INTERNATIONAL ENERGY AGENCY

energy conservation in buildings and community systems programme

Annex III

Residential Buildings Energy Analysis

Guiding Principles Concerning Design of Experiments, Instrumentation, and Measuring Techniques

Swedish Council for Building Research

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GUIDING PRINCIPLES CONCERNING DESIGN OF EXPERIMENTS, INSTRUMENTATION AND MEASURING TECHNIQUES

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PREFACE

INTERNATIONAL ENERGY AGENCY

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Program was formulated among a number of industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organization for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under special arrangement.

As one element of the International Energy Program the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy techologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

ENERGY CONSERVATION IN BUILDINGS AND COMMUNITY SYSTEMS

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programmes, building monitoring, comparison of calculation methods etc. The differences and similarities among these comparisons have told us much about the state of the art in building analysis and have led to further IEA sponsored research.

ANNEX III RESIDENTIAL BUILDINGS ENERGY ANALYSIS

Energy conservation retrofits are an important part of the energy saving plan in all IEA countries. For the individual home-owner as well as for the nation as a whole, it is vital that correct evaluations can be made of the energy saving potential of different retrofits. Since most of the analysis and installation of these retrofits are not done by architects and/or engineers, there is considerable concern that the retrofits will not be properly selected nor perform up to expectations.

All IEA countries need to develop for the marketplace simple, reliable calculation methods. The calculated recommendations then need to be applied in houses and tested for validity.

Recommendations may include new heating, ventilation and air conditioning systems, new appliances, new insulating material, new glazings etc. Because of the large number of possibilities of calculation types and recommended retrofits, international co-operation will accelerate the resolution of the problems involved.

The main problem, common to all, is how to generalize experimental results from time to time, place to place, on the national level. If this probem is solved, findings in one country could also be used in another, and consequently extensive national research programmes could be reduced and retionalized.

In order to generalize experimental results two things are needed: A reliable technique to observe and measure the conservation effect, and methods for converting these data to other environments. The main effort in Task III has therefore been made at finding the limitations and the best use of a number of calculation models that are currently used for predicting the energy consumption of dwellings (Subtask A), and at collecting and summarizing guiding principles concerning the design of experiments, instrumentation and measuring techniques (Subtask B). Finally the results of these two subtasks have been used when studying the energy conservation effect of a night-temperature setback in dwellings (Subtask C).

The participants in the Task are: Belgium, Denmark, Italy, the Netherlands, Sweden, Switzerland, Turkey, and the United States.

This report documents work carried out under subtask B of this task. The cooperative work and resulting report is described in the following section.

EDITORS FOREWORD

The aim of this Report is to supply to technicians and scientists involved in energy conservation in buildings the basis for setting an experimental apparatus devoted to the evaluation of retrofit effects. The word "retrofit" represents every operation on a building aiming at a reduction of its energy demand. Side effects, e.g., on indoor comfort, rising from retrofit actions, are also taken into consideration.

Italy, as the Lead Country, proposed to the other Participants the contents of this Report in September 1979. Afterwards, the Participants of all Countries, including the Lead Country, took upon themselves the responsibility for one or more items, according to their personal interest, field of research, and to the experience of their Institutes and/or Organizations. Every Participant engaged himself to convey Report B material to competent organizations in his own country, whenever the topic was beyond his specific knowledge, in order to obtain advice and suggestions.

Since September 1981, when the first draft of this Report was completed several meetings were held, both in the framework of Annex III, and specially devoted to Subtask B, in which the contents of every single chapter were discussed among Subtask B Participants and in case revised. Suggestions from other Annex III Participants have also been considered.

In September 1981 the first draft of the Report was distributed to all Participants and to a number of experts from each Country. Their comments were collected and delivered to the Lead Country by each Participant.

At the beginning of 1982 the Lead Country member started the complete rewriting and editing of the Report together with the Swedish Participant. Overlappings were thus eliminated, the single Chapters were rearranged in such a way that a better balance among the various items was achieved. The second draft of the Report was therefore completed in April 1982 and delivered to all the Participants of Annex III.

