors were accounted for. Similarly, changing weather over time or from one location to another cannot be ignored. These factors can be normalized by either manipulating the simulation inputs or by normalizing the measured results using the appropriate parameters (e.g., kJ/m2- DD). The most difficult anomalies to account for are occupant effects, which can result in varying indoor temperature set-points, internal gains, infiltration rates, and so on.

Table 3.2 lists performance factors for building end-use energy comparisons and for solar subsystem performance comparisons. The end-use energy performance factors include the normalized heating energy use for the monitored building and the reference case. Additional factors for comparison are peak electric power demand and thermal comfort parameters. Energy savings due to building envelope improvements can be determined from the total corrected heating loads.

Table 3.2. Performance Factors

I. END-USE PERFORMANCE RESULTS

A. Total auxiliary heating delivered to the load (kJ/yr)

B. Heat removed from conditioned space by cooling system (kJ/yr)

C. Total purchased energy delivered to the load (kJ/yr)

D. Normalized auxiliary heating delivered to the load (kJ/m$^2$-yr, kJ/m$^2$-dd)

E. Normalized heat removed from conditioned space by cooling system (kJ/m$^2$-yr)

F. Normalized total purchased heating delivered to the load (aux & int gain) (kJ/m$^2$-yr, kJ/m$^2$-dd)

G. Total corrected heat load (kJ/m$^2$-yr, kJ/m$^2$-dd)

H. Normalized heat load

(1) Normalized gross heat load (kJ/m$^2$-yr, kJ/m$^2$-dd)

(2) Normalized net het load (kJ/m$^2$-yr, kJ/m$^2$-dd)

I. Reference building results based on measured inputs
  - (1) Monthly net heating and cooling loads (kJ/mo)
  - (2) Weather data summary (°C, $W/m^2$, m/hr)
  - (3) Internal gains (scheduled, same as simulation of solar building) (W)
  - (4) Occupant Effects,
    - a) Internal gains (shown above)
    - b) Infiltration (usually fixed)
    - c) Ventilation (scheduled)
    - d) Set points (scheduled)
  - (5) Indoor temperature - output of simulation (°C)

J. Peak electric power demand (hourly average peak) (kW)

K. Thermal comfort parameters
  - (1) Monthly average indoor temperature (°C)
  - (2) Monthly maximum indoor temperature (°C)
  - (3) Monthly minimum indoor temperature (°C)
  - (4) Average daily maximum indoor temperature (°C)
  - (5) Average daily minimum indoor temperature (°C)
  - (6) Mean radiant temperature statistics (°C)
  - (7) Mass temperature statistics (°C)
  - (8) Mean squared error
  - (9) Effective Temperatures
  - (10) Predicted mean vote

L. Meteorological values
  - (1) Average ambient temperature (°C)
  - (2) Monthly maximum temperature (°C)
  - (3) Monthly minimum temperature (°C)
  - (4) Average daily minimum temperature (°C)
  - (5) Average daily maximum temperature (°C)
  - (6) Average daily horizontal solar radiation ($W/m^2$)

(7) Total horizontal solar radiation (W/m$^2$)

(8) Average daily south facing solar radiation (W/m$^2$)

(9) Total south facing solar radiation (W/m$^2$)

(10) Degree days (dd)

II. SOLAR SUBSYSTEM PERFORMANCE RESULTS

A. Gross solar energy on collection area (kJ)

B. Net solar energy collected (gross x 0.85 transmitted) (kJ)

C. Usable solar energy delivered by subsystem ($Q_{gross}$-$Q_{int}$-$Q_{aux}$) (kJ)

D. Gross solar collection efficiency of system

E. Net solar utilizalion efficiency of system

F. Solar fraction of net heating load

G. Solar fraction of corrected gross load

End-use energy results should be normalized to account for differences in building size, climate, and occupant operation. Dividing the energy use by the heated floor area is a convenient method, as long as the heated floor is determined in a consistent manner for all houses. Weather is considered by dividing by heating degree days; however, to account for variations in indoor temperatures, the degree days should be calculated using the measured indoor temperature as well as using a fixed base temperature. Finally, auxiliary energy use comparisons can be misleading if there are significant differences in internal gains. Thus, a more consistent performance factor includes both auxiliary and internal heat inputs. It is important to note that the auxiliary energy is the delivered energy, not the gross fuel consumed, so that different equipment efficiencies do not introduce bias into the analysis.

The recommended thermal comfort performance parameter is the mean squared error, or difference, between the effective temperature and the preferred temperature, according to Carroll's method(s) (5). The error is squared before averaging to prevent underheating and overheating conditions from compensating for each other. It is also instructive to create histograms of the comfort error in order to evaluate the relative frequency of uncomfortably warm and cool conditions. Fanger's method of a predicted mean vote may also be used as a thermal comfort factor (6).

The energy delivered by the passive or hybrid solar subsystem must be corrected to exclude energy that causes overheating. This correction is implicit in the subtractive approach, but it must be carefully applied to the solar terms in the additive approach. The two convenient normalization factors for delivered solar energy are: 1) dividing by incident radiation to determine net solar efficiency; and 2) dividing by the net heating load or the corrected gross load to determine the "solar fraction."

## 3.6 Use of Computer Models

The primary use of computer models will be to simulate the performance of the monitored solar building and the reference building. Weather data from the monitored building must be formatted for use with the simulation models, and the actual schedules for thermostat settings, internal gains, etc. should be repeated as precisely as possible. Auxiliary heating and cooling energy and internal gains will be calculated using the models and compared to the monitored solar building. If possible, the mean squared error of effective temperature should be calculated in the model. If this is not possible, the average daily maximum and minimum indoor temperatures should be calculated on a monthly basis. The heating degree days, based on actual indoor temperature, should also be calculated in order to properly normalize the results, as discussed above.

A comparison of the monitored performance results to those predicted by a simulation of the solar building should be undertaken prior to creating and simulating the reference building. Those thermal parameters which can be directly measured at the site should be used in the solar building model to minimize errors due to incorrect inputs. The results can be compared for both the overall building performance and the solar subsystem performance. At this point, any discrepancies between the measured and predicted results can be evaluated to determine if the errors are due to the building or component, the occupant, or the modelling procedure. Appropriate "fine tuning" of the model can be made to improve agreement with the monitored data, so long as unrealistic changes to the building or modelling assumptions are not made.

When an acceptable level of agreement has been achieved between the monitored and predicted performance of the solar building, the solar building model can be modified to reflect the thermal design conditions of the reference building. This new reference building model represents the conventional home, and the difference between its energy performance and that of the monitored solar building is the energy saved by the solar and energy conservation design features.

## 3.7 Definitions of Performance Factors and Measured Parameters

Equations 1 and 2 define the basic energy balance terms, based on the gross and corrected heating loads. The individual terms and some normalizing factors are defined in detail in Equations 4-8 in Table 3.3. The thermal comfort parameters are defined in Equations 9-12 in Table 3.4. In order to determine the humidity ratio from measurements of relative humidity, one must first determine the saturation pressure, which is a function of dry-bulb temperature. This relationship is a complicated equation which can be found in most thermodynamic texts. It is given on page 5.2 of the 1981 ASHRAE Handbook of Fundamentals (See Appendix 2.) If these measurements and computations exceed the scope of the monitoring project, the average daily maximum basis minimum indoor temperatures should be reported on a monthly basis as substitute performance factors.

Table 3.3. Defining Equations - End-Use Energy

AUXILIARY COOLING = $\sum E_{cool}$ eq. 4

Where $E_{cool}$ = auxiliary cooling energy delivered to the load

AUXILIARY HEATING = $\sum E_{aux}$ eq. 5

Where $E_{aux}$ = auxiliary energy delivered to the load

INTERNAL HEATING =

$$\sum(E_{tot} - E_{aux} - E_{out} - N_{dhw} E_{dhw} - N_{dry} E_{dry}) - Q_{occ} \qquad \text{eq. 6}$$

Where $E_{tot}$ = total purchased energy

$E_{out}$ = energy used outside living space

$N_{dhw}E_{dhw}$ =, $N_{dry}E_{dry}$ = energy use by water heater and clothes dryer that does not enter living space

$Q_{occ}$ = heat gain rate from occupants

DEGREE DAYS = $\int(T_{set} - T_{amb})\,dt$ if $T_{set} \geq T_{amb}$ eq. 7

$T_{set}$ = thermostat set temperature during occupied hours

$T_{amb}$ = ambient temperature

PEAK ELECTRIC POWER = $E_{tot}$ if $E_{tot}$ > previous peak eq. 8

Table 3.4. Defining Equations - Thermal Comfort

EFFECTIVE COMFORT TEMPERATURE, $T_e$

$T_e = 0.51\ T_{in} + 0.42\ T_r + 130W + 0.45^oC$ eq. 9

Where $T_{in}$ = indoor dry-bulb temperature ($^oC$)
$T_r$ = mean radiant temperature ($^oC$)
$W$ = humidity ratio

$$W = \frac{0.622\ Rh\ P_{sat}}{P_{atm} - P_{sat}} \qquad P_{sat} = F(T_{in}) \qquad \text{eq. 10}$$

MEAN SQUARED ERROR, MSE

$$MSE = \frac{\int (T_e - T_p)^2\ dt}{\int dt} \qquad \text{eq. 11}$$

Where $T_p$ = preferred temperature
and $T_p = 0.1\ T_{amb} + 22.5^oC - N$ eq. 12

$$N = \begin{cases} 2^oC \text{ during sleeping hours} \\ 0 \text{ otherwise} \end{cases}$$

Equations 13-16 in Table 3.5 define the individual solar energy terms to be used in the additive calculations for hybrid systems and for enhanced analysis of passive systems. Free convective heat delivery from the solar components to the living space is not included in these equations; and because this process is difficult to monitor. However, if the primary passive solar heating system requires convective heat delivery, a fan should be installed to provide the necessary air flow in a more predictable and controllable fashion. Another difficult term to evaluate is conductive heat delivery. Equations 17-22 suggest some possibilities for calculating this term for a variety of passive and hybrid configurations, although each system may have unique requirements in this part of the analysis.

Table 3.5. Defining Equations - Delivered Solar Energy

GROSS ENERGY DELIVERED BY SOLAR SUBSYSTEM $Q_{solar-g} = Q_{conv} + Q_{cond}$ eq. 13

DIRECT GAIN:

$$Q_{dir} = \sum_i A_{gl,i} \; \bar{\tau} \int I_{or,i} \, dt \qquad \text{eq. 14}$$

Where $A_{gl,i}$ = orientation glazing area

$\bar{\tau}$ = average net solar transmittance

$I_{or,i}$ = orientation solar radiation flux

$$Q_{conv} = (\rho c_p)_{air} \; q_{fan}(T_{sup} - T_{ret}) \, X_{fan} \, dt \qquad \text{eq. 15}$$

Where $(\rho c_p)_{air}$ = heat capacity of air

$q_{fan}$ = fan volumetric flow rate

$T_{sup}$ = supply temperature

$T_{ret}$ = return temperature

$X_{fan}$ = fan status (1 = on, 0 = off)

CONDUCTION/RADIATION

$$Q_{cond} = \frac{KA_m}{l} \int (T_{node} - T_{surf}) \, dt \qquad \text{eq. 16}$$

Where K = material thermal conductivity

$A_m$ = surface area

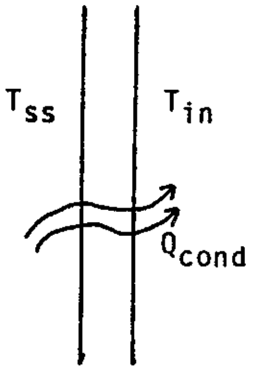
l = distance from interior surface to next node

$T_{surf}$ = surface temperature

$T_{node}$ = temperature at next node (may be outer surface for low-mass material)

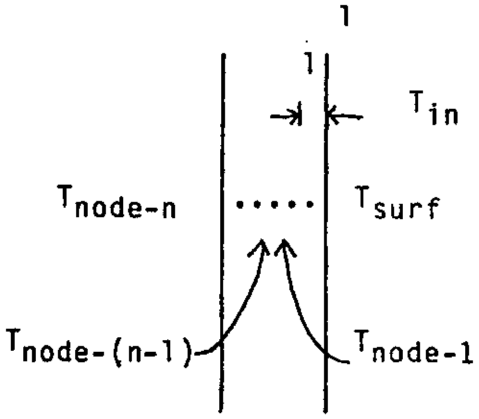
Table 3.5. (Cont.) Ideas for Measuring/Calculation $Q_{cond}$

### LIGHT-MASS SUNSPACE WALL



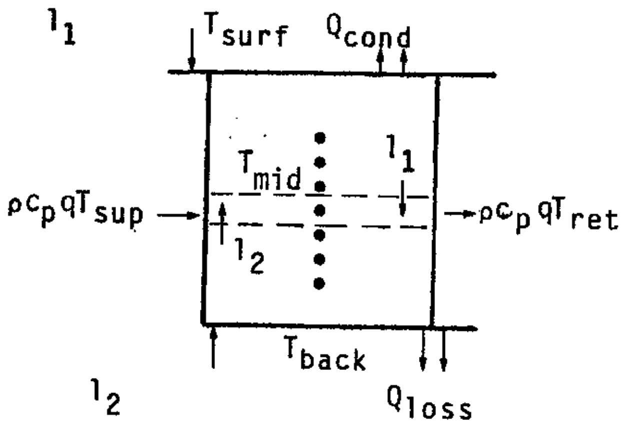
$$Q_{cond} = UA_{wall}\,(T_{ss} - T_{in}) \quad \text{eq. 17}$$

### TROMBE WALL



$$Q_{cond} = \frac{KA_m}{l}\,(T_{node-1} - T_{surf}) \quad \text{eq. 18}$$

## ACTIVE-CHARGED FLOOR SLAB



$$\Delta E + Q_{cond} + Q_{loss} = \rho c_p q(T_{sup} - T_{ret})$$

eq. 19

$$\frac{Q_{loss}}{Q_{cond}} = \frac{l_1\ (T_{back} - T_{mid})}{l_2\ (T_{surf} - T_{mid})}$$

eq. 20

$$E = (\rho c_p)_{mass}\ (l_1 + l_2)\ \Delta\bar{T}$$

eq. 21

$$\rightarrow Q_{cond} = \frac{\left[(\rho c_p)_{air}\ q(T_{sup} - T_{ret}) - (\rho c_p)_{mass}\ (l_1 + l_2)\ \Delta\bar{T}\right]}{1 + \frac{l_1}{l_2}\ \frac{(T_{back} - T_{mid})}{(T_{surf} - T_{mid})}}$$

eq. 22

Table 3.6. Defining Equations - Solar Performance Factors

USABLE ENERGY DELIVERED

$$Q_{solar-net} = \int Q_{solar-g} \cdot \frac{T_{set} - T_{amb}}{T_{in} - T_{amb}} \cdot dt \qquad \text{eq. 23}$$

GROSS SOLAR EFFICIENCY

$$\eta_{gross} = Q_{solar-g}/(I_{or} \ A_{gl}) \qquad \text{eq. 24}$$

NET SOLAR EFFICIENCY

$$\eta_{net} = Q_{solar-net}/(I_{or} \ A_{gl}) \qquad \text{eq. 25}$$

SOLAR FRACTION OF NET HEATING LOAD

$$F_{net} = Q_{solar-net}/(Q_{solar-net} + Q_{aux}) \qquad \text{eq. 26}$$

SOLAR FRACTION OF CORRECTED LOAD

$$F_{cor} = Q_{solar\ net}/(Q_{solar-net} + Q_{aux} + Q_{int}) \qquad \text{eq. 27}$$

Equations 23-27 in Table 3.6 define the solar energy system performance factors, all of which concern solar heating. Another instructive factor that can be determined using the additive energy balance equations is the gross heat delivered from the solar subsystem during the summer months. This can indicate the contribution of the solar features to summer overheating and cooling energy use.

## 3.8 Continuously Measured Parameters

Table 3.7 lists the parameters that must be measured to determine the recommended performance factors. Some of the parameters, such as auxiliary heating and ambient temperature, can be measured directly, while others, such as the additive solar energy terms, must be determined from a number of measured values. For the simple subtractive analysis, measuring these parameters will require approximately 16 sensor channels in most applications. The additive analysis may require two to three times as many sensors. See Chapters 4 and 5 for a more complete discussion of continuously measured parameters.

Table 3.7. Measured Parameters

I. END-USE ENERGY PERFORMANCE

A. Auxiliary heating
B. Auxiliary cooling
C. Internal heating (lights, appliances,...)
D. Solar radiation (direct + diffuse)
E. Ambient temperature
F. Indoor temperature (each major zone)
G. Wind speed
H. Gross building heat loss coefficient
I. Mean radiant temperature (by zone)
J. Humidity (by zone and outdoor)

II. SOLAR SUBSYTEM PERFORMANCE - ADDITIONAL PARAMETERS

A. Energy delivered by direct gain
B. Energy delivered by conduction/radiation
C. Energy delivered by forced convection
D. Ratio of corrected load to gross load
E. On-times of vents, fans, shades, etc...
F. Primary thermal mass temperatures

## 3.9 Short-Term Measurements

Table 3.8 lists the necessary constants to be measured on a short-term or one-time basis. Many are simple dimensions or physical properties that are easily obtained. It is important, however, that values such as floor area and apparent thermostat settings be evaluated in a consistent manner to avoid introducing bias into the performance comparisons. All descriptive values and related information should be included in a detailed <u>site handbook</u> describing the building and the measurements taken. Thermal parameters such as heat loss coefficients can be measured in controlled tests over periods of a few days. These tests may require temporarily relocating the building's occupants. See Chapters 4 and 5 for a more complete discussion of short-term measurements.