At the last Working Meeting in June 1982, the Report was again discussed in detail and new modifications were suggested. The Report was therefore revised, and the third draft was ready by the end of September 1982, and delivered to the participants of the Subtask for final comments. Thereafter the final draft was prepared by the Editors and sent to the Executive Committee of the IEA Energy Conservation in Buildings and Community Systems for approval in February 1983, whereafter the manuscript of this Report was written.

The experiments about energy retrofits on buildings studied in this Report are thought to be applied on a building level rather than on a national level as a basis for large-scale energy conservation plans.

No economical evaluations have been made, because that would have provided irrecoverable discrepancies among the Countries and would have accelerated the obsolescence of the Report. Moreover, even if a need for recommendations is felt in many Countries, the Report does not provide standards for the implementation of this kind of experiments. The principal idea was that every experiment has its own validity once it has been correctly planned, even if the available economic budget is not large and, consequently, the experimental goals are not ambitious. An effort has been made to describe a number of different methods and techniques for every kind of measurement pointing out the related advantages and disadvantages.

The building is such a complex system that the applied measurement techniques, experimental designs, and methods for evaluation have to be collected from many different research fields, such as building physics, meteorology, measurement technology, aerodynamics, statistics, mathematical modelling, social sciences etc. Particular emphasis was set on the description of the behaviour of occupants as regard to energy management and on how it can affect the experimental results.
The Report has been divided into four Sections:

I. BASIC PRINCIPLES

This Section describes the fundamental problems in planning experiments and provides general theory about the energy related features of the building, the environment, the heating system, and the occupants.

II. DESIGN OF THE EXPERIMENT

This Section provides a detailed analysis of different comparison procedures adopted to evaluate the energy retrofit effect. Significant examples are given to illustrate the procedures.

III. MEASUREMENTS ON BUILDING AND ENVIRONMENT

This Section describes the measurement techniques and the guidelines for sensor installation and data acquistion for every measurement field related to the building (infiltration, heat flow across the envelope, heating system) and the outdoor and indoor environments.

IV. MEASUREMENT ANO OATA COLLECTION ON OCCUPANCY AND HOUSEHOLD ENERGY

This Section is devoted to the study of the occupancy related terms in the energy budget. In this case, statistical i nformation is provided, along with measurement techniques.

All representatives of the Subtask B Countries have participated in the writing of this Report:

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Torino March 1, 1983

G.V. Fracastoro M.D. Lyberg

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BASIC PRINCIPLES

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- general introduction

The aim of this report is to provide the basis for the design and setup of experiments for the evaluation of the effects of energy conservation measures in residential buildings.

A number of methods can be applied to achieve this result, ranging from the mere measurement of indoor-outdoor temperatures and energy consumption to the most sophisticated monitoring techniques. Each method will produce an information, the quality of which depends on the complexity of the experiment and even more so on the quality of its design.

This report will describe how to perform those field measurements aiming at the determination of the energy flows through the building envelope. This requires the monitoring of physical quantities giving rise to the energy flows or describing the thermal comfort of the building occupants. We will often refer to these experiments as energy monitoring.

Field measurements, aiming at a quick check-up of the thermal performance of the building, are also considered in this report. These experiments are referred to as energy auditing.

This report, although its purpose is very specific, will therefore provide useful information about measurements on buildings in general, such as auditing and monitoring.

The Report consists of four Parts. The first one deals with general planning of the experiment, basic principles of building physics, thermal comfort and energy related behaviour of occupants. The second Part describes the design of the experiment, that is the comparison on which the evaluation of energy savings is based. The third Part is devoted to measurement techniques, data acquisition, and installation rules in the different fields of building physics and heating systems. Finally, the fourt Part deals with monitoring of occupants and their energy related activities.

- energy balance of a building

Buildings are complex systems, consisting of a great number of non-homogenous components. From the thermodynamic viewpoint they can be considered as open thermodynamic systems. The general expression for the energy conservation equation for this kind of system is:

$$\Sigma Q + \Sigma W + \Sigma H = \Delta U \qquad \text{(I a-1)}$$

where

Q is heat exchanged at the system boundary (>0 when entering the system)

W is work exchanged at the system boundary (>0 when entering the system)

H is enthalpy, i.e., energy associated with mass flows across the boundary (>0 when the mass enters the system)

U is the internal energy of the system (kinetic energy can be neglected)

When eq. I a-1 is applied to a building, the following steps should be considered:

1) definition of the system boundary
   This step is very important: what is contained in the building and what belongs to the environment? Is the heat generator a part of the system? A nonambiguous definition of the system boundary is necessary.

2) definition of the energy flows crossing the boundary
   Energy flows between the building and its environment are radiative, convective, and conductive heat transfers. Solar radiation, atmospheric radiation,and infrared emission from the building envelope are examples of radiative heat transfers. Convective heat transfers take place at the external and internal surfaces of the building enclosure. Examples of conductive heat transfer are heat transfers to the basement, and to the ground, across the building envelope.

3) definition of the work entering (or produced by) the system
   Work enters the building as electric energy. Examples are: electricity for appliances, illumination, cooking, and sometimes for space heating.

4) definition of the mass flows across the boundary
   Mass flows across the building envelope are: air flows in ventilation systems and air flow caused by infiltration, cold tap and sewage water,

gas for cooking etc. If the heat generator is part of the system, fuel and flue gases should be considered (the fuel enthalpy is roughly equal to its heating value); if the heat generator is not part of the system, supply and return water to the terminals should be considered as mass flows.

- the retrofit

A retrofit is defined as :

" a retrofit is an alteration of an existing system aiming at the improvement of its performance with regard to its function, but not introducing new uses of the system"

Therefore, building retrofits may refer to any of the functions accomplished by the building itself. However, in the context of this Report, a retrofit will refer to actions aiming at the reduction of energy consumption, or at the improvement of thermal comfort in residential buildings, or both.

Side effects of retrofits must also be taken into account and studied along with the determination of energy saving. This, in its turn, should not, in principle, be achieved at the expense of human thermal comfort, which should be in any case preserved or improved upon. An important question is therefore, what degree in energy reduction can the retrofit programme achieve.

In general, retrofits automatically lead to the improvement of comfort: for example, extra wall insulation and extra window glazing give rise to an increase of inside surface temperatures if the air temperature is kept constant. Such retrofits will also lead to a better insulation from external noise. Window tightening will cause a reduction of indoor draughts close to the windows, thus improving comfort.

On the other hand, superinsulated houses will often be uncomfortable during summertime and mid-seasons, due to the high amount of solar radiation and internal heat gains which cannot be dissipated by transmission through the envelope. Similarly, tightness of buildings should not be improved beyond a certain limit at which the natural removal of odours and pollutants is prevented. Typical retrofitting activities in house tightening have resulted in

10%-35% reduction in air leakage. Houses tightened may have an air change rate by natural ventilation which is less than 0.5 air changes per hour (ACH), in some countries it may even be as small as 0.1 ACH. With this degree of tightness mechanical ventilation is a necessity. If the air leakiness of houses can be made very small, then air-to-air heat exchangers can be justified as an additional energy conservation measure.

Other negative side-effects that have to be taken into account are, for instance, the possible appearance of moisture stains at the intersection with interior walls, due to emphasized cold bridges when applying extra wall insulation to the inside surface. Bad craftmanship will in some cases lead to similar effects.

It must be stressed that in central heating systems controlled through the measurement of outdoor air temperature no energy will be saved if the retrofit is not supported by a suitable readjustment of the control system.

Educational campaigns addressed to occupants must also be employed to prevent a retrofit from giving only rise to higher indoor temperatures, exceeding the comfort level. This can reduce the energy saving.