Table 3.8. Short-Term (1 time) Measurements

FLOOR AREA $A_f$

APPARENT THERMOSTAT SET TEMPERATURE $T_{set}$ (day, evening, night)

$$\left.\begin{array}{l}\text{Glazing area } A_{gl}\\ \text{Tilt angle}\\ \text{Azimuth}\\ \text{Average transmittance}\\ \text{Shading geometry}\end{array}\right\}\text{ for each orientation and subsystem}$$

Occupant heat gain rate $Q_{occ}$
internal gain factor for water heater and dryer $N_{dhw}$, $N_{dry}$
Heat capacity of air $(\rho c_p)_{air}$ (depends on elevation)
Volumetric flow rate for fans $q_{fan}$
Thermal conductivity of mass elements $K$
Heat capacity of mass elements $(\rho c_p)_{mass}$
Surface area of mass elements $A_m$
Node thickness for mass elements (depends on geometry, diffusivity)
Conduction heat loss coefficient
Infiltration rate

<u>OPTIONAL:</u>

Correction factors for movable insulation, heat exchanger, etc.
Exposed mass heat capacity

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# 4 MONITORING PLAN

The main purpose of this chapter is to serve as a checklist when preparing a monitoring plan. This will ensure that whatever should be thought of ahead of the the actual monitoring is thought of. To ease the understanding, certain repetitions of what has already been stated in the previous chapters have been allowed.

## 4.1 Monitoring objectives

The primary objective is to quantify the energy consumption and in particular the space heating energy contribution that is attributable to the passive solar features of a particular occupied building. In conventional space heating systems and most active solar systems, it is possible to measure the system "output", which is the contribution to the space heating load.

In passive solar systems, however, such direct measurement is extremely difficult. This is primarily due to the fact that most passive solar heating systems are integrated into the construction of buildings, that is, the building itself is the system. Directly monitoring such systems requires very extensive and expensive instrumentation, a great deal of time, and probably an unoccupied building. An alternate technique is therefore required.

The preceding chapter (3.0) has presented the basic mandatory level of monitoring and analysis required in IEA Task, this approach is summarized again here.

The best approach begins by examination of the heating season energy balance for a passive solar building. In its simplest form, this can be expressed as:

$$Q_{aux} + Q_{int} + Q_{solar} = Q_{loss} \qquad (1)$$

Where $Q_{aux}$ is the auxiliary heat delivered to meet the space heating requirements of the building.

$Q_{int}$ is the internal heat gain due to lighting, appliances, occupants, etc. which is applied to the space heating requirements of the building.

$Q_{solar}$ is the passive solar heat contribution toward meeting the space heating requirements of the building.

$Q_{loss}$ is the gross heat loss from the building.

Assuming it is easier to determine each of the other elements in the energy balance directly, the passive heating term can be determined subtractively. Rearranging the terms of equation 1:

$$Q_{loss} - Q_{aux} - Q_{int} = Q_{solar} \qquad (2)$$

The monitoring problem then becomes one of determining $Q_{loss}$, $Q_{aux}$, and $Q_{int}$ over time, with reasonable accuracy and at a reasonable cost. This can be done through a combination of:

1. continuous measurement of a limited number of variables.

2. short-term tests, physical measurements, engineering calculations regarding building and energy equipment characteristics which do not vary significantly over time.

3. adjustment (fine-tuning) of certain measured values through the selective use of predictive correlations for variables which are too difficult or expensive to monitor directly (i.e., infiltration and below-grade heat losses).

$Q_{loss}$ is fully defined as the gross envelope conduction and infiltration heat loss from the living zone of the house. In a number of passive solar performance calculations the term "building loss coefficient" (BLC) is used. Due to the widepsread use of this term it is important to note that it refers to a "net" loss as opposed to the "gross" loss we are using here. The difference is simply that the "net" loss excludes losses through the passive aperture and the "gross" loss includes them.

The "living zone" of the house is defined as the environmentally-conditioned, normally occupied space and any other spaces which are maintained within 2°C of the normally occupied space. In the simplest cases, $Q_{loss}$ can be calculated as:

$$Q_{loss} = \int (L_c + L_v)\ (T_{in} - T_{amb})\ dt \tag{3}$$

where $L_c$ is the living zone conduction heat loss coefficient.
$L_v$ is the living zone ventilation heat loss coefficient.
$T_{in}$ is the average temperature of the living zone.
$T_{amb}$ is the outside air temperature.

If the term $L_c$ is assumed to have a constant value, then capacitance effects in the thermal mass of the building will cause errors in the results of equation 3 over hourly, and in many cases, daily periods, depending upon the time constant (s) of the building. However, over the period of a month these should be insignificant in most cases. Due to this, and similar time-response effects in other factors, the energy balances will then be accurate only as monthly values.

The living zone conduction heat loss coefficient ($L_c$) if it is assumed to be constant, can be determined by a short-term test (see chapter 4.5.1).

The living zone ventilation heat loss coefficient ($L_v$) is taken as a constant average value if the infiltration is extremely small, or calculated as a variable from short-term test results. It may be adjusted as a function of both measured wind and temperature.

If there is significant below-grade heat loss, this loss should be calculated as a means of fine-tuning $Q_{loss}$.

$Q_{aux}$ is continuously monitored, as directly as possible. For evaluation accuracy, it is preferred that auxiliary heating, as well as all other energy use in the building, be electric. This will make direct and accurate monitoring of $Q_{aux}$ relatively simple and inexpensive.

$Q_{int}$ is continuously monitored as directly and completely as possible. As long as most internal gains are due to electrical use, monitoring is reasonably simple. However, several adjustments are usually required on a site-specific basis. Appliances such as water heaters and clothes dryers contribute only a portion of the energy they use to internal gains and must be adjusted accordingly. Heat contributed by occupants, energy used by a freezer in the garage, remote water pumps, etc., all require similar adjustments. Some of the these can be precisely monitored. Others are so small that estimating or calculating their heat contribution will not cause significant errors.

In addition to the measurements outlined above, building occupant(s) can provide additional information on building and system performance. A primary goal of passive solar systems is to provide desirable environmental conditions for persons, and in this respect, people can provide information, both general and detailed, on the success of a system. While this information may be more subjective than quantitative, it is an essential aspect of performance evaluation and may provide information which would be difficult to discover with any kind of instrumentation.

Non-instrumented evaluation also recognizes that there is an interaction between many passive solar systems and the building occupants. The system affects the occupants and the occupants affect the system. At a minimum, such interactions must be documented to put in context and better understand the measured performance of the building. Similarly, building occupancy profiles and activities will affect performance and must be documented to allow for meaningful performance analysis.

## 4.2 Monitoring restrictions and requirements

A methodology which would be applicable to all buildings in all situations would be prohibitively complex and expensive. In order to keep monitoring relatively accurate and inexpensive, the methodology described in this manual involves some restrictions on the occupants and the house.

While exceptions may be possible, and would certainly be desirable if shown to be reasonable within the context of the monitoring programme, the following list identifies recommended minimum requirements for an accurate and inexpensive monitoring programme:

1. No wood stove, coal stove or fireplace should be used during the monitoring period, as it cannot be accurately measured.
2. If gas or oil auxiliary heating system is used during the monitoring period, then it has to be shown that the particular equipment and monitoring technique used will not introduce unacceptable error into the energy balance.
3. The occupancy schedule must be reasonably regular and continuous on a monthly basis because occupancy is not measured continuously.
4. Access to maintain the data acquisition system every 1 to 3 weeks for a full year must be acceptable to the occupant(s).
5. Access for instrumentation, data recovery and short-term tests must be acceptable to the occupant(s).
6. Occupant operation of manually-operated system components should be assured and standardized.
7. There should be no uncontrolled ventilation (doors or windows left open) during the heating season unless due exclusively to solar overheating because it is not monitored.

8. Below-grade heat loss should not exceed 40% of the total heat loss for the building, on an annual basis. It will introduce too much uncertainty in results due to imprecision in calculation techniques.

9. Infiltration heat loss should not exceed 40% of the total heat loss for the building, on an annual basis. It will introduce too much uncertainty in results due to imprecision in calculation techniques.

10. Unless this methodology is being used to monitor a non-solar "reference" building, the expected passive solar heating contribution to load, estimated by simple calculation prior to monitoring, should be at least 15% of the load, on an annual basis. Otherwise, uncertainty in the load determination will cause too much uncertainty in the subtractive passive heating determination.

11. This methodology is considered appropriate only for residential buildings.

Additionally, there is a number of difficulties and constraints which should be considered in assessing a particular site for monitoring:

1. Electrical resistance heating is, by far, the preferred form of auxiliary heating from a monitoring standpoint. It can be measured directly with a high degree of accuracy. Within this category, baseboard heating systems offer the further advantage of having no distribution losses. Distribution heat losses which can occur with electric furnaces can lead to system efficiencies substantially below 100%, the precise determination of which can be another source of potential error in determination of performance results.

2. If an electric heat pump is used for auxiliary heating, it is necessary to make a number of additional continuous measurements and short-term tests or the uncertainty of results may be too great.

3. The efficiency of combustion systems will vary over time. Most significant will usually be variation with daily-cycle (part-load effects) and variation in fuel consumption rate (cyclical and drift). Combustion appliances which do not have independent, outdoor air supplies may also cause induced infiltration loads on the building which will cause unacceptable inaccuracy if not accounted for adequately. Accordingly, it is recommended that only extremely high efficiency combustion systems be monitored, that outside air supplies be used and should be carefully analyzed before monitoring to determine if uncertainties in monitoring will introduce excessive errors into the energy balance.

4. If a site is selected for monitoring prior to completion of construction, the instrumentation can be integrated into the building more easily. Wiring can be run inside walls and sensors can be less obtrusive. Electrical wiring circuits can be set up with consumption monitoring in mind. However, experience has shown that there are several problems which can arise in this situation. One is that the building, when complete, may not be appropriate for monitoring. For example, it may be too leaky, critical elements may never be completed, or it may otherwise perform poorly and be of no interest.

5. The data acquisition system installation will not normally, but could, affect liability insurance. Similarly, most instrumentation does not pose problems with regard to building codes or other safety regulations. These may, however, affect the choice of instruments and their installation.

6. An increase in energy costs which the occupants would not normally experience may be caused by the monitoring (for example, not burning any wood and using electricity instead during the monitoring period). There will also be significant inconvenience to the occupants and some limited "wear and tear" on the house. It is reasonable to compensate the occupants for these items.

7. Heating systems should be carefully assessed to see that they are not coupled to the ground (eg.: under-slab ducts). Such arrangements pose very difficult monitoring problems.

8. Complex control systems may be integral elements of a building and an intended subject of monitoring. It should be noted however, that such complex control systems may significantly complicate monitoring and that failures in such control systems can render passive system monitoring useless.

## 4.3 Occupant´s agreement

It is absolutely necessary to come to an agreement with the occupants of a house to be monitored, in order to ensure the cooperation from the occupants during the whole monitoring period. The agreement should be written in order to avoid any discussion during the monitoring phase, and should contain the paragraphs described below:

1st All monitoring equipment brought onto the premises by laboratory personnel, its agents, subcontractors or consultant, including data loggers, sensors, meters, wire, associated hardware, tables and storage equipment, shall remain the property of the laboratory unless otherwise noted in this agreement. Installation of this equipment may require brief interruption of electrical service to the structure.

2nd All monitoring equipment shall be removed from the premises by the laboratory no later than the last day of this agreement unless other written terms are prescribed under mutual consent of the owners and the laboratory. All systems will be returned to their operating condition and function which existed prior to implementation of the monitoring program.

3rd The laboratory shall have the right to publish, translate, reproduce, deliver, perform, use and dispose of in any manner, any and all data collected from the monitored house. All data shall be made available to the owners by the laboratory at no cost.

4th Laboratory personnel, its agents, subcontractors or consults, shall have the right of access to the described premises for the purpose of installing, removing, operating, maintaining and monitoring thermal performance monitoring equipment and to perform the various tasks as described in the monitoring programme. Access shall be during reasonable hours of the day and at other times as mutually agreed upon, for the full period of this agreement.

5th No equipment will be installed to monitor the use of woodburning stoves and fireplaces. The owners agree to discontinue the use of these devices for the period of this agreement in the interest of accuracy in data collection and analysis.

6th Adequate space shall be provided within the premises to locate all monitoring equipment, and existing electrical utilities will be provided at no additional charge to the laboratory by the owners to operate the monitoring equipment.

7th The owners agree to exercise reasonable care to prevent the loss of or damage to laboratory equipment installed on the premises.

8th The laboratory shall identify to the owners, its designated personnel and representatives with a need to enter the premises, and shall use its best efforts to minimize the impact of interference with the owner´s use of the premises, so far as is consistent with optimum monitoring procedures.

9th The laboratory shall, whenever the instrumentation involves unusual use or whenever wiring is to be modified which is covered by the Electrical Code, use a licensed electrician to perform the work required.

10th Any data which may result from this building monitoring are not necessarily comparable with any other data or analysis performed by others on the premises.

11th In consideration for participation in this passive solar monitoring program, the laboratory shall pay the owner a full and final compensation upon signing this agreement.

If the occupant is to read monitoring meters, mail cassettes, etc., this should be stated in the agreement.

## 4.4 Monitoring phases

The process of obtaining reliable performance data from newly built occupied houses is a time-consuming one. In most cases it is necessary to measure performance data for at least two years.

An organised monitoring and evaluation programme has several important phases. Three major divisions are:

a. A pre-monitoring diagnostic period (see chapter 4.5) to discover if the installed system components and the control equipment are functioning as designed and to determine certain values (one-time measurements). The monitoring equipment must be adequately checked and on-site calibration may have to be carried out. Allow 3-6 months for this phase.

b. An actual monitoring phase (see chapter 4.6) to find out how the total system functions in practice in comparison with its predicted behaviour, and to evaluate differences. A minimum of 18 months is required.

c. A post-monitoring diagnostic period to discover if the installed system components and the control equipment are still functioning properly. The time needed is 1-3 months.

## 4.5 One-time measurements and calculations

A number of short-term tests and calculations must be performed at the start of the monitoring programme to discover if the installed system components and the control equipment are functioning as designed and to determine certain values which will be taken as constants in the calculation of performance factors. Some of these may require retesting or recalculation at subsequent times during the monitoring period, either to verify them, determine them more precisely, or modify them for changing conditions. Typically this will involve:

1. a several-day test to experimentally determine building load coefficient(s) and auxiliary heating system efficiency (if not 100%)

2. a standard test of building airtightness using fan pressurization/depressurization

3. determination of parameters by one-time observation

4. short-term energy use or heat loss test for major energy equipment

5. several simple engineering calculations based on the above determinations.

Some of these results will be used only in site documentation. Several of these values will be used in the calculation of performance factors.

A full list of potential one-term measurements and calculations, is contained in table 4.1. Most of them are required for all buildings. Others, as identified in the table, are applicable only to some buildings.

Table 4.1 One-time measurements and calculations

X = measurement and/or calculation M = measurement

| Quantity | Required for all buildings | Required as appropriate | Units |
|---|---|---|---|
| Overall building conduction heat loss coefficient | M | | W/K |
| Wall and ceiling conduction heat loss coefficient | | X | W/K |
| Floor conduction heat loss coefficient | | X | W/K |
| Movable insulation heat loss correction factor | | X | W/K |
| Building airtightness | M | | ACH |
| Air infiltration | M | | $m^3/h$ |
| System efficiency of auxiliary heating system | M | | - |
| Water heater jacket heat loss rate and space heating | X | | W |
| Clothes dryer energy use rate and space heating | | X | W |
| Solar operating energy use rate | | X | W |
| Ventilation fan energy use rate | | X | W |
| Ventilation flow rate | M | | $m^3/h$ |
| Other internal heat gain adjustment | | X | W |
| Heat gain rate from occupants | X | | W |
| Apparent indoor set point temperature | X | | $^oC$ |
| Heated floor area | X | | $m^2$ |
| Heated volume of house | X | | $m^3$ |
| Solar aperture area | X | | $m^2$ |
| Building effective thermal mass capacitance | X | | MJ/K |

### 4.5.1 Conductive heat loss

An appropriate conductive heat loss coefficient for the entire building ($L_c$) has to be determined. If below-grade heat loss is not very significant (not more than 10% on an annual basis), then a single overall coefficient can be used.

A short-term test which can directly measure the heating load of a building is the "electric co-heating" technique.

Before starting an actual test, it is very useful to employ an infrared scanner inside the building. Using this techique the building envelope can be carefully studied in order to ascertain whether there are any additional heat losses due to heat sources (e.g. embedded pipes, heat emitters, etc), imperfections in the thermal insulation, thermal bridges, moisture in the fabric, air leakage, etc. In thermography i.e. using an infrared scanner the infrared radiation is detected, separated from other radiation (e.g. solar) and converted into differences in surface temperatures. Thermography can only be used if the temperature difference between inside and outside is at least 15 K and the surfaces to be studied are not exposed to direct solar radiation. Air leakage paths are easier to find if the entire building is depressurized during the thermography test (see chapter 4.5.3).

Based on experience in using "the electric co-heating" technique the following procedures are recommended:

1. For the duration of the test, it is necessary to maintain the average living zone at a substantially warmer temperature than the outdoor temperature. If the outdoor temperature does not vary significantly during the test period (not more than 5°C) then the minimum indoor-outdoor temperature difference required during the test is 15°C. Otherwise, an average temperature difference greater than 20°C will probably have to be maintained.

2. The living zone should be set up in the normal heating season configuration:

- sunspace, porch, garage, unheated basement and utility room doors closed

- if there is movable insulation, the test should be run twice; once with the insulation all open and once with it all closed. The ratio of the heat loss coefficient with the movable insulation in place (all closed) to the heat loss coefficient when the insulation is all open is defined as the "movable insulation heat loss correction factor". By continuously monitoring the status of the movable insulation, this factor will be used to modify the heat loss of the house over time. If the effect of movable insulation on the overall heat loss of a building is small (less than about 10%), the comparison of co-heating test results will probably not be a reasonable approach. In such cases, the heat loss correction factor will have to be calculated and the co-heating test should be run only with the movable insulation open.

3. Before the actual test, the building must reach close to steady-state conditions. This will require a period of between two days and one week, depending on the time constant of the building. The intent of this period is to reduce thermal storage effects in the building to a negligible level and to bring the building into a condition which approximates steady-state heat loss. To accomplish this, the building should be maintained at a constant temperature of at least 15°C (or 20°C, as noted above) above outdoors for the pre-conditioning period.

4. For the last day (or two days if the total glazing area is over 20% of the floor area), all principal glazing on the south, east and west sides of the building should be covered to prevent solar gain. Black polyethylene sheet stapled over the glazing on the outside works well. Alternately, reflective materials may be fitted tightly against the glazing from the inside. If the building is equipped with mechanical ventilation, this system should be turned off when the windows are covered and not turned on until the entire test is conducted. This will avoid the added inaccuracy caused by an estimation of ventilation heat losses.

5. The test should be conducted overnight on a night when the minimum indoor minus outdoor temperature conditions are met and the outdoor temperature is expected to be reasonably stable.

6. The test requires an accurate measurement of the heat input required to maintain a constant indoor temperature during the test. In most cases, this will require placing a number of portable electric heaters in the house. To ensure good mixing, these should be the type of heaters with built-in fans. Thermostats controlling the heaters should have a dead band (cut-off temperature minus cut-on temperature) of less than 2.0°C. Most of the thermostats built into portable heaters do not meet this requirement, so separate in-line thermostats must be added.

   While the number of heaters used will largely be governed by the number of rooms, the distribution by heating load should ideally be such that the heater duty cycle will be 60 to 80%. Oversizing of the heaters for the particular load they will be meeting during the co-heating test should be avoided, as it makes short-term temperature control much more difficult. A good way to avoid this is to use heaters with a selectable variable output.

7. The portable heaters should be placed near outside walls with the direction of their heat flow towards the exterior wall. Care should be taken to see that the flow from the heaters is not directed toward temperature sensors or thermostats. The portable heaters should be spread around the house evenly.

   Once all the heaters have been located, the total current draw when all the heaters are on should be checked to see if it overloads any circuits. When checking circuit capacity, remember to account for any possible electricity use from appliances and lighting which could occur during the test; if one fuse has gone you could have to do the test all over again.

8. In the case of houses with basements which are not part of the living zone, but are partially heated by the furnace or boiler jacket, or by duct or piping losses, it may take several days to stabilize the house. Once the furnace or boiler is turned off, the basement temperature will drop and the increased loss to the basement from the living zone will have to be met by the portable electric heaters. In such cases, the test period will not be able to be started until the heat loss to the basement has restabilized.

9. Both for the pre-conditioning period and during the test, all indoor temperatures, outdoor temperatures and purchased energy should be monitored by the installed data acquisition system.

10. The electric heaters and thermostats should be placed in their locations at least eight hours before the night of the expected co-heating test period. After the thermostats have had several hours to stabilize, the portable heaters should be plugged in and the normal (auxiliary) heating system turned off at the thermostat(s). Then turn up the thermostat on each heater just to the point at which it activates. Observe individual room temperatures using the data acquisition system. Adjust the individual heater thermostats. The target is to smoothly transfer the heating load from the auxiliary system used during the pre-conditioning period to the co-heaters without causing any fluctuations in the temperatures maintained in each room.

11. During the co-heating test period, the heat provided to meet the space heating requirements of the building has to be measured as accurately as possible. The solar heat contribution is eliminated and all auxiliary heating is shifted to the light and appliance circuits. In terms of the energy balance we are left with $Q_{int} = Q_{loss}$.

    Heat provided from the portable electric heaters can be measured with a high degree of accuracy, but the other components of $Q_{int}$ are potential sources of error to varying degrees. To make the results of the co-heating test as accurate as possible, steps should be taken to minimize these errors. Ideally, all other sources of internal gain should be eliminated, in which case the total consumption of electricity = $Q_{loss}$.

12. To separate the infiltration component from the conductive component of heat loss for the test interval, infiltration should be monitored continuously during the test.

    If a predictive model is used, wind velocity must be monitored for the duration of the test period.

13. Having made all the preparations above, the test period can usually be conducted over a one-night period. Examine the temperatures to determine when reasonable stability has been reached. This will be the start of the co-heating test period, which must then be followed by at least six hours (up to twelve are preferred) where conditions remain reasonably stable. This stability can be quantified in the following terms:

- The standard deviation of the hourly average inside temperature should be less than 0.1°C.

- The outdoor temperature should not change at a rate which exceeds 0.6°C per hour.

The test may have to be continued or repeated until the above conditions are attained.

14. Using the data from the total test period when stability was maintained, the conduction heat loss coefficient can now be determined:

$$L_c = |\Delta Q_{int}/(\Delta t\ \Delta T)| - L_i$$

| | |
|---|---|
| where $L_c$ | is the conduction component of heat loss |
| $\Delta Q_{int}$ | is the change in the accumulated value of internal heating over the test period (MJ) |
| $\Delta t$ | is the length of the test interval (hrs) |
| $\Delta T$ | is the time-averaged value of $(T_i - T_o)$ for the test period |

$L_i$ is the infiltration component of heat loss

For buildings where heat loss is largely a function of the temperature difference between the inside and outside air, an overall conductive heat loss coefficient ($L_c$) for the living zone can be determined using the electric co-heating. The level of this dependence can be quantified by calculating the fraction of the heating season value of living-zone heat loss which is lost below grade. If below-grade loss is less than 10% of the annual heat loss, the single-conductance model of heat loss will usually be required. The model to be used will depend on the configuration, construction and use of the basement.

### 4.5.2 Ventilation heat loss

Ventilation (i.e. mechanical and natural) is very often a significant variable in houses. It usually represents a major portion of the total heating load, due to the low conduction heat losses found in in most passive and hybrid solar heated homes. With the subtractive energy balance methodology, any error in ventilation determination will have a direct impact on primary performance results because the resultant heating load error will be credited to or subtracted from the solar heating contribution.

Infiltration is defined as the uncontrolled air leakage of outside air into the heated "living zone" of a house. It results from the differences of pressure across the building envelope caused by wind and the inside-to-outside temperature difference. It will vary with the magnitude of these pressures and the size and location of openings in the building envelope.

The level and type of ventilation determination necessary for a particular site will vary as follows:

- When a co-heating test is performed, infiltration must be determined over the test period.

- If there is interest in analyzing hourly or daily data on energy flows in the monitoring house, it will be useful to employ a treatment for infiltration which measures or estimates it at a corresponding hourly or daily level.

- If only monthly analysis is of interest, ventilation can be measured or estimated as a monthly average.

- The level of sophistication used to determine ventilation for a particular site will depend on the magnitude of ventilation losses relative to total heat loss, the relative sensitivity of the specific building to the two driving forces of infiltration (wind and temperature difference) and the site-specific variability of the two driving forces over time.

There are several techniques for continuous monitoring of infiltration. High cost and inconvenience prevent their use during the whole monitoring phase.

An estimation technique appears to be the best approach. This will mix estimated values with measured values, but the "adjustment" of overall heat loss ($Q_{loss}$) by an estimated infiltration value can improve accuracy over the use of a single heat loss coefficient which combines conduction and infiltration, implicitly assuming the infiltration rate to be constant. Unfortunately, the estimation of infiltration for individual buildings is very difficult.

### 4.5.3 Airtightness testing

A test of building airtightness by fan pressurization/depressurization is required for every house to quantify airtightness as part of the building documentation. This test is preferably combined with thermography to find the air leakage paths (see chapter 4.5.1).

A standard test, as described by e.g. the Swedish Standard, should be conducted (8). In this test, the house is pressurized and depressurized at a number of pressure differences between 20 Pa and

55 Pa. As a measure of the airtightness of the house the average value of the air leakage at ±50 Pa is used:

$$ACH_{50} = C\ (50^{n})\ /\ V_h$$

where $ACH_{50}$ is the air change rate at 50 Pa (air changes per hour)

$V_h$ is the volume of the heated "living zone" of the house ($m^3$)

and C and n are constants determined from the test.

To achieve the most accurate results, it is recommended that pressurization/depressurization testing be conducted at a time when the wind velocity at ceiling height is less than 10 m/s.

If the house has an attached sunspace, the following procedure is recommended:

1. If the sunspace is defined as part of the living space (maintained within 2°C of the primary living zone), then it is recommended that the two areas be treated as a single zone for infiltration purposes. This means they will be assumed to have free flow of air between them, the pressurization/depressurization test should be done on the whole building, and the air leakage will be the total air leakage to the outside from both spaces.

2. If the sunspace is closed off from the living space all of the time, with no doors, windows or vents ever left open, it is <u>not</u> defined as part of the living space and should be treated as outside for infiltration purposes. Accordingly, the air leakage of the building will be taken to be the total air leakage to outside plus the air leakage of the wall to the sunspace.

3. If the sunspace is not defined as part of the living space, but sometimes is open to the living space, the air leakage of the house should be taken as a variable. The pressurization/depressurization test of the <u>house</u> should be done twice, once with the sunspace closed off and once with normal openings between the spaces. If infiltration is continuously estimated, the status of the doors or windows may then be continuously monitored and the appropriate air leakage selected for each interval.

### 4.5.4 Air infiltration testing

There are three different tracer gas techniques for monitoring infiltration; the decay technique, the constant flow technique and the constant concentration technique (8).

With the first technique the decay of a tracer gas is monitored, and whole house ventilation rates can be measured. With the second one a constant tracer gas flow is supplied. This method should preferably be used for measuring the air flow in a ventilation duct, but can also be used for monitoring of long-term average ventilation rates. The last technique maintains a constant concentration of a tracer gas in a house. The supply of fresh air to individual rooms can be monitored simultaneously and continuously.

An automated, continuous tracer gas testing technique is recommended. A low-cost approach is the system (AIMS) using passive emitters (constant flow) and absorbers which has been developed in the United States. (Russel Dietz, Brookhaven National Laboratory). AIMS has been used in a number of field applications, and is now available for widespread use. An advantage of this system is that the elements can be changed once a month, thus determining a monthly averaged value of infiltration, see ref. 5 and 6.

There is one simple technique for short-term measurements of infiltration, the bag sample technique. It has been used extensively in previous monitoring but results are not yet conclusive as to its usefulness.

In this test a quantity of a tracer gas is injected using prefilled syringes into the house in a manner to ensure that it is well mixed. At least three mixed samples of the indoor air using sample bags are then taken at intervals of 30 to 60 minutes after the initial injection. The concentration of each sample is determined in a laboratory and the air exchange rate found by fitting the best exponential curve to the concentration decay data.

### 4.5.5 Air infiltration predictions

As discussed above, infiltration in a house will vary as a function of the two driving forces, wind and temperature difference. A wide variety of modelling techniques has been developed to cope with the problems of estimating air infiltration rates in buildings, with no single method being universally appropriate (7). In general, methods can be divided into two categories. The first comprises empirical regression approaches which tend to be only loosely based on the physical principles of air flow. The second category covers models which are based on a much more fundamental approach involving the solution of the equations of flow for air movement through openings in the fabric of the building. While empirical models are normally straightforward to use, they either tend to be unreliable or to have a limited field of application. On the other hand, theoretical models have a potentially unrestricted range of applicability but are often demanding in terms of both data and computer execution time. Despite the theoretical limitations of the former approach, it has proved very popular, especially to perform rudimentary design calculations. The latter technique, however, is essential for a more detailed appraisal of the air infiltration process.

Many uncertainties are involved in these predictions, and for practical purposes it is recommended to measure the air infiltration rate (for a typical winter day) by the tracer gas method. Based on these results a constant air exchange rate for the building may be assumed to be used as input for the building simulation model, i.e. if the air infiltration rate is very low. Otherwise an air infiltration model should be used.

An infiltration model developed at Lawrence Berkeley Laboratory is included as Appendix 3.

### 4.5.6 Heating system efficiency

The only determination which may need to be made, given an electric auxiliary heating system, is the <u>system</u> efficiency. While the electrical energy conversion to heat can be taken to be 100%, the system efficiency will very often be less than 100%. If the heating equipment (e.g.: furnace) or any distribution (e.g.: ducts) are outside the defined "living zone", jacket and distribution losses will result in a system efficiency of less than 100%. Radiant ceiling panels may also have less than 100% delivery efficiency due to back losses.

To determine system efficiency, an extension of the electric co-heating test should be used. This can be performed immediately after the heat loss co-heating test period if there is enough time left where the specified test conditions can be maintained. Otherwise, it can take place over the following night. If the test is done on the following night, the window covers should be set back up during the day, removed in the evening and all other guidelines listed for the heat loss co-heating tests should be followed. If there was a necessary waiting period for stabilization after switching to the portable heaters for the co-heating test, there will usually be a similar stabilization period when the switch back to the normal system is made.

The system efficiency test simply involves switching the load from the portable electric heaters back to the normal auxiliary heating system of the house to maintain the same average indoor temperatur as used in the heat loss test, under close to steady-state conditions.

### 4.5.7 Domestic hot water system

The stand-by losses can be determined by either (1) calculation, based on the size, type and insulation of the water heater, or (2) measurement of energy consumption over a period (typically about 8 hours) when there is no hot water use. If the water heater is located outside the heated "living Zone", and is reasonably well insulated, the calculation method will be adequate. If the measurement technique is used, the length of test required is determined by the time it takes to acquire data from one or more full cycles of operation (heater off, heater on, heater off). It may be useful to average the data from tests on several nights to make this calculation.

If a fuel-burning water heater is present, the preferred monitoring technique is continuous direct measurement with a pulse initiating meter. If this is not possible, a determination must be made of the fuel consumption rate. For a gas water heater, a short-term test should be conducted as follows:

1. Turn the water heater off manually and read the household gas meter.

2. Turn the water heater on manually and leave it on long enough to use at least 0.3 $m^3$ of gas. This will ensure that the effects of the pilot light consumption are insignificant. Monitor the elapsed time in minutes and seconds.

3. Turn off the water heater. Read the elapsed time and consumption.

### 4.5.8 Clothes dryer

The impact of a clothes dryer on the building energy balance is highly variable and site-specific, depending on the frequency and duration of its usage, as well as its location and venting.

While it is preferred that the clothes dryer energy use rate be monitored continuously as a variable, if the dryer energy use rate is always the same when it is "on", its status may be continuously monitored. In this case, the energy use rate when the dryer is on should be measured in a short-term test.

### 4.5.9 Mechanical ventilation

Devices to be monitored include:

- sunspace vent fans to outdoors
- living space exhaust fans
- living space supply fans

- vent fans from sunspace to living zone
- fans from sunspace to storage bed
- air-to-air heat exchanger in ventilation systems

In most cases these are devices which can be monitored continuously for their status (on/off, or high/low/off, etc.). The operating time, determined from monitoring status, can be multiplied by an air flow rate to yield total ventilation flow, and by an energy use rate to yield total energy consumption.

The forced ventilation flow rate ($m^3/hr$) between inside and outside which occurs when a given ventilation fan is operated, should be determined by a one-time direct measurement, unless it is used very infrequently, in which case it may be calculated from the fan specifications. It should be noted that wind pressure can cause significant deviation in flow rates from those which would occur with no wind.

If there is such forced ventilation, without heat recovery, the heat loss $Q_{loss}$ should be incremented by:

$$q_{vent} = \rho c_p (T_i - T_o) t_{vent} dt$$

where $q_{vent}$ is ventilation flow rate
$\rho$ is the average density of air at the location of the site
$c_p$ is the average specific heat of air at the location of the site
$t_{vent}$ is the fractional ventilation operating time

Where there is heat recovery from vented air, such as is found with typical residential air-to-air heat exchangers, the adjustment is different and several techniques may be used.

### 4.5.10 Solar operating energy

This quantity is relevant only when there is a fan, blower or pump used in the operation of the solar heating system (including indoor air circulation devices). Multiple units can be calculated as one, provided that they always operate in parallel. In the case of multiple units which do not operate in parallel, it will probably be easier to monitor combined energy use of all units as a continuous measurement. As long as expected monthly consumption is anticipated to be below 100 kWh, this rate can be taken off the nameplate or from manufacturers specifications on the device. If there are several devices separately monitored in this fashion, they will each have their own energy use rate.

### 4.5.11 Ventilation fan energy

This is the energy use rate of any fan(s) or blower(s) used to ventilate the space to the outdoors i.e. air-to-air heat exchangers and exhaust fans.

The same guidance as provided above for multiple units and/or multiple-speed units applies here. Again, the rated consumption of the units can be used if the monthly total is anticipated to be less than 100 kWh.

### 4.5.12 Other internal heat gain

This is a catch-all term for other adjustments which may be necessary in the proper calculation of internal heat gains. It may be either a constant rate at all times or a rate which is added in only some of the time. If it is not constant, it can be added as a function of a status measurement, at certain times of the day or under certain conditions which are continuously monitored. It can be either a positive or negative value. The use of this factor for appliances which do not contribute 100% or their energy input as heat gain will not be necessary if they have been separated out in the wiring for continuous monitoring. Some examples are:

- a dishwasher with a built-in water heater on a normal lights and appliances circuit (negative value)

- major shop tools in an unheated basement or garage which are on an indoor lights and appliances circuit (negative value, but only a % based on the relative temperature of the spaces)

- heat gains or losses from pipes, tanks and/or pumps of a solar water heating system (positive value).

### 4.5.13 Heat gain from occupants

This quantity should be calculated as an average daily value based on the number of people in the house at different times, their typical activities, and the information below.

| Activity | Average heat gain (W) |
|---|---|
| sleeping | 55 |
| seated, quiet | 75 |
| seated, eating or light work | 120 |
| light housework | 160 |
| heavy housework or other activities with moderate movement | 230 |

### 4.5.14 Apparent indoor setpoint temperature

This is the temperature at which the occupants will maintain the primary living space by auxiliary heating in the absence of solar heating. It can be determined, after some data collection has taken place, by examination of the recorded temperatures for the primary living space. Use only data from cloudy periods during the heating season, when the primary living areas were occupied. If this temperature is thermostatically controlled, this will be the temperature maintained by the thermostat set-point. It is the temperature to which these particular occupants feel it is valuable to heat for adequate comfort. If the temperature varies during normal occupancy, this should be a time-weighted average value of the monitored temperatures. This temperature provides important information on one aspect of the interaction between the occupants and building performance.

## 4.6 Continuous measurements

The instrumentation plan for a particular monitoring site must be carefully developed. A decision has to be made as to which quantities have to be monitored continuously and which can be determined using one-time measurements and calculations. A useful process can be:

1. Work backwards from the general energy balance equation to identify all the site-specific quantities which may vary over time and are needed in order to calculate the required performance factors. Use this manual as a guide for identifying these variables, but look for the unusual that we could not anticipate.