Little information has so far been gathered about side effects of retrofits, in particular about those altering the human behaviour. It is the task of the experimenter to investigate side effects produced by retrofits and their influence on the energy savings.

Retrofits can be classified as follows:

- retrofits improving the thermophysical properties of the building envelope
- retrofits improving the performance of the heating, lighting, tap water, or other systems in the building.

Some example of retrofits belonging to the first category are:

- window improvement
  . adding of extra glazing
  . replacing the existing glazing or window with a more energy efficient one
  . adding of an extra window (storm window)
  . sealing or weather stripping of the joints
  . sealing or insulation of the roller blinds container

- extra wall insulation
  - . insulation applied to the inside surface (prefabricated panels provided with gypsum board are commercially available)
  - . insulation in the air space of cavity walls (foam or granulous substances are poured or blown into it)
  - . insulation applied to outside surfaces (finished with materials resistant to thermo-mechanical stresses and watertight)

- roof insulation
  - . pouring, blowing or laying insulation on the loft floor
  - . placing the insulation layer below the ceiling
  - . placing a watertight, and thermomechanically resistant, insulation layer directly over the roof

- ground floor insulation
  - . applying the insulation to the cellar or crawl space below the floor

Some retrofits belonging to the second category are:

- improving the burner-boiler efficiency
- extra insulation of domestic hot water storage tank
- placing insulating-reflecting panels behind the heat emitters
- replacing tungsten filament lamps with fluorescent lamps
- zoning of heated space
- night temperature set-back
- heat recovery from mechanically exhausted air
- heat recovery from waste water
- placing thermostatic valves on heat emitters
- balancing of heating and ventilation systems
- installation of damper regulators
- installation of motorshunt valves

- experimental evaluation of the retrofit effect

A retrofit, as it was stated before, can produce both energy savings and the improvement of thermal comfort. The aim of the experiment is therefore to evaluate these two effects. Regarding the improvement of comfort, the effect of a retrofit cannot be defined in a precise way, as there are many different ways of qualifying the indoor climate (see ch. Ic and IIIc).

The energy saving, which is the main reason for a retrofit, can be defined as the variation of energy consumption, due to the retrofit itself, over a certain period (usually one heating season).

Therefore we define the retrofit effect as:

" the retrofit effect is the amount of energy saved by a retrofit if all factors are kept constant except for the retrofit itself, and changes in the behaviour of the occupants induced by the retrofit.

Sometimes it will be convenient to compare the retrofit effect to, e.g., the average of the energy consumptions in the retrofitted and non retrofitted buildings. The relative retrofit effect will therefore be defined as the ratio of: the retrofit effect to the average of the energy consumptions in the retrofitted and the non retrofitted buildings.

The retrofit effect should not be confused with the observed energy saving. This one will be influenced by differences in external climate, indoor climate, and changes in the occupancy and behaviour of the occupants not due to the retrofit. Knowledge of the impact of the occupants' behaviour on energy consumption in residential buildings (see ch. Ie and Part IV) is still quite scarce, and there is even less information about how occupants react to retrofit actions. Moreover, the effect of the quality of craftmanship has seldom been investigated.

These factors can only be partially taken into account and correctly introduced in even the most sophisticated theoretical models of building thermal behaviour. Yet, as experience shows, these factors are responsible for marked differences between the expected and the measured results. Therefore, there are good reasons why the evaluation of retrofit effects should be checked experimentally on buildings where people actually live.

The experiment itself will consist in the comparison of the energy consumption in retrofitted and non retrofitted buildings. This comparison is made difficult by the fact that energy consumption depends not only on the building thermal features, but also on uncontrollable factors, i.e. the occupants behaviour and the weather. Some facts that should be taken inte account by the experimenter are:

- it will always be hard to separate the retrofit effect from the effect due to the variation of the other factors
- these types of experiments are expensive and time consuming: consequently a superficial or hasty planning could result in a great waste of time and money
- the building, the heating system, and the occupants represent a complex and heterogeneous system which will react with different promptness and intensity