2. Using the definitions found in this manual:

   - Identify the conditioned "living zone" of the building.

   - Identify the "primary zone" (in many cases, the same as the "living zone").

   - Identify the "secondary zone" (a sunspace if there is one, otherwise any other space of interest which may have comfort conditions different from the primary zone).

   - If there is a basement or crawl space, determine whether it is heated, unheated or partially heated (by jacket, duct, or piping losses).

   - Determine whether there is significant spatial variation in thermal conditions within each zone.

3. Using the above guidance to determine the number of temperature measurements necessary to continuously calculate the heat loss.

4. Determine whether, for the anticipated monitoring period, indoor comfort conditions are reasonably approximated by drybulb temperature alone. For the heating season, this is a reasonable assumption unless there is (1) a relatively large-aperture direct gain system which would cause the occupants to be in direct sunlight a significant amount of the time, or (2) indoor humidity levels are unusually high (i.e. over 75% R.H.). For these two conditions, as for the cooling season, a more careful examination of the significance of radiant temperature, humidity and air movement may be necessary.

5. Identify all the auxiliary heating sources in the building and determine whether any of them are outside the "living zone". Determine the quantity and type of measurements necessary to continuously monitor the auxiliary heating or cooling.

6. Identify all the other energy uses in the building. Determine which are inside the "living zone". Determine the quantity and type of measurements necessary to continuously monitor the internal heating.

In Chapter 5 required and optional continuous measurements are presented and discussed.

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## 4.7 Monitoring checklist

| | | see chapter |
|---|---|---|
| 1. | Define monitoring objectives | 4.1 |
| 2. | Define monitoring restrictions and requirements | 4.2 |
| 3. | Make an agreement with the occupants | 4.3 |
| 4. | Decide upon necessary one-time measurements and calculations | 4.5 |
| 5. | Plan the continuous measurements | 4.6 |
| 6. | Document the site and the monitoring system | 7 |
| 7. | Instrument the house | 5.3 |
| 8. | Check the monitoring system | 5.5 |
| 9. | Continuously check the monitoring system | 6.4 |
| 10. | Continuously evaluate heat balances for the house | 6.3 |

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## 5 DATA AND INSTRUMENTATION REQUIREMENTS

When considering the variables that should be monitored continuously in a given system, it is important to concentrate on the main energy flows and the energy transfer processes that occur (see also Chapter 3 and 4 ). Detailed knowledge of these flows is the ultimate objective of any monitoring programme, and it is with reference to these that the measuring points must be selected. Individual system layout should be considered after this stage, to establish the best physical position to locate the sensors.

A list of required and optional continuous measurements are presented in Table 5.1. To allow for reasonable flexibility and tailoring of each site, this should be approached as a list of "variables" to be determined as part of the monitoring, rather than a list of sensors for data acquisition. The list should not be considered as a complete list as individual systems and special requirements may require further variables.

| | Quantity | Designation | Required or optional | Typical sensor |
|---|---|---|---|---|
| Outdoor environment | Solar radiation | $I_h$ | Required | pyranometer |
| | Wind velocity | W | Optional | anemometer |
| | Outdoor temperature | $T_o$ | Required | temperature sensor |
| Indoor environment | Primary zone temperature | $T_1$ | Required | temperature sensor |
| | Secondary zone temperature | $T_2$ | Required | temperature sensor |
| | Other indoor temperature(s) | $T_3$, $T_4$,... | As necessary | temperature sensor |
| | Basement temperature | $T_b$ | Required | temperature sensor |
| | Radiant temperature | $T_r$ | Optional | black globe temperature sensor |
| | Relative humidity | RH | Optional | humidity sensor |
| Energy use | Total electricity use | $E_{elec}$ | Required | pulse-initiating kWh meter |
| | Purchased energy for auxiliary heating | $E_{auxh}$ | Required | pulse-initiating kWh meter |

Table 5.1. Continuous measurements.

| | Quantity | Designation | Required or optional | Typical sensor |
|---|---|---|---|---|
| Energy use | Purchased energy for auxiliary heating | $E_{auxh}$ | Required | pulse-initiating gas meter<br>pulse-initiating oil flow meter |
| | Purchased energy for lights & appliances | $E_a$ | Required | pulse-initiating kWh meter |
| | Purchased energy for water heating | $E_w$ | Required | see auxiliary heating |
| | Purchased energy for clothes dryer | $E_d$ | As necessary | status relay |
| | Purchased energy for other uses | $E_{other}$ | As necessary | kWh transducer |
| | Purchased energy for auxiliary cooling | $E_{auxc}$ | As necessary | kWh transducer |
| | Operating energy | $E_{op}$ | As necessary | status relay |
| System operation | Movable insulation operating time | $t_{mi}$ | As necessary | status switch |
| | Control element operating time | $t_{s1}-t_{s8}$. | Optional | status relay or switch |
| | Primary storage temperature | $T_{ps}$ | Optional | temperature sensor |
| | Secondary storage temperature | $T_{ss}$ | Optional | temperature sensor |

Table 5.1: Continuous measurements (continued).

When system type and scematic sub-systems have been defined, it is relatively straightforward to determine the number and approximate location of the measuring points needed.

In general, measuring instruments must be simple, reliable and kept to the minimum number consistent with the analytical requirements. The instruments selected should be those which best meet the detailed requirements of accuracy, compatibility with other equipment, and reliability.

The following is a checklist of questions to be asked when selecting or comparing available instruments.

1. Does the instrument cover the required range of measurement?
2. Does it cause any significant change in the performance of the loop where mesurement takes place (For example, the pressure drop caused by a flow sensor should be as small as possible).
3. Does it give a large output, sensitive to the measured value?
4. Can the output be easily measured and registered?
5. Is it compatible with the data acquisition system?
6. Is the response speed satisfactory?
7. Does it fall within the required range of accuracy?
8. Is the resolution satisfactory?
9. Is it reliable?
10. Does it have calibration certificate?
11. Can it be suitably maintained?
12. Can it be easily installed?
13. Can it easily be checked on site?

Finally, any instrument selected should not (if possible) need modification outside the supplier's works, other than calibration checks, to achieve the necessary accuracy and performance.

## 5.1 Overall accuracy requirements

Some recommended maximum limits of measurement uncertainty are given in the table below. These limits of uncertainty include all sources of uncertainty such as instrumentation calibration, resolution and installation effects. A reduced level might be acceptable in a programme with few sensors in each system. This could be the case e.g. in a survey of system operation (uncertainty in the order of 1°C).

| Element | Maximum limits of uncertainty |
|---|---|
| Overall system uncertainty for energy measurements | 10 % |
| Solar radiation | 5 % |
| Wind | 0.5 m/s |
| Liquid temperature, direct | 0.3 °C |
| differential | 0.1°C for $\Delta T < 10$ °C |
| differential | 1% for $\Delta T \geq 10$ °C |
| Air temperature, direct | 0,5 K |
| differential | 0,5 K $\Delta T < 10$ K |
| differential | 2% $\Delta T \geq 10$ K |
| Humidity | 5 % (10 % < R.H. < 90 %) |
| Liquid flow rate | 2 % |
| Air flow rate | 5 % |
| Electrical consumption | 2 % |
| Non-electric auxiliary heating | 5 % |

## 5.2 Continuous measurements

### 5.2.1 Outdoor environment

Solar Radiation ($I_h$) - While solar radiation is not used in the energy balance determination, it is a required measurement due to the following uses:

1. It provides a basis for normalizing performance results to long-term average solar radiation values.

2. It provides a basis for extrapolation of results to other locations with different environmental conditions.

3. It provides a basis for identification of the relative sunniness of different performance intervals.

4. It provides the input for a "trial energy balance" where the subtractively determined passive solar heating is compared to a calculation of potential heat gain through the aperture.

5. It provides a necessary input for running computer models.

A solar radiation measurement in the plane of collection would be best suited to the fourth of these uses, but the first, second and fifth are best served by a horizontal measurement. Accordingly, a single, continuous measurement of total solar radiation incident on a horizontal plane is recommended for all sites.

Wind Velocity (W) - The primary reason for measuring wind velocity is if it is used in the computation of the infiltration component of heat loss. If wind measurement is to be used, but only to adjust the monthly infiltration value, it is possible to use data from a nearby, off-site measurement location. Then, the relative terrain and shielding factors for the site and wind monitoring location can be used in a model (such as the LBL model) to predict average wind velocity at the site. Alternately, if a number of tracer gas sample tests are done under a variety of wind conditions, it may be possible to find a correlation between the remotely measured wind velocity and the wind-driven component of infiltration.

An on-site measurement of wind velocity avoids the problem. If wind measurement is made on site, and used in an infiltration model, similar options exist for adjustment as for the off-site measurement. The best approach is probably to locate the anemometer in any location that will be insensitive to wind direction and use the tracer-gas technique to find a correlation between the measured wind velocity and the wind-driven component of infiltration.

Outdoor Temperature ($T_0$) - Outdoor, dry-bulb temperature is a required measurement for all sites.

### 5.2.2 Indoor environment

Primary Zone Temperature ($T_1$) - The dry-bulb temperature of the primary zone is required measurement for all sites. This will normally be the area of the building which is primarily occupied during the day (living room, dining room, kitchen), but must be a single thermal zone. If temperatures in various parts of this zone are reasonably uniform, or can be expected to vary in parallel (and with similar magnitude), a single average temperature measurement location for the zone can be identified. In some cases, multiple temperature measurements may be required and a volumetrically space-weighted average of the two should be taken as the zone temperature.

Secondary Zone Temperature ($T_2$) - If there is a secondary temperature zone in the building its dry-bulb temperature will be a required measurement. If there is a sunspace, greenhouse or buffer space which is sometimes occupied, this will be defined as the secondary zone. If these spaces do not exist, the secondary zone in the building (after the primary zone and other than the basement) will typically be bedrooms, a formal living or dining room, or unused rooms. As for the primary zone, in most cases a single temperature measurement can be made to give the average for this zone, but in certain cases additional sensors may be required.

Basement Temperature ($T_b$) - The average dry-bulb temperature of a basement will be required if a building has a basement thermally distinct from the primary living area. If there is more than one thermal zone in the basement, multiple measurements may be required and space-weighted to yield the average.

Radiant Temperature ($T_r$) - This measurement is needed only if radiant temperature has a significant impact on thermal comfort in a normally occupied area of the living zone. While it may be difficult to make this determination without measurement, a good indicator is the amount of direct gain glazing. It will typically have to be with high U-values or over 20 % of the floor area for radiant temperature to be significant. Another rule of thumb which could be used is: if the occupants will normally be in a space where they are close to large glazing areas more than one hour per day, measure radiant temperature in that zone. The standard technique for monitoring this variable will be a measurement of black globe temperature.

Relative Humidity (RH) - This measurement is needed only if humidity has a significant impact on thermal comfort in the primary living zone and it varies significantly over short periods of time (less than one month). This too may be difficult to determine prior to actually measuring it and making comfort calculations, however, some guidance can be given. In general, humidity will not require continuous monitoring during the heating season in most cold climates. Levels of moisture in the air are generally low or too low and do not vary significantly.

During the summer, humidity can have a significant impact on indoor comfort conditions in certain locations and may merit continuous monitoring.

### 5.2.3 Energy use

Total Electricity Use ($E_{elec}$) - Total electricity use is a required continuous measurement for all buildings, both to compute total purchased energy and peak electrical demand performance factors. The preferred method for this measurement is a pulse-initiating watt hour meter, either replacing or in series with the utility meter. If all of the uses of this electricity are submetered Watt-hour transducers may be used for these measurements, but they do not offer the redundancy which can be obtained through manual reading of meters, either for confirmation of automatically acquired data or reconstruction of performance factors when there is a breakdown in the data acquisition system. It should be noted that, for many sites, if carefully planned submetering is done, manual readings can be used to provide redundancy in calculation of the primary monthly balance.

Purchased Energy Auxiliary Heating ($E_{auxh}$) This quantity is critical to the calculation of the energy balance for the building and errors due to any uncertainty in system efficiency will produce equal errors in the determination of passive heating and savings.

To monitor the purchased energy for electric resistance heating, the preferred technique is to use a pulse-initiating electric submeter or transducer which monitors all electric heating elements. If this is difficult or not possible, continuous voltage and current monitoring can be used instead. For such current measurements, either all heaters can be monitored by one current sensor, or sensors can be used on each circuit.

To monitor the purchased energy for gas heating a standard gas meter can be used. The meter should be equipped with a pulse-initiating sensor, e.g. an optical read-out to the dial mechanism. In the case of an oil-fired furnace the oil flow can be monitored continuously using a remote sensing positive displacement meter, or by monitoring burner-time. The heat supplied to the building should be monitored with a heat meter i.e. the volume or the flow of the heat transport medium and the temperature difference are integrated.

Purchased Energy for Lights and Appliances ($E_a$) - This continuous measurement is required for all buildings. The preferred basic monitoring technique is the use of a pulse-initiating electric submeter or transducer which would monitor all electricity use not for auxiliary space heating or water heating. If total auxiliary heating and water heating electrical use are all monitored with electrical submeters, it is equally acceptable to determine this quantity by subtracting auxiliary and water heating from the total. If submetering is not possible, continuous current and voltage measurements can be substituted, using one or more current sensors.

It should be noted here that in order to determine internal heat gains, it is necessary that monitoring be done in such a manner as to permit separation of purchased energy for lights and appliances which contribute to internal heat gains from those which do not. In most cases, this separation will be based on whether the energy use is inside or outside the heated space, but in some cases it will also depend on the fraction of energy consumed which can be taken as an internal heat gain.

Each piece of energy using equipment outside the heated space and any pieces of equipment inside the heated space which do not necessarily contribute their input energy as internal gains should be listed, examined and dealt with appropriately in the monitoring program. Among the items which should be considered are:

- water pumps
- outdoor lighting and appliances
- automobile engine heaters
- hobby and shop equipment

Purchased Energy for Water Heating ($E_W$) - This continuous measurement is required for all buildings. The preferred monitoring technique is a pulse-initiating meter or transducer. If this is not possible, an electric water heater may be monitored by continuou s current and voltage monitoring. A gas water heater may alternately be monitored based on a short-term measurement of fuel consumption rate and continuous monitoring of burner status.

Operating Energy ($E_{op}$) - This continuous measurement is required for all buildings where there is operating energy consumption. It refers to the electrical energy used in operation of the solar heating system. Typically this will be one or more fans, blowers or pumps. These devices may be used to transport solar heat into or out of storage, or to circulate or destratify air. Each device can be continually monitored for status or multiple units can be monitored by continuous current and voltage monitoring.

### 5.2.4 System operation

Movable Insulation Operating Time ($t_{mi}$) - Continuous monitoring of this variable is required in any building with a movable insulation system that affects the building heat loss. It will be very complex if the insulation is operated variably instead of in two modes: all open or all closed. Accordingly, it is important to secure the cooperation of the occupant(s) to ensure that the movable insulation is deployed only in the all open or all closed positions during the period of building monitoring. Then, status of the movable insulation can easily be continuously monitored with a switch.

Control Element Operating Time ($t(_{s1}$ to $t_{s8}$) - In most cases, continuous status measurement will be sufficient. Elements which should be monitored, if present, include:

- doors or vents between sunspaces and living spaces
- dampers in thermosyphon collector or mass storage walls
- movable shading devices
- fans or dampers in air moving systems

Primary Storage Temperature ($T_{ps}$) - If the building has any significant mass which acts as thermal storage, at least one temperature measurement of this mass will be useful. Mass may be assumed to be significant if it is an intentional passive system element (mass wall, water tubes, rock bed, etc.) or if the house construction itself is of heavy weight (thermal capacity greater than 0.1 MJ/$^{o}$K per $m^2$ floor area). The "primary" thermal mass is defined as the primary mass which is actually available to store solar heat gains. The measurement which should be made is one which will indicate the average temperature of the thermal storage mass which is communicating with the living space of the building (eg.: near the surface of a mass storage wall or floor).

Secondary Storage Temperature ($T_{SS}$) - If the building has more than one thermally distinct and significant mass, a second mass temperature may usefully be monitored, following the same guidelines as for the primary mass temperature.

Other Temperature

The measured temperature of a buffer area like an attached garage can be used to determine the impact that any appliance heat gains in that space will have on $Q_{int}$. Similarly, a temperature near the control element of a device like a greenhouse vent fan can indicate if it is working properly.

## 5.3 Installation

### 5.3.1 Horizontal solar radiation

The primary uses of monitored solar radiation data require a standard measurement of available solar radiation on the horizontal plane at the monitoring site. These end uses of data require an on-site measurement analoguous to standard meteorological measurements made of total (global) solar radiation incident on a horizontal surface.

Location of the pyranometer to measure total horizontal solar radiation is primarily determined by (1) exposure and (2) convenience for installation and maintenance.

The pyranometer should be located so that its hemispherical view of the sky is as unobstructed as possible. Particular obstructions to watch for are trees, nearby buildings, chimneys, and TV antennas.

In some situations, care must also be taken to avoid reflected radiation from objects, buildings or the ground surface.

Particularly in the case of pyranometers with a high temperature response, a mounting location should be chosen which will not be influenced by local heat generation sources (e g: directly over a solar absorbing surface) and mounting should allow free passage of air around the sensor. Many pyranometers are also asymmetric (they have an azimuth error). Accordingly, unless otherwise specified, the sensor should be oriented so that the output wires are on the north side of the sensor.

The second major installation consideration is convenience for installation and maintenance. Remember that the sensor will need to be cleaned off at least once a month.

Measured horizontal radiation can be used as the basis for the calculation of appropriate radiation value to be used in computer models, e.g. direct normal radiation and diffuse radiation. However, a more accurate calculation of these values can be made if a second radiation measurement is taken. This could be diffuse horizontal radiation or total radiation on an inclined surface.

### 5.3.2 Wind velocity

Wind velocity is measured only if it is used to adjust the infiltration component of building heat loss. Several different approaches are possible, and wind measurements may be made differently in each case.

If wind velocity is measured on-site for use in an infiltration predictive model, the measurement should be made at a location assumed in the model. In the Lawrence Berkeley Laboratory (LBL) model, wind velocity is taken at the "ceiling height" of the building. Due to the effect of the building itself on immediately surrounding air flows, this quantity cannot be measured close to the building.

A second option is to locate the anemometer high enough above the ground that the building influence on the wind velocity measurement will be minimized. Some infiltration models (such as the LBL model) include calculation of the wind speed at ceiling height from measurements made at greater height. In this approach, the object is to measure wind velocity as independently of site conditions as possible, as is done for standard meteorological station wind measurements. The rule of thumb regarding obstructions is that for a given height of an obstruction, the anemometer should be at least ten times that dimension away from the obstruction. At meteorological wind measurement locations, where measurement is made over a smooth surface, the standard height is 10 m. Wind measurements made above or near a building would have to be quite high to be in the free air stream and the cost of the mast may be considerable.

A third option of on-site wind velocity measurement can be used when the method employed for infiltration modelling involves the empirical derivation of coefficients relating the driving forces (wind and temperature difference) to resultant infiltration (using a series of tracer gas tests). In this case, the precise relationship between measured wind velocity and resulting infiltration does not depend on a model which assumes the location of wind measurement. The wind velocity can be measured in any location, as long as it varies as directly as possible with the resultant infiltration. In this case, a location closer to the building can be selected, for example, a few meters above the highest point on the roof. The primary concerns in choosing this location are that it be one which is equally exposed to wind from all directions, that it not be a location where the vertical component of wind is likely to be significant (immediately over a vertical surface), and that it be appropriately distant (10 times the height difference) from nearby objects that are higher than it is, such as chimneys.

### 5.3.3 Temperature

The outdoor temperature sensor should be located on the north side of the building, at least 1.5 m above the ground, in a location away from surfaces warmed by the direct rays of the sun. Care should also be taken to see that the sensor is not near any sources of atypical local heating of the air, such as vents from inside the house, chimneys, warm building surfaces, or warm ground surfaces (asphalt paving).

This sensor should be in an outdoor radiation shield, protected from above to avoid radiation, rain and snow entry.

The concept of radiation shields is that the majority of radiation striking the shield on the outside will be reflected (the shield should be reflective metal or white). Any radiation which is absorbed will cause a slight increase in the temperature of this outer shell. Ventilation will help to remove some of this heat, but some will radiate in from the outer shield to the inner shield, where again some will be absorbed. Adequate ventilation on both sides of the inner shield will again help to remove heat.

Indoor air temperature sensors will be required both to determine environmental conditions maintained and for calculating the living zone heat loss. Locate the sensor 1.2 m above the floor of rooms which represent the various temperature zones of the building. If the living zone is at different levels, at least one sensor should be on each level. On the level with the primary passive solar aperture, locate a sensor in both the north and south portions of the level if there is any likelihood that the temperatures may be different in these two locations. In choosing the numbers and locations of indoor temperature sensors, the quantities to be determined should be kept in mind: (1) primary zone temperature, (2) secondary zone temperature, and (3) average living zone temperature. The zone temperatures are indicators of comfort conditions maintained. Accordingly, the number and location of sensors should represent the average temperature conditions experienced by the occupants in each zone (hence the 1.2 m sensor height). This can usually be achieved through careful placement of a single sensor in each zone.

The average living zone temperature will usually require a number of sensors in various locations. Usually these will include the zone-temperature sensors, but they will be processed differently. The use of this measurement is for calculating the heat loss from the house, so the number and location of sensors will be determined by the definition of heated floor area, geometry of the house, and the heat loss calculation technique being used. The input from the various sensors used will be weighted by the relative envelope heat loss rate corresponding to each temperature measurement when calculating the average living zone temperature.

Indoor temperature sensors should not be located near heating or cooling system outlets, should be away from any drafts to the outside (when doors or windows are opened), and should not be located where they will be affected by heat from lamps, stoves, refrigerators and other appliances. They should all be located inside radiation shields and placed where they will not be exposed to direct sunlight.

Sunspace air temperature sensors should be located midway between the floor and ceiling. This is intended to provide a measure of average sunspace temperature. If this location is more than 2 m high, and there is a significant vertical temperature gradient, this will not be a good indicator of temperature experienced by occupants in the space. Accordingly, if the sunspace is high and occupies some of the time, a second sensor at 1.2 m above the floor may be useful. If possible, the sunspace temperature measurement should be in a location which is not directly irradiated by the sun. In any case, the sensor should be located in a large (7-12 cm diameter) double-walled radiation shield which is open at the top and bottom to allow a high degree of ventilation from natural convection. All other considerations are the same as for the indoor sensor, particularly as regards locating the sensor so it will not be influenced by local heat from lighting, hot room surfaces, heaters, etc.

Basement and buffer space air temperature sensors should be mounted at any mid-height location in the space where they will best represent the average temperature of the space. Local heating sources should be avoided, including lighting, water heaters, furnaces, ducts, and freezers.

### 5.3.4 Electrical consumption

kWh meters, kWh transducers, current and voltage measurements may be used in various combinations to measure different electrical consumption quantities.

For total electrical use, the simplest approach is to replace the normal household utility meter with a pulse-initiation meter.

If monitoring is anticipated prior to completion of construction, it is possible to plan household wiring to facilitate instrumentation. In such cases, complete submetering may be possible.

Another approach to monitoring electrical consumption is simultaneous measurement of current and voltage. This is particularly suitable for individual appliance and circuit monitoring, but can also be used for monitoring the primary components in the energy use such as water heating and auxiliary space heating. Current is then measured with current transformers. The "amp clamp" type commonly used with test instruments is usually used because of the openable-jaw design which makes it possible to install and remove without interrupting or disconnecting the wire to be monitored.

### 5.3.5 Fuel consumption

The recommended method for monitoring fuel consumption is a pulse-initiating meter with a satisfactory resolution. These fuel flow meters are analogous to the pulse-initiating kWh meters discussed above and can be used both for monitoring total fuel flow into the house and that used by specific appliances.

In the case of water heaters and clothes dryers which normally operate in an on/off mode, it may be acceptable to substitute an one-time (or periodic) measurement of fuel flow rate and continuous monitoring of on/off status.

### 5.3.6 Status

Status sensors may be switches or relays of various types, depending on the nature of the device or operation being monitored.

Magnetically operated reed switches are usually the simplest approach to monitoring the opening and closing of doors, windows, vents, movable insulation, and similar devices. While bare reed switches and magnets can be used, the packaged devices used in security systems are inexpensive and easy to install.

A second option for similar applications is the use of mechanical contact micro-switches. The single-pole, double-throw variety are most suitable, using either the normally open or normally closed terminals depending on which will indicate "operating time" of the monitored device. Micro-switches provided with long actuating arms (sometimes with a roller on the end) are usually easier to install in a manner that will ensure switch operation when the monitored device is operated. Mounting brackets may need to be fabricated to locate and secure these switches in place.

In certain applications, mercury tilt switches mahy also be useful, mounted to the operating section of the device.

Reed or mechanical contact micro-switches used to monitor the status of manually operated system components are capable only of detecting small relative displacement between both halves of the switch. Thus, for example, if a door is partially open, the output of the status sensor will be the same as if the door was completely open. For most accurate interpretation of the status sensor(s)' output, the occupant(s) must be advised to standardize operation of manually controlled systems such as door, windows, vents, movable insulation and similar devices for the period of building monitoring. The simplest method of standardizing is to ensure that system components are either completely closed or completely open. No intermediate positions are allowed as these will cause unquantifiable errors in interpretation of the data.

Relays may be used advantageously to monitor the status of numerous electrically operated or controlled devices, including:

- ventilation fans
- clothes dryers
- heating system blowers
- air-to-air heat exchangers
- single on/off appliances to be excluded from internal heat gain calculations
- solenoid-controlled dampers or valves

Relays should be installed directly across (in parallel with) the electric power to the load being monitored. Putting relays across thermostat control circuits can affect the anticipator setting.

Another approach, which is often very straightforward, is to use an electromagnetic sensor. A sensor is placed with the help of a velcro fastener on the cover of the device to be monitored.

### 5.3.7 Humidity

If continuous indoor humidity monitoring is required, a single sensor will usually be sufficient. It should be located in the primary living zone, in close proximity to the location of primary zone temperature measurement. (It should experience the <u>same</u> dry-bulb temperature as is monitored). Several types of sensors are possible. Each is discussed below, along with appropriate installation guidelines.

The simplest recommended sensor is a direct-measurement electrical hygrometer. The sensor in such a device is a very thin polymer film. Relative humidity is sensed as a capacitance change in this film as it absorbs water vapour. It has a fast response. There is a number of electrical resistance hygrometers which operate similarly. All of them will drift over time, at varying rates, and will have to be recalibrated periodically. They also all require a power supply.

Another humidity sensor which may be used is a saturated, heated lithium chloride sensor. This sensor indicates relative humidity by sensing the temperature at which a saturated lithium chloride solution reaches equillibrium with the ambient humidity. The sensor is subject to drift and errors in calibration, as well as being relatively slow to respond.

Another approach to sensing relative humidity is to directly measure the wet-bulb temperature. This is done by covering a temperature sensor with a moistened wick and forcing air over the wick at a rate of over 4 m/s. While the results will be affected by the purity of the water, cleanliness of the wick, radiation effects, and other factors, this technique can be highly accurate ( 5% of relative humidity) for high levels of humidity (over 50%).

Other techniques of monitoring humidity are available, including hair hygrometers, and dew point hygrometer. Both can be adapted for continuous electronic monitoring.

### 5.3.8 Radiant temperature

The relevant quantity which is used in thermal comfort determinations is "Mean Radiant Temperature", which can be calculated from measured air movement and "Globe Temperature" (5). Accordingly, in sites where radiant temperature measurement is required, a globe temperature measurement should be made.

The globe thermometer is a black globe, .15 m in diameter, with a temperature sensor in the middle (usually the same type of temperature sensor used for other measurements with the particular monitoring system). The globe may be either plastic or metal, but thin (1 mm plastic is preferred due to its much shorter time constant).

The globe thermometer should be located in the primary living zone in a location which is typical of occupancy in the space. It should be in very close proximity to the dry-bulb (and relative humidity, if used) sensors.

### 5.3.9 Sensor wiring

Experience has shown that poor attention to sensor wiring details is a primary source of equipment malfunction and erroneous results when buildings are monitored in the field. Faulty wiring can confuse sensor identification, introduce errors into sensor outpupts, and sometimes seriously damage a data acquisition system. It should be approached carefully and systematically, using the right tools and materials, and with careful testing before final hook-up.

### 5.3.10 Data acquisition system

Grounding and lightning protection of the data acquisition system are critical to protect the system and ensure the safety of the operator and building occupants. Static discharge to sensors or the data acquisition system and high voltage power line transients can interrupt data collection, and in some cases damage the system. Strong radio frequency signals can cause erroneous sensor readings which are sometimes difficult to detect. Experience has shown that installations made using the techniques described below will prevent or minimize the impact of these problems.

Special attention to grounding the system will reduce system downtime as well as the likelihood of damage to the system. The ground provided as part of the electrical wiring in the house is not necessarily adequate to serve as the ground for the data acquisition system, and should not be used unless verified to be adequate.

Two general types of undesirable electrical situations must be considered with respect to sensor lines: (1) high voltage transients and (2) interference which affects sensor readings.

All sensor lines which could experience high voltage transients should have a transient protections device installed on them. Typically this will be at the data logger end of the line, but in the case of outdoor sensors, it may be at the point where they enter the house.

Installations near large radio frequence sources can have serious interference problems which are not necessarily very easy to detect (e g, a consistent several degree error in temperature readings). If an installation is less than one kilometer from an RF, filtering may need to be employed. It should also be noted that ground loops are particularly serious in this situation.

Even with good protection on the sensor lines and good grounding, system crashes or damage can occur from undesirable transients on the power supply to the data acquisition system.

While most good data acquisition systems will have some internal protection on their external power supplies (typically fuses), additional protection is usually warranted in field installations.

## 5.4 Calibration

It is absolutely necessary that all the monitoring equipment is calibrated and if necessary recalibrated. A discussion of calibration procedures for different sensors follows below. All sensors should be calibrated together with the data aquisition system to be used.

### 5.4.1 Solar radiation

It is recommended that, if possible, all pyranometers should be calibrated in a laboratory using a standard procedure before use. An absolute accuracy of ±3% (in the range 0-1300 $W/m^2$) is recommended for horizontal measurements, and this should be attainable with good quality instruments. For measurements in the inclined plane, however, larger inaccuracies may be introduced due to the tilt angle and cosine response. It is also recommended that a pyranometer be recalibrated each year in a laboratory. Any discrepancies between calibrations should be noted. Alternatively, a test instrument may be mounted adjacent to the installed pyranometer at the same time intervals, and the readings compared for corrections to be applied.

The zero offset should be checked by placing a light tight box over the pyranometer. The instrument will not always give a zero reading outdoors at night because of the low values of effective sky temperature which sometimes occur. Low sky temperatures depress the zero readings.

The output of a pyranometer is affected by the temperature of the pyranometer body. The calibration constant may vary by approximately 0.1 to 0.2% $K^{-1}$.

### 5.4.2 Wind velocity

The air speed should be measured to within 0.5 $m.s^{-1}$, and the anemometer should be recalibrated at yearly intervals using a standard laboratory procedure.

### 5.4.3 Temperature

Two types of temperature sensors are discussed below; thermocouples and resistance thermometers.

As the voltage generated by thermocouple junctions may be affected by the methods of joining the two metals, each thermocouple should be calibrated against a reference thermometer over the range of temperatures for which it is to be used, and a calibration curve obtained.

The need for a complete recalibration at frequent intervals may be avoided by immersing the thermocouples in a suitable insulating material so that the effects of strain hardening and oxidation are reduced. Annual calibration checks at a few selected points on the calibration curve may be sufficient to verify the calibration.

Thermopiles may be calibrated for temperature difference by placing one thermopile in a thermal reference and the other in a fluid at a higher temperature, measured by a reference thermometer. The indicated temperature difference should be monitored by the data recording device.

A zero check for the differential thermopile arrangement should be made by placing both thermopiles in a fluid bath at temperatures in the normal test range. Depending on the quality of the thermocouple and of the recording instrumentation it may be necessary to derive a correction curve as a function of the absolute fluid temperature and/or the ambient temperature.

The calibration of resistance thermometer sensors, associated connecting leads, bridge circuit and read-out devices should be verified approximately once per year. Standard platinum resistance thermometers have a tolerance of 0.3°C, but it is possible to manufacture sensors with an accuracy better than 0.03°C. The long-term stability is usually better than for thermocouples.

### 5.4.4 Electrical consumption

New electricity meters are cheap, and often reconditioned meters are available.

A typical standard specification for the calibration of an electricity meter asks for 1% accuracy at full load, (usually 30 A), 1/10th load (usually 3 A) and half load at 70% power factor. Accuracy falls off rapidly below 1/10th load as friction begins to become more important. New meters will have a minimum starting load of perhaps 30-40 watts, but old meters may well require 120 watts to overcome their basic friction and yet still pass the above tests.

This effect shows itself particularly on light domestic loads where two meters that both passed the above tests can differ by 30% when reading the consumption in the same house. It is a symptom of worn bearings when the starting load is high.

It is possible to buy special devices that can read the revolutions of the disc by either looking at the reflections from painted marks on the disc, or by watching for the passage of holes drilled in the disc. The presence of 2 mm holes only affects the calibration slightly (about 1%) provided they are drilled symmetrically. The pulses from these optical devices can be counted in the data logger.

### 5.4.5 Fuel consumption

Standard domestic gas meters can be easily purchased. Standard gas meters may be calibrated only at one flow rate, which may be higher than the normal domestic consumption rate. Accuracy falls off at very low loads and there is a fairly large temperature coefficient.

The addition of an optical read-out to the dial mechanism is not difficult but care must be taken to ensure that no additional drag is imposed on the drive (the calibration is very sensitive to this).

It should be noted that the meter is calibrated by changing a gear wheel in the dial mechanism. This gear usually has the same diameter but has a range of numbers of teeth.

Auxiliary boiler gas consumption may be measured continuously using a positive displacement meter or, alternatively, burner time can be monitored and then calibrated with burner gas consumption.

A standard of accuracy to ±2% is normal among meters in standard use and this should be acceptable.

Oil consumption by a boiler can also be monitored continuously using a remote sensing positive displacement meter, or by monitoring burner time. The modifications required for automatic readout are similar to those mentioned in the sections above.

### 5.4.6 Humidity

Most sensors can be calibrated in a laboratory to an accuracy of ±5% in the range from 15% R.H. to 90% R.H. This can be done using different salt solutions, at least three of them should be used. Frequent recalibrations are recommended.

### 5.4.7 Volume flow

There is a wide variety of flow meters, most of which are calibrated by the manufacturer. In general, flow meters have calibration curves which are flow dependent, Acceptable turbine and vane wheel types are ±2% down to 50% of the design flow, and ±5% below this down to a minimum flow. For the remaining types, accuracy is usually given as a percentage of the actual range and/or the full range.

Figures quoted are only valid for properly installed new meters, and performance degradation is common. For example, the accuracy of a vane wheel meter used for three years in a radiator circuit of a heating system can change from ±2% at the beginning to about 7%, due to cumulative magnetic effects on the magnetic rotation sensor. Wear in wheel bearings also causes variation in output.

All flow meters where a pressure-drop is measured need to be recalibrated, and in particular if they are not installed with the proper straight away. The flow meter should then be installed, the same way as in the house, in a laboratory and calibrated. Air flow meters can preferably be calibrated against a standard sharp-edged orifice plate.

An alternative flow meter is a magnetic flow meter, which has the advantage of no pressure drop.

The calibration of all flow meters should be checked twice a year if possible. Calibration should be carried out for different working temperatures.

## 5.5 Monitoring system check-out

Use the manufacurer's instructions provided with the data logger to set it up for the initial power-up and check-out. Enter the site-specific calibrations and values from short-term tests and measurements. Once this is done, enter the data collection mode and print out instaneous channel values. Check these to see that they are generally reasonable. If not, investigate to determine the problem and correct it. When the readings from all sensors appear to be reasonable, it is recommended that the following procedures be used to check these values more closely:

1. Temperature - Check all sensors with a partial-immersion mercury thermometer (or other temperature measurement device) of certified calibration which can be read to less than .1°C and is accurate to .2°C or better at the temperatures being checked. Place the thermometer inside the radiation shield next to the sensor being checked. Allow sufficient time for the thermometer to stabilize and then compare its reading to the simultaneous reading printed out by the data logger for the sensor being checked.

   This procedure can be used both to check temperature sensor readings and to "fine tune" the calibrations if desired. If all sensor readings are systematically off, systematic error sources should be investigated, such as incorrect sensor terminal coefficient or failure to correct for sensor self-heating. If a sensor is significantly in error, it should be checked at other temperatures. Either that sensor or its signal conditioning card may need to be replaced. If a sensor is within specification, but a little bit off (less than 1°), then it may be desirable to adjust the programmed calibration for greater accuracy. For most indoor sensor, where the temperature measured does not vary by more than 10°C, this can be done with a simple adjustment to the programmed intercept value. For the outdoor sensor, and any other which must function over a wider range, either the slope or intercept, or both, will have to be modified, based on at least three checks at significantly different temperatures.

2. Solar Radiation - Check the total solar radiation value for the first full day of data collection against the value recorded for the same day at the nearest station where standard meteorological measurements are made. If they are not within 10% of each other, further investigation may be necessary.

3. Energy Consumption - Check the total values accumulated by each sensor against manual meter readings for at least a six hour period. If any errors are in excess of sensor specifications, investigate further and correct.

4. Status - Check each status channel by forcing the monitored device to operate in its various modes and check against the instantaneous values displayed or printed out by the data logger. Correct any problems.

5. Wind Velocity - Use professional judgement to determine whether instantaneous readings appear to be reasonable. If not, it may be necessary to bring in a second instrument for comparison. Contact-closure type anemometers can be manually rotated, and switch clicks or revolutions compared to data logger output.

6. Humidity - Instantaneous values may be checked using a sling psychrometer.

7. Globe Termperature - Use professional judgement to determine whether globe temperature measurements are reasonable. They will normally be slightly higher than dry-bulb temperatures. In addition to checking the sensor values, the computed function values should be checked for reasonableness. Some of these can be checked immediately by forcing a print-out, but some will not be reasonable over a period of time less than an hour, or in some cases a day (for example, the subtractively computed passive contribution).

Before commencing routine data collection, it is also a good idea to check the operation of time dependent functions.

## REFERENCES

1. IEA (energy conservation in buildings and community systems programme, Annex III, REsidential Building Energy Analysis), "Guiding Principles Concerning Design of Experiments, Instrumentation, and Measuring Techniques". Swedish Council for Building Research, D11: 1983.
2. Hamilton, B. and R. Alward. "Level B Monitoring Manual for Performance Evaluation of Passive Solar Homes". Memphrenagog Community Technology Group, Mansonville, Quebec, Canada, 1983 (draft).
3. Commission of the European Communities, "Monitoring Solar Heating Systems - A Practical Handbook". Pergamon Press, 1983.
4. Frey, D., M. McKinstry, J. Swisher. "Installation Manual: SERI B Passive Solar Data Aquisition System". Solar Energy Research Institute, 1982.
5. ISO 7730. "Moderate Thermal Environments - Determination of the PNV Indices and Specification of the Conditions for the Thermal Comfort, International Organization for Standardization, First edition, 1984.

# 6. DATA REDUCTION

## 6.1 Objectives

This chapter deals with the treatment of the data taken by a data acquisition system. Figure 6.1 presents a typical monitoring system set-up including the computer for the final data analysis. As indicated on the figure, the treatment of measured data can be subdivided into 4 major steps:

1 The transformation of electric signals to engineering units.

2 On-site data reduction and analysis

3 Transmittance of data from site to remote computer

4 Refined data analysis

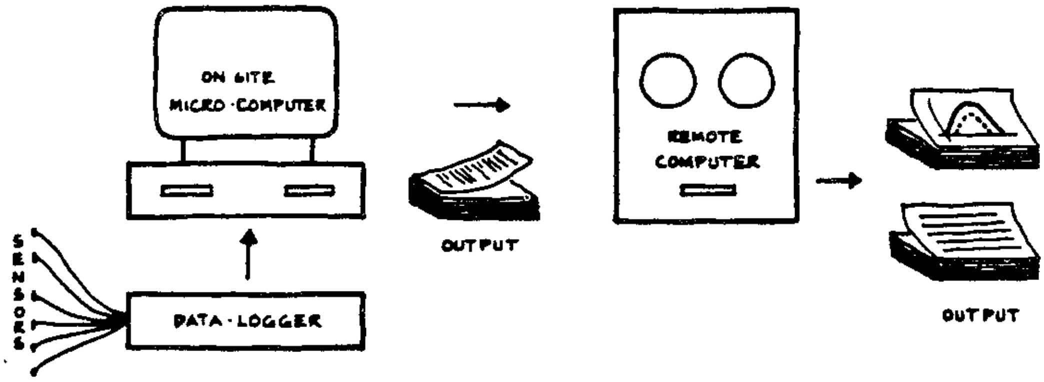

Fig. 6.1 Total Monitoring and Data Evaluation System

The reduction of data from numerous electrical signals to meaningful numbers in engineering units serve two purposes. First, it is a necessity for the evaluation of the performance of the system being monitored. Second, equally important to the success of the project, it allows for watching over both the energy system and the monitoring system itself for quickly access of any malfunctioning.

As indicated in figure 6.1, data analysis can be performed both at the on-site monitoring system and at a remote computer facility. In both cases a careful planned output can be used for as well as performance evaluation as for watching over. For practical reasons the emphasis of the on-site system data analysis should be on the watching over function of the output, and, naturally, more stress will be put on the data analysis and performance evaluation aspects when using the central computer. However, at both levels, data reduction and analysis should be seen as a means to continuously evaluate and watch over the system.

## 6.2 State variables

### 6.2.1 On-site analysis

A minimum requirement to a data acquisition system is the capability to produce a real time display of the current state of the monitored system. This implies the conversion of the electric signals to engineering units to be performed immediately following each data-sampling. The real time display should include temperature, flow rates and system mode indication.

Malfunctioning of the measuring equipment is likely to be seen at a quick glance at this display, which, of course, can be replaced by a printout. At the same time this output is useful for the understanding of the dynamic performance of the system/building.

A continuous plot of some of the main variables and system mode indicators produced simultaneously with the data gathering would make the system complete.

### 6.2.2 Remote analysis

Computer plots of the major state variables are the most illustrative and most comprehensive way of presenting the dynamic performance of the building/system being analysed. Missing data will show up immediately at such plots.

## 6.3 Energy flows and balances

### 6.3.1 Daily tables

The simplest and most powerful way to always be on top of the system is to make a calculation of a daily table with hourly values of all relevant heat flows preferably using the on-site data logging system microcomputer. This table can be used for a quick evaluation of the performance of the energy system as well as for checking if there is something wrong with the data for this day. This check is further improved by a calculation of the relevant heat balances for the system. If a balance cannot be obtained, it is most likely because of an error in the monitoring system (see paragraph 6.4).

In the ideal situation, a daily table as described above is printed out each day and checked by the site operator. For practical reasons a site operator may not be able to visit the site every day, but the daily table should anyway still be produced and be available to the site operator when he arrives, to make it possible immediately to check the data and have any malfunctioning repaired.

### 6.3.2 Monthly and yearly tables

A primary objective of the monitoring programme is the verification of the measures taken to reduce the consumption of non-renewable energy fuels. The creation of monthly and yearly tables of heat/energy flows and balances not only serves this purpose but also allows for a gross evaluation of the performance of each of the energy conserving techniques employed.

When these tables are completed with the relevant performance factors (see chapter 3), they present the essence of the results for the communication to third person.

## 6.4 Checks during the continuous measurements

Incorrect readings are caused by either constant (C) or temporary (T) problems. The first could have been prevented by more precautions during installation; the second by greater precaution during the monitoring period. Possible sources of these errors are described below.

a. Defect of the sensor (T or C).
Example: Deposits on the vanes of a turbine flow meter (T).

b. Wrong (C) or degenerated (T) positioning of the sensor.
Examples: Turbine flow meter too close to a pump (C).
Thermal contact of the sensor on the back of the absorber poor because of corrosion (T).

c. Disturbance by the environment.
Examples: High temperatures around sensor (C or T).
Spikes on mains disturbing sensors or data-logging system (C or T).

d. Incorrect software of data collection system (C or T). Temporary faults can be introduced by changing the software during the monitoring period.
Example: Incorrect equation for transformation of raw data into engineering units.

e. Hardware Defect (Analogue - digital converter, counters, etc.)
Example: Contact resistance in worn out reed switches of analoque scanners.

During the monitoring period, immediate warning of a fault in the monitoring system or solar installation is essential. For example, if a fault in the flow meter is not revealed for several months, the value of the whole package of data from these months will be drastically decreased. A faulty pump or valve affects the data even more drastically as it may influence the performance of the complete solar installation.

During the monitoring period regular checks should be performed on the sensors. The frequency of checks and the number of sensors to be tested depend on what other precautions have been taken to ensure accuracy. Special attention should be paid to sensors known to change their calibration such as flow meters and pyranometers. Conversely, temperature sensors often perform satisfactorily throughout a monitoring programme of 1-2 years. Therefore, once the sensor has passed the initial test, it can normally be regarded as stable throughout, for instance, a two year monitoring period, if precautions have been taken against corrosion or mechanical damage.

Tests on various instruments are discussed in more detail below:

a. Mass flow meters and pyranometers

Regular tests can be performed either on site or in a laboratory. On-site tests need reference instruments which can be monitored for a short period in parallel with the original instruments. In the case of the flow meter it should be possible to plug the reference instrument into each loop in series with the flow meters to be tested. Such a procedure is easy and inexpensive if allowed for when designing the heating system. Mounting a reference pyranometer next to the original one is also fairly easy, if the check instrument is equipped with a suitable tripod to allow easy fastening and adjustment of orientation and tilt.

The choice of test method depends upon the availability of field test instruments and the extent to which the field tests will interfere with the normal life of the inhabitants in the house. Yearly tests are often a reasonable choice, assuming the test is performed at a non-critical time of the year for data collection.

b. Field instruments

Suitable reference instruments can be found for on-site checks of most mass flow meters and pyranometers in use. Water meters with an accuracy of ±2-5% can be tested against meters with an accuracy of ±1% such as a magnetic meter with adjustable flow range.

If pyranometers are not recalibrated in a national centre, a reference pyranometer with an accuracy of ±1%, can be used. The readout of the test instruments can either be separate or via the data logger.

## REFERENCES

1. Commission of the European Communities, "Monitoring Solar Heating Systems - A Practical Handbook". Pergamon Press, 1983.

# 7 DOCUMENTATION OF BUILDING AND MONITORING SYSTEM

Description of the building, its environmental setting, the data acquisition system and reduction functions and all short-term and continuous measurements and calculations must be done in sufficient detail that future data analysis can be made and the details of exactly what was measured and how can be understood. The documentation must contain the following six items:

- building environment
- building description
- passive/hybrid system sensor location
- short-term measurement and calculation values
- continuous measurements
- documentation of data reduction functions.

Much of the information will remain unchanged throughout the monitoring period. However, the values of several quantities determined by short-term measurements change over time, due either to actual changes in these quantities, or to improved accuracy. If changes are made, record them and note the date the value changes occurred.

## 7.1 Building environment

This description should contain type of terrain, soil, climate and solar exposure. The terrain can be described as urban, suburban or rural. An urban setting is considered to be a typical downtown location with numerous high, medium, or low-rise buildings, in close proximity to the monitored building. A suburban setting assumes a residential area where the houses are separated by large yards. Village locations will typically fall in the suburban category. Rural implies a non-built up area, with no buildings other than farm and maintenance buildings with 100 metres of the residence.

The site soil type can be characterized as one of the following:

- well drained (sand, gravel, loam)

- damp (loam, clay)
- wet (heavy loam, clay)
- rocky (specify)

The details for average site climate can be obtained from standard climatological references for the nearest weather station.

Site solar exposure is partitioned into three categories. Completely exposed means that no shading occurs on the major aperture during the heating season. Minor shading includes some early morning or late afternoon shading of part of the aperture, by bushes, trees or buildings, or some limited mid-day shading of the aperture during December. Significant shading occurs when leafless decidous trees cast their shadows across the aperture between 10:00 and 15:00 hours or when adjacent buildings, building sections, or evergreen trees shade the aperture for more than 2 hours total at either or both ends of the solar day or for more than 1 hour total within 2.5 hours of solar noon.

## 7.2 Building description

The building should be described by building construction, foundation, heating system, ventilation system, etc. The building description must include line drawings of the floor plan(s) which show the living zone and any buffer areas such as porches, garages, greenhouses and sunspaces. Include detailed sketches of wall, floor and roof sections including basement walls and any areas of unusual construction. Provide photographs of east, west and north elevation and any other pertinent features.

Building type can be selected from among the following:

- detached one-family (1 storey)
- detached one-family (1 1/2 storey)
- rowhouse/townhouse
- multi-unit
- other (describe)

Construction type can be selected from among the following:

- standard wood frame
- lightweight wood frame (I-beams of masonite and wood)
- wood frame with masonry exterior
- masonry with exterior insulation
- other (describe)

Foundation/Basement type can be selected from among the following:

- slab on grade
- unheated crawlspace
- heated full basement
- unheated full basement
- other (describe)

The auxiliary heating system equipment type will be selected from the following:

- gas (furnace/boiler)
- oil (furnace/boiler)
- electricity
- heat pump
- other (specify)

The type of distribution system will be:

- forced air
- hydronic
- convective air
- radiant
- other (specify)

The ventilation system can be selected from the following:

- unpowered vents
- unpowered vertical ducts
- mechanical exhaust ventilation
- mechanical exhaust-supply ventilation

The daytime thermostat setting is the daytime temperature at which the occupants will maintain the primary living space by auxiliary heating in the absence of solar heating. Similarly, the night thermostat setting is that night-time temperature at which the occupants will maintain the primary living space by auxiliary heating in the absence of solar heating.

Domestic hot water system energy saving features may include:

- reduced flow shower heads
- timers
- off-peak electricity use
- other (specify)

## 7.3 Passive/hybrid system

Make detailed sketches of south elevation and all other elevations containing areas of glazing which might add significantly to passive solar gain. Include detailed sketches of typical aperture/wall sections. Provide passive/hybrid features both inside and outside the house.

The dominant solar heating system description must include passive system type: direct gain, isolated gain (attached sunspace) or indirect gain (Trombe wall); glazing orientation and tilt from the horizontal; operational modes; details on quantity, location and type of thermal storage mass; and specifics on the heat distribution or movement system, that is, whether it is forced or natural and how it moves from collector to storage to living space.

Night insulation should be described by including its U-value, area and location of coverage, whether it is automatically or manually deployed and if automatic, what the control system is and its setting.

Other special energy conserving features of the house will include descriptions of such items as energy-conserving water heaters, air-to-air heat exchangers, super insulation and airtight construction.

## 7.4 One-time measurements and calculations

Record as many pertinent details of the measurements or calculations as possible. Indicate whether the value was determined from test or other measurements, was estimated (including calculations and use of table values), or was obtained from equipment specifications. Record the value determined for the quantity and the date of this determination.

## 7.5 Continuous measurements

All the sensors should be documented as to channel, symbol, quantity measured, type of sensor, sampling period, resolution, overall measurement accuracy and relevant information on calibration.

A map showing sensor locations should be drawn. On this "sensor map" indicate measurements such as height of floor and distance from corners, etc.

Provide photographs of each sensor, clearly illustrating where and how each is mounted. Record any location details not included on the sensor map. Also record any other relevant details of the sensor installation, for example, whether a micro-switch status sensor makes or breaks contact when the door opens.

## 7.6 Data reduction

A complete listing of the data reduction functions should be made. If the data reduction functions or any part of the program are changed during the monitoring period, or if optional functions are used, these changes should be clearly documented with explanatory notes.

## 7.7 Reporting format

Detailed guidelines for documenting the Subtask D construction projects are given in the "Reporting Format" produced by Task I of the IEA Solar Heating and Cooling Programme, (1). Within Task I an amendment to this format was produced to also cover passive and hybrid solar low energy buildings. The special designations used in these documents can be omitted. It is stressed that this is to be considered as reporting guidelines and examples, and that whenever a discrepancy is observed between these two documents and the previous chapters of this document, the latter should be considered valid.

Under the CEC Passive Solar R&D programme a less detailed reporting format has been developed (2). This is recommended as a guideline for minimum project documentation requirements.

## REFERENCES

1. IEA Program to develop and test Solar Heating and Cooling systems, Task I, "Reporting Format", for Thermal Performance of Solar Heating and Cooling Systems in Buildings, 1980.

2. Commission of the European Communities "Reporting Format for Solar Heating Systems, Passive Space Heating Systems", 1981.

APPENDIX 1

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# AN INDEX TO QUANTIFY THERMAL COMFORT IN HOMES

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## ABSTRACT

The discomfort index presented here quantifies the thermal discomfort associated with the design and operation of residential buildings during the heating season. Discomfort under steady-state conditions is estimated from the squared difference between the actual and a preferred temperature (which is assumed to vary with clothing and activity levels). The difference is found using a simple linear approximation to the ASHRAE ET* that treats humidity effects only implicitly. A penalty is also assessed for transient discomfort effects. The index allows calibration for individual preferences.

The proposed index is similar to the currently used Predicted Percentage of Dissatisfied, but is simpler and better suited to simulations of residential environments. Simulations can integrate the index over a heating season along with energy use to estimate the overall thermal performance of a building. These two complementary aspects of performance can be combined into one overall index, by using thermostat settings as an indicator of the relative weights that people assign to comfort and energy use.

## 1. INTRODUCTION

Most analyses of building "thermal performance" rely exclusively on computed energy savings as the figure of merit. This is acceptable when one is comparing techniques which provide similar indoor environments. For example, most homes using forced-air space heating systems can be fairly compared. However, high-mass buildings with significant solar gain provide indoor environments different from those found in more conventional buildings. Using thermostat settings and energy use as the sole parameters in comparisons of dissimilar buildings implies that all conditions within some deadband are equally acceptable, and all conditions outside the deadband unacceptable.

The index proposed here permits a more balanced comparison of dissimilar buildings. The details of the index are necessarily tentative, but the index is intended to be consistent with existing knowledge. Refs. 1-3 provide a good introduction to the literature up to their dates of publication.

The basic argument for such an index is similar to that for simulation work in general: the index is not perfect, but it allows the evaluation and ranking of many cases by the consistent application of a complex set of assumptions derived from various sources.

Besides being simpler than the PPD and other models of human thermal response (1-6), the proposed index is also more relevant to residential environments, since it deals with transient effects and uncontrolled clothing levels. Like the PPD, this index quantifies discomfort rather than comfort: low scores indicate that comfort is not a problem and that design efforts can focus elsewhere.

The remainder of the paper discusses the following issues in detail:

- Effective Temperatures
- Preferred Temperatures
- Penalizing Non-Optimum Temperatures
- Thermal Transients
- Some Excluded Issues
- Using the Discomfort Index

## 2. EFFECTIVE TEMPERATURES

Thermal sensations are a function not only of air temperatures, clothing, and activity levels, but also of radiant exchanges, humidity ratio W, and relative air velocity V between air and body. The combined effect of these variables can be expressed using the ASHRAE "Effective Temperature", which is:

> the dry-bulb temperature of a black enclosure at 50% relative humidity (sea level) in which a solid body or occupant would exchange the same heat by radiation, convection, and evaporation as in the existing nonuniform environment. (1)

Fanger's general heat balance equation (2) permits any environment to be compared to the reference condition. That equation is quite complex. However, for cases with low air velocity and small wetted skin fraction, moderate clothing and activity levels, and MRT near Tair, this linear approximation is adequate:

$$ET = .51\,T_{air} + .42\,MRT + 130\,W + .45\ \text{Celsius} \quad [1]$$

The .45 Celsius offset term is due to the fact that saturation humidity ratios are not proportional to temperature. A humidity term is present because of latent respiratory and skin diffusion losses. Where the indoor humidity ratio W is not known, the following alternative may be used:

$$ET = .51\,T_{air} + .42\,MRT + .04\,T_{amb} + 1.1\ \text{Celsius} \quad [2]$$

The humidity correlation used is very rough, but the errors are usually less than .3C during the heating season (unless there is a humidifier). The correlation is inadequate in warm weather because W affects evaporative cooling and because W varies more widely then.

Equations [1] and [2] neglect the cooling effect of air movement, and hence will overestimate the ET (and thus discomfort) during venting in warm weather.

The relative importance of Tair and MRT varies with conditions between about 1:1 and 2:1. The 51/42 weights used above are consistent with the 55/45 weighting used by Wray (7) in an "equivalent temperature" concept that does not include humidity effects. The high importance of Tair relative to the MRT is surprising to many people. It has several causes: the "concave" shape of the human body reduces radiative interchange with room surfaces, while body movements, high delta-Ts, and respiration all serve to increase the coupling between the body and room air. The true importance of $T_{air}$ may be even higher than indicated, because Fanger's analysis does not include "infiltration" through clothing.

The "MRT" in the ET equation is the true mean radiant temperature, which includes not only surface temperatures but also air emittance (.05–.10 in winter) and solar gain. Direct solar gains onto people may be simply accounted for by assuming that the sun raises the MRT for people the same amount that it raises the MRT at an average room surface.

## 3. PREFERRED TEMPERATURES

The term "preferred temperature" is frequently used in ASHRAE literature. It means the ET which minimizes the number of dissatisfied people in a group, given fixed levels of clothing and activity. Experiments indicate that activity and clothing levels are all-important: other factors such as climate, season, age, sex, and race have little impact on preferred temperatures of groups of people (2,8). In this paper, "PT" refers to the best compromise ET for occupants of a house, given their individual preferences, typical activity levels, and preferred clothing levels (i.e., what is worn at home when thermal comfort is not an issue).

Ignoring PT variations due to random variations in clothing and activity levels creates no bias; it is only important in parametric studies to include the variations in PT which correlate with variations in building performance. We include only the two effects we regard as most important: variations due to the effect of ambient temperature on typical indoor clothing levels, and nighttime reductions in the PT.

High energy costs increase the seasonal changes in indoor conditions in public buildings. This tends to increase the seasonality of clothing worn not only during the day but also at home. If weather has very little effect on preferred conditions when clothing and activity levels are fixed (2), then the weather should have an effect on the PT when clothing levels vary with the weather.

Errors in estimating metabolic rates and clo-values (which at night include bedding) can lead to errors in estimating the PT, so using empirical correlations based on metabolic rates and clo-values may turn out to be simply a way of hiding the guesswork. It is more straightforward to specify a PT formula explicitly. Arguments regarding the PT formula can then be based on estimates of activity and clothing, or on data such as typical thermostat settings. Our PT formula is:

$$PT = PT_{base} + K\,(Tamb - PT_{base}) - N \qquad [3]$$

where $PT_{base}$ is the preferred ET in mild weather ($Tamb = Troom = PT_{base}$), K represents the effect of Tamb on clothing and thus on the PT, and N is a shift in the PT during hours when people are normally in bed. The above definition of "$PT_{base}$" simplifies translation between SI and English units.

Although values of the discomfort index are highly dependent on the $PT_{base}$ used, the default $PT_{base}$ is not critical because the functional form of the index allows simple after-the-fact adjustments to different bases. We use a default $PT_{base}$ of 25 Celsius (77F). This seems quite high, but it is 1C lower than the PT of 26C (79F) found in extensive studies at KSU involving persons in light clothing doing sedentary activities at student desks. This and other studies on preferred temperatures are described in (9) and (10).

We assume that the coefficient K=.1. It may seem that K should be negative, because people often appear to prefer higher thermostat settings as Tamb decreases. As clothing styles vary more strongly with outside conditions, however, this tendency changes. In addition, any existing correlation partly reflects the typical levels of insulation in existing homes: the MRT and W vary with weather, so that the ET changes with Tamb even if $T_{air}$ is held fixed. The model used in (11) indicates that in an R19/R11 house with single-glazed windows, variations in MRT will shift the ET about .06C per 1C shift in Tamb. Humidity effects cause ET variations about 4% as large as Tamb variations. Thus even if $T_{air}$ is fixed, changes in MRT and W in typical existing insulated buildings will shift the ET about .1C per 1C shift in Tamb.

The above values of $PT_{base}$=25C and K=.1 can be substituted in the PT formula, giving:

$$PT = 22.5\ \text{Celsius} + .1\ Tamb - N \qquad [4]$$

Formula [4] is consistent with a negative correlation between Tamb and the most comfortable $T_{air}$ in poorly insulated houses and a positive correlation in well insulated houses. If [4] is accurate, then the most comfortable $T_{air}$ during the day is about 24C (75F). (The 1C offset from $PT_{base}$ is due to MRT and W effects.)

There seems to be little research on nighttime preferences. However, several observations can be made:

1. Room temperature is less important at night.
2. PTs are often lower at night than during the day.
3. Non-thermal issues such as being "snug" have an effect on preferred bedding levels.

We shift the PT 2C downwards between 11pm and 7am, by making N equal 2C then and 0C at other times. Whatever nighttime shift is chosen should be less than typical night setbacks, since setbacks also result from the lower importance of the ET at night.

## 4. PENALIZING NON-OPTIMUM TEMPERATURES

The simplest way to assess a penalty for the deviation of a room from preferred conditions is to note the percentage of people dissatisfied. Fanger developed this concept, and defined the "PPD" as follows (2):

> ...that percentage of people in a large group of persons who can be expected to feel definitely uncomfortable in a given environment. As it is precisely the decidedly dissatisfied who in fact will be inclined to complain about the thermal environment, PPD would seem to be a meaningful factor in rating the quality of a given climate.

The PPD curve determined at KSU for "standard clothing and activity levels" (1) is plotted in figure 1.

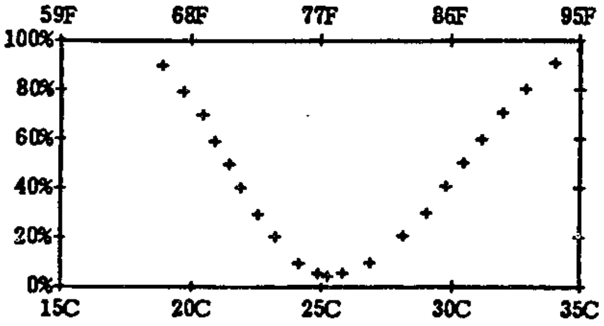

Fig. 1. "Predicted Percentage of Dissatisfied"

The function proposed here is far simpler: the square of the temperature "error", E, where:

$$E = ET - PT \qquad [5]$$

A quadratic function does not fit the PPD curve very well because it is not skewed like the PPD and does not "saturate" when E is large. However, these differences actually turn out to favor a quadratic function.

Fanger argued in (2) that the PPD should be symmetrical, but experimental work at KSU showed it to be skewed. The experimental conditions held clothing and activity levels fixed in order to evaluate strictly physiological effects—vasoconstriction and shivering when it was cold, and vasodilation and sweating when it was warm. The skewness indicates that the physiological responses to heat are less bothersome than those to cold. Since the typical response in homes is to adjust clothing levels before discomfort becomes serious, a symmetrical curve seems appropriate.

The PPD was intended as a tool for evaluating HVAC systems when clothing and activity levels are fixed and only moderate deviations from PT are being evaluated (2). However, it is an inappropriate tool if clothing is uncontrolled or if there are large deviations from PT. For example, if the PPD is used to optimize control strategies, the "optimum" for some fuel costs is to run a HVAC system in mild weather but turn it off entirely in more severe weather.

Smoothly concave functions have the more plausible corollary that the use of HVAC systems always becomes more likely as the weather worsens. A quadratic penalty has a specific corollary: once energy costs (rather than noise, drafts, or transients) are the main "cost" of HVAC operation, then typical deadbands should be nearly proportional to operating costs.

An additional argument unrelated to the PPD points precisely towards a quadratic penalty. The appropriate penalty in parametric studies is the average of many hypothetical individual "discomfort functions". Given any arbitrary set of concave curves as measures of individual discomfort vs ET, if discomfort is averaged over random variations in individual differences, activities, clothing preferences, local conditions in a building, and errors in simulated or measured conditions, the resulting average curve approaches a parabola. This is true even if the original curves have sharp kinks or are consistently skewed in one direction: the average curve straightens out the kinks and decreases the skewness.

Furthermore, a quadratic penalty has convenient mathematical properties, and it results in an index which is easy to understand and use. These practical arguments are actually the most important because if the index is hard to use, it will simply not be used.

A simple example will show how a quadratic "mean square error" penalty can be used to rank houses. If one house is always 3C too cool in the winter, while another house is just right on 2 sunny days but 5C too cold on a third day, a quadratic penalty predicts that the average person would find the second house slightly more comfortable, despite the occasional excursions in that house. If that 5C excursion occurred half of the time, then a quadatic penalty predicts that people should fairly clearly prefer the more consistent house. This comparison assumes that the excursions occur over periods of several days; variations within a day are further penalized by the penalty for transient effects described below.

## 5. EVALUATING THERMAL TRANSIENT EFFECTS

The basic argument for penalizing thermal transients is that different houses may have the same annual distribution of values of E but different behavior within each day. Houses with short-term transients should be penalized more heavily, since they force occupants to adjust their clothing frequently.

A simple way of handling this is to compute the mean square rate of change of the error E. This scheme overly penalizes high-frequency variations unless the transients are filtered to damp the high-frequency components. We filter the variations as follows:

$$E_{old} = (E_{old} + E_0)/2 \qquad [6]$$

$$R = E_0 - E_{old} \qquad [7]$$

where $E_{old}$ is the "decaying" history, $E_0$ is the temperature error for the current hour, and R is the ramp rate in degrees/hour. The updated value of $E_{old}$ is saved till the next hour. R is then squared to obtain the transient penalty.

Data reported by Berglund & Gonzales (12) indicates that many people in controlled test environments actually find ramps in temperature over a day more comfortable than a fixed temperature. Their work compared fixed conditions with a fixed ramp rate of .6C/hr over an 8 hour period (for a total range of 5C). Basing our transient penalty on E rather than on the ET means that the preferred ET in a house should vary about .5-1C during a day. Since this is in addition to the 2C shift in PT between day and night, our assumptions predict that the optimum indoor diurnal range is about 2.5-3C. We use this implicit optimum profile only because there is no adequate evidence for a more complex profile or a larger ramp.

The above transient penalty is based on the "bother" of adjusting clothing, so transients which occur when people are changing their clothing anyway should not be penalized. We assume this occurs at 7 am and 11 pm, and also at 4 pm in houses which are unoccupied during the day. Our algorithm for transient penalties handles these occasions by replacing $E_{old}$ with the current E and setting the transient penalty to 0. Non-optimum temperatures at those times are still penalized—it is only the transient effects that are disregarded.

## 6. SOME EXCLUDED ISSUES

Detailed HVAC calculations for large buildings model spatial variations in conditions explicitly, and thus calculate a PPD for different locations in a building. If those scores are averaged, the result will be a higher PPD score in buildings with spatial variations than in buildings which are uniform in temperature. The LPPD concept (Lowest Possible Percentage of Dissatisifed) is based on this (2), and allows an estimate of the discomfort due purely to spatial variations in a building.

The same logic cannot be applied to simulation of residential buildings, even if simulation models were to accurately indicate local temperatures in a house. The LPPD concept assumes that people are arbitrarily assigned to different locations in a building. As a result, local variations in conditions will always displease more people than they please. In a home, on the other hand, occupants can each choose their favorite locations (next to the Trombe wall, etc.). The end result might be higher levels of comfort than if the house were completely uniform.

Two related issues have also been excluded. Houses with easily predictable temperature histories will permit anticipatory adjustments to clothing levels. This will tend to minimize the discomfort associated with thermal transients. Houses with easily adjusted temperatures will have a slightly different advantage, in that temporary shifts in PT due to activity level variations can easily be accommodated.

Humidity has an effect on overall sensations of warmth, as discussed in the ET section. It also has intrinsic effects on comfort, as indicated by the connotations of the words "parched" and "clammy". Buildings with attached greenhouses will have higher than usual humidities indoors, and this effect can carry through even at night, since many materials such as rugs, upholstery, and wood can absorb and store moisture brought into the house. However, current simulation programs do not model humidity effects properly, so there is no reason to try to incorporate them in the discomfort index. Excluding intrinsic humidity effects from the discomfort index usually creates no bias, since most insulated, weather-stripped houses have similar humidities indoors.

The effect of W on the ET is based on an assumption that in cool rooms, humidity variations affect thermal sensations by affecting latent heat losses through respiration and passive skin diffusion. High humidity reduces latent losses, so people should feel warmer. This seems to run against everyday experience: people complain more about the cold when it is damp than when it is dry. Such complaints may stem from a lower-than-average MRT when it is damp (no direct or stored solar gains), but they may also due to variations in skin or clothing properties. If such effects exist, then the ET concept requires some changes.

Ventilating a room not only reduces $T_{air}$ but also improves convective cooling and thus has a direct cooling effect on occupants. If the effect of ventilation on the relative air velocity between air and occupants is known, then the reduction in ET can be estimated from charts in (1). Note that if people are active, relative air velocities can be high even in still air. Estimating discomfort in well-ventilated buildings in warm weather requires a more careful treatment of both humidity and air movement than is possible with the linear ET equations, but [2] and [3] should be adequate for the heating season.

Additional effects related to thermal comfort in residences which have not been included in the discomfort index include assymmetric radiation, the cooling effect of drafts in poorly weatherstripped buildings, foot comfort in contact with floors, possible benefits of variety in thermal sensation, and special considerations for children, the elderly, and infirm people. These issues are discussed at length in (1,2,3,8,13). Fanger also discusses (8) the notion of "positive comfort": the possibility that some environments may be more pleasurable than others which provide the same net thermal sensation. An issue related to "positive comfort" is that environments with a high MRT, low $T_{air}$, and low W will tend to be comfortable over a wider range of activity levels than environments with higher MRT and W.

The issues listed above have been excluded either because they would require a quantum leap in complexity, or because they cannot be modelled well at any level of complexity. They affect the rankings of various houses only if their net effect on comfort varies significantly with parameters under study.

## 7. USING THE DISCOMFORT INDEX

The penalties for steady-state and transient effects can be integrated over time if the relative importance of different times of day is specified. We use full weight from 7am to 11pm and half weight at night. For simulating houses which are unoccupied during the day (9am - 4pm), we use a day thermostat setback and zero daytime comfort weighting. These schedules are only default values; other schedules can be used.

The effective temperature deviation or error E is the difference between the ET [2] and the PT [4]:

$$E = .51\,T_{air} + .42\,MRT - 21.4\,Celsius - .06\,T_{amb} + N \quad [8]$$

Programs which calculate "room temperature" rather than $T_{air}$ and MRT can substiturte ".93 $T_{room}$" for the first two terms in [8]. The use of a room node in comfort calculations underestimates the importance of $T_{air}$ and hence introduces biases in estimating the comfort effects of HVAC system operation (11).

Values of E and $E^2$ can be averaged over a heating season to obtain the mean error (ME) and the mean squared error (MSE) in the ET of a house. The ME indicates whether the ET is too high (+) or low (-) on the average. The MSE is the quadratic penalty for non-optimum temperatures. $(ME)^2$ of this penalty is due to the average error, and the rest is due to scatter in the error. The penalty for transient effects is the weighted mean square of the filtered ramp rate R (in degrees per hour), and can be referred to as the MSR.

The MSR has no analogue in ASHRAE literature, but the ME and MSE are analogous to the concepts of the PMV (Predicted Mean Vote) and PPD (1,2,14,15). The MSR simply adds a penalty for transients insofar as they force clothing changes.

Changing the $PT_{base}$ does not affect the MSR, but it does change the ME and MSE. Since the ME and MSE are first and second moments about the $PT_{base}$, the ME and MSE for a $PT_{base}$ X other than 25C (77F) are:

$$ME_X = ME_{25} + (1-K)(25-X) \quad [9]$$

$$MSE_X = MSE_{25} - (ME_{25})^2 + (ME_X)^2 \quad [10]$$

The relative weight of the MSR and the MSE in an overall discomfort index may be estimated indirectly by ranking episodes which are designed to test the tradeoffs between transient and steady-state effects. Such episodes consist of an dual ramp that begins and ends at the same uncomfortably low temperature. If such an episode is very long, then transient penalties can be neglected, and the most comfortable episode will have a temperature ramp which minimizes the MSE. (To do so, it must be too warm in the middle, by half the amount that it is too cold at the endpoints.) In short episodes, however, the transient penalty becomes important, and so the most comfortable episode will have a smaller variation and thus a lower $T_{middle}$.

Predictions of the most comfortable episode depend on both the weight assigned to the MSR relative to the MSE and the half-life used to filter high-frequency transients. We use a half-life of one hour and an MSR/MSE weight of 5:1 because they predict optimum episodes that seem reasonable (16). The MSR is always much smaller than the MSE, so even with 5:1 or higher weights assigned to the MSR, it has little effect except with poorly-controlled or high-direct-gain houses. If simplicity is important, the MSE can serve as the discomfort index and the MSR need not even be computed. If the MSR is computed, then the overall discomfort index (DI) is:

$$DI = MSE + 5\,MSR \quad [11]$$

The DI can be interpreted physically: its square root indicates what fixed deviation from the PT is most representative of the average level of steady-state plus transient thermal discomfort in a building. A conventional home with R19/R11 insulation and double-glazed windows will have a DI of about 16 (in Celsius ET units) if $T_{air}$ is kept at 20C (68F) during the day, with a 4.5C (8F) thermostat setback between 11pm and 7am. This baseline DI can serve as a reference point for parametric studies of house designs and/or operating strategies. Work described in (16) indicates that passive houses with the same thermostat settings can have a much lower (or much higher) DI.

Changes in thermostat setpoints will normally have opposite effects on the DI and energy use, so it is useful to combine these effects into an overall thermal performance or comfort cost index, CCI:

$$CCI = d\,DI + C_e \quad [12]$$

where d is the weight attached to discomfort and $C_e$ is the estimated present value of the life-cycle energy cost of heating the building.

It is possible to infer the proper weight d and the proper $PT_{base}$ to use in a given case from data on preferred heating and venting temperatures. First a set of simulations is done, with the heating and venting setpoints varying around the preferred values, and CCI values are calculated for a range of d and $PT_{base}$ values. The weather chosen for the simulations must result in significant loads for both heating and venting. Then the proper values of d and $PT_{base}$ are whichever values predict that the preferred setpoints minimize the CCI. For accurate calibration, it is necessary either to assign some positive or negative value to the side-effects of ventilation, or to assume that venting is done only for cooling purposes and has no other value associated with it.

Once the PTbase and discomfort weight d are calibrated for a given set of preferences, it is possible to truly optimize overall thermal design by minimizing the CCI. We have not yet formulated rules of thumb for this calibration process, but we have found that a PTbase of 25C (77F) seems consistent with wintertime heating/venting settings near 20C/25.5C (68F/78F) and 4.5C (8F) night setbacks.

An algorithm which computes the discomfort index is included as an appendix. It is written in Pascal for maximum readability.

## 8. CONCLUSION

The discomfort index described above is easy to use. It ranks house designs and operating strategies based on their overall comfort implications, and thus permits a more balanced comparison of various passive, hybrid, active, and conventional house and HVAC system designs. The index should be particularly useful in evaluating buildings which use off-peak heat, intentionally under-sized HVAC systems, or no conventional HVAC system at all, and can identify and evaluate worst-case episodes in those buildings.

The inputs to the index (ME, MSE, and MSR) are useful in identifying and solving design problems once the index has indicated their existence. Those inputs can also aid in cross-calibrating simulation programs, because they provide a concise summary of what is left out when energy use predictions are compared.

Studies of building design and control strategies which report the discomfort index along with energy use can be found in (16). Those results are expressed using Wray's "equivalent temperature" scale (7) in degrees Fahrenheit, and are $(1.8/.93)^2$ as large as on the Celsius ET scale. It is recommended that future work always report results in terms of the Celsius ET scale, and that the PTbase, K, N, and time-of-day weights used always be listed with the results.

## 9. ACKNOWLEDGEMENTS

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## 11. APPENDIX: COMPUTING THE DISCOMFORT INDEX

```
{Initialization & report procedures are in ref. 16.}
Var {GLOBAL VARIABLES:}
    SimpleVersion, Empty9to4: Boolean;
    Hour, Day: Integer;
    SumDaily, SumWeights, Air, MRT, Amb, Eold: Real;
    Weight, SumE, SumE2, SumR2: Array[1..24] of real;
    DailyDI: Array[1..365] of real;
PROCEDURE COMFORT;   {done each hour}
Var {LOCAL VARIABLES:} E, E2, R2: Real;
   Begin
   If Hour in [7..22]
       then E:= 0.51*Air + 0.42*MRT - 0.06*Amb - 21.4;
       else E:= 0.51*Air + 0.42*MRT - 0.06*Amb - 19.4;
   E2:=Sqr(E);
   SumE[Hour]:= SumE[Hour]  + E;
   SumE2[Hour]:=SumE2[Hour] + E2;
   If SimpleVersion then Exit(COMFORT);
   If Hour=1 then SumDaily:=0;
   If ((Hour in [7,23]) or (Empty9to4 and (Hour=16)))
       then begin Eold:=E; R2:=0; end
       else begin
             Eold:=(Eold + E)/2;
             R2:=Sqr(E-Eold);
             end;
   SumR2[Hour]:=SumR2[Hour] + R2;
   SumDaily:=(E2 + 5*R2) * Weight[Hour] + SumDaily;
   If Hour=24
       then DailyDI[Day]:=SumDaily/SumWeights;
   End;
```

APPENDIX 2

Humidity Parameters
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# ASHRAE HANDBOOK

# 1981 FUNDAMENTALS

*An Instrument of Service*
*Prepared for the Profession*
*containing*

A TECHNICAL DATA SECTION OF REFERENCE MATERIAL PERTAINING TO SYSTEMS FOR HEATING, REFRIGERATING, VENTILATING, AND AIR CONDITIONING, AND BASED ON—ASHRAE TRANSACTIONS—THE INVESTIGATIONS OF THE ASHRAE RESEARCH PROGRAMS AND COOPERATING INSTITUTIONS—AND THE PRACTICE OF THE MEMBERS AND FRIENDS OF THE SOCIETY: COMPLETE INDEX TO TECHNICAL SECTIONS OF ALL CURRENT VOLUMES.

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AND
AIR-CONDITIONING ENGINEERS, INC.
1791 TULLIE CIRCLE NE, ATLANTA, GA 30329

## THERMODYNAMIC PROPERTIES OF WATER AT SATURATION

Table 3, Chapter 6, shows thermodynamic properties of water at saturation in conventional U.S. units, for temperatures from −80 to 300 F, calculated by the formulations described in Ref 7. Symbols in the table follow standard steam table nomenclature. Table 4 of Chapter 6 shows corresponding properties in SI units for temperatures from −60 to 200°C.

In determining a number of moist air properties, principally the saturation humidity ratio, the *water vapor saturation pressure* is required. Values may be obtained from Table 3 or 4 of Chapter 6 or calculated from the following formulas, published in Ref 7.

The saturation pressure over *ice* for the temperature range of −100°C (−148 F) to 0°C (32 F) is given by:

$$\ln(p_{ws}) = C_1/T + C_2 + C_3 \cdot T + C_4 \cdot T^2 + C_5 \cdot T^3 + C_6 \cdot T^4 + C_7 \cdot \ln(T) \qquad (3)$$

*where:*

$C_1 = -5674.5359$
$C_2 = 6.3925247$
$C_3 = -0.9677843 \times 10^{-2}$
$C_4 = 0.62215701 \times 10^{-6}$
$C_5 = 0.20747825 \times 10^{-8}$
$C_6 = -0.9484024 \times 10^{-12}$
$C_7 = 4.1635019$

The saturation pressure over *liquid water* for the temperature range of 0°C (32 F) to 200°C (392 F) is given by:

$$\ln(p_{ws}) = C_8/T + C_9 + C_{10} \cdot T + C_{11} \cdot T^2 + C_{12} \cdot T^3 + C_{13} \cdot \ln(T) \qquad (4)$$

*where*

$C_8 = -5800.2206$
$C_9 = 1.3914993$
$C_{10} = -0.048640239$
$C_{11} = 0.41764768 \times 10^{-4}$
$C_{12} = -0.14452093 \times 10^{-7}$
$C_{13} = 6.5459673$

In both Eqs 3 and 4,

$\ln = \log_e$
$p_{ws}$ = saturation pressure, Pa (1 Pa = 0.000145 psi)
$T$ = absolute temperature, K (K = °C + 273.15)

## FUNDAMENTAL HUMIDITY PARAMETERS

*Humidity ratio* (alternatively, the moisture content or mixing ratio) $W$ of a given moist air sample is defined as the ratio of the mass of water vapor to the mass of dry air contained in the sample:

$$W = m_w/m_a \qquad (5)$$

*Mole fraction* ($x_i$) of a given component in a mixture is equal to the number of moles ($n_i$) of that component divided by the total number of moles ($n$) of all components in the mixture. The mole fraction for dry air is $x_a$; for water vapor, $x_w$; for water vapor at saturation, $x_{ws}$. By definition, $x_a + x_w = 1$. Also, the humidity ratio ($W$) is equal to the mole fraction ratio ($x_w/x_a$) multiplied by the ratio of molecular weights; namely, 18.01534/28.9645 = 0.62198, i.e.:

$$W = 0.62198\, x_w/x_a \qquad (6)$$

*Specific humidity* $q$ is the ratio of the mass of water vapor to the total mass of the moist air sample:

$$q = M_w/(M_w + M_a) \qquad (7)$$

In terms of the humidity ratio:

$$q = W/(1 + W) \qquad (8)$$

*Absolute humidity* (alternatively, water vapor density) $d_v$ is the ratio of the mass of water vapor to the total volume of the sample:

$$d_v = m_w/V \qquad (9)$$

The *density* $\varrho$ of a moist air mixture is the ratio of the total mass to the total volume:

$$\varrho = (M_a + M_w)/V = (1/v)(1 + W)$$

*where* $v$ is the moist air *volume,* ft³/lb dry air, as defined by Eq 25.

## HUMIDITY PARAMETERS INVOLVING SATURATION

The following definitions of humidity parameters involve the concept of moist air saturation:

*Saturation humidity ratio* (mixing ratio) $W_s(t, p)$ is the humidity ratio (mixing ratio) of moist air saturated with respect to water (or ice) at the same temperature $t$ and pressure $p$.

*Degree of saturation* $\mu$ is the ratio of the air humidity ratio $W$ to the humidity ratio $W_s$ of saturated air at the same temperature and pressure:

$$\mu = \left.\frac{W}{W_s}\right|_{t,p} \qquad (10)$$

*Relative humidity* $\phi$ is the ratio of the mole fraction of water vapor $x_w$ *in a given moist air sample to the mole fraction* $x_{ws}$ in an air sample, saturated at the same temperature and pressure:

$$\phi = \left.\frac{x_w}{x_{ws}}\right|_{t,p} \qquad (11)$$

Combining Eqs 6, 10, and 11:

$$\phi = \frac{\mu}{1 - (1 - \mu)x_{ws}} \qquad (12)$$

*Dew point temperature* $t_d$ is the temperature of moist air, saturated at the same pressure $p$, with the same humidity ratio $W$ as that of the given sample of moist air. It is defined as the solution $t_d(p, W)$ of the equation:

$$W_s(p, t_d) = W \qquad (13)$$

*Thermodynamic wet-bulb temperature* $t^*$ is the temperature at which water (liquid or solid), by evaporating into moist air at a given dry-bulb temperature $t$ and humidity ratio $W$, can bring air to saturation adiabatically at the same temperature $t^*$, while the pressure $p$ is maintained constant. This parameter is considered separately in a later section.

## PERFECT GAS RELATIONSHIPS FOR DRY AND MOIST AIR

When moist air is considered to be a mixture of independent perfect gases, dry air, and water vapor, each is assumed to obey the perfect gas equation of state:

$$\text{dry air: } p_a V = n_a RT \qquad (14)$$

$$\text{water vapor: } p_w V = n_w RT \qquad (15)$$

*where* $p_a$ is the partial pressure of dry air, $p_w$ is the partial pressure of water vapor, $V$ is the total mixture volume, $n_a$ is the number of moles of dry air, $n_w$ is the number of moles of water vapor, $R$ is the universal gas constant [8.31441 J/(g mol) · K or 1545.32 ft-lb$_f$/lb-mol · F(abs)], and $T$ is the absolute temperature. The mixture also obeys the perfect gas equation:

$$pV = nRT \qquad (16)$$

or

$$(p_a + p_w)V = (n_a + n_w)RT \qquad (17)$$

Appendix 3

# Lawrence Berkeley Laboratory
# Air Infiltration Model

An AIR INFILTRATION MODEL is described in the following. The primary input to the model is the air leakage of the entire building envelope, which is given as an effective leakage area:

$$L = Q \left(\frac{\rho}{2\Delta P}\right)^{1/2}$$

where $Q$ is the airflow ($m^3/s$)
$\Delta P$ is the pressure drop across the building envelope (Pa)
$L$ is the effective leakage area ($m^2$) and
$\rho$ is the density of air ($kg/m^3$).

Because the pressures driving infiltration are normally within a limited range (1 to 10 Pa), the effective lakage area is calculated for a pressure difference of 4 Pa.

The forces that drive infiltration are pressure differences across the building envelope caused by wind forces and by indoor-outdoor temperature differences. The stack-induced infiltration is calculated as follows:

$$Q_s = L\, f_s \; (\Delta T)^{1/2}$$

where $Q_s$ is the stack-induced infiltration ($m^3/s$)
$f_s$ is the stack parameter ($m/sK^{1/2})$) and
$\Delta T$ is the inside-outside temperature difference (K).

The stack parameter is given by the following expression:

$$f_s = -\frac{(1+R/2)}{3} \left| 1 - \frac{X^2}{(2-R)^2} \right|^{3/2} \frac{gH}{T}^{1/2}$$

where $R = \dfrac{L_{floor} + L_{ceiling}}{L_{tot}}$

$$X = \frac{L_{ceiling} - L_{floor}}{L_{tot}}$$

$g$ is the acceleration of gravity ($m/s_2$),
$H$ is the inside height of the structure (m) and
$T$ is the inside temperature (K).

The wind-induced infiltration is calculated as follows:

$$Q_w = L\ f_w\ v$$

where $Q_w$ is the wind-induced infiltration ($m^3/s$)
$f_w$ is the wind parameter (dimensionless) and
$v$ is the wind speed (m/s)

The wind parameter is given by the following expression:

$$f_w = C'\ |(1-R)^{1/3}|\ \left(\frac{\alpha\ (\frac{H}{10})^{\gamma}}{\alpha'\ (\frac{H'}{10})^{\gamma'}}\right)$$

where $C'$ is the generalized shielding coefficient (see table 1).
$\alpha$, $\gamma$ are terrain parameters (see table 2) at the structure,
$\alpha'$, $\gamma'$ are terrain parameters at the site of the wind measurements,
$H$ is the inside height of the structure (m) and
$H'$ is the height of the wind measurement (m).

Table 1. Generalized shielding coefficients

| Shielding Class | C' | Description |
|---|---|---|
| I | 0.324 | No obstructions or local shielding whatsoever |
| II | 0.285 | Light local shielding with few obstructions |
| III | 0.240 | Moderate local shielding, som obstructions within two house heights |
| IV | 0.185 | Heavy shielding, obstructions around most of perimeter |
| V | 0.102 | Very heavy shielding, large obstruction surrounding perimeter within two house heights |

Table 2. Terrain parameters for standard terrain classes

| Class | | | Description |
|---|---|---|---|
| I | 0.10 | 1.30 | Ocean or other body of water with at least 5 km of unrestricted expanse |
| II | 0.15 | 1.00 | Flat terrain with some isolated obstacles |
| III | 0.20 | 0.85 | Rural areas with low buildings, trees or other scattered obstacles |
| IV | 0.25 | 0.67 | Urban, industrial or forest areas or other built-up area |
| V | 0.35 | 0.47 | Center of large city or other heavily built-up area. |

The air flow resulting from the two driving forces must be combined to arrive at the total infiltration. If the expression for wind- og stack-induced infiltration are interpreted as effective pressure differences across the leakage area of the structure, the total infiltration can be determined by adding these pressures. If the flow is proportional to the square-root of the pressure, then two flows acting independently must add as follows:

$$Q_{tot} = (Q_w^2 + Q_s^2)^{1/2}$$

This equation is useful for a structure without any specially designed ventilation system. Many new houses do however have unpowered vents or a mechanical ventilation system. Unpowered vents protrude beyond the envelope and should therefore not be included into the total leakage area. Their ventilation should be calculated separately.

The ventilation through the vents should be combined with the other flows using superposition:

$$Q_{tot} = (Q_w^2 + Q_s^2 + Q_{vent}^2)^{1/2}$$

If the house is equipped with an exhaust fan the same discussion as for an unpowered vent applies i.e.

$$Q_{vent} = Q_{exhaust\ fan}$$

where $Q_{exhaust\ fan}$ is the rating of the fan ($m^3/s$).

A balanced ventilation system should not affect the pressure drop across the envelope caused by natural driving forces. The fan flow can therefore simply be added to the natural ventilation:

$$Q_{tot} = Q_{fan} + (Q_w^2 + Q_s^2)^{1/2}$$

where $Q_{fan}$ is the rating of the fan ($m^3/s$).

The best approach to improving model estimation may be the combined use of a model and tracer gas measurements. The results of tracer gas can be compared to model predictions for the same period as a means of "adjusting" the model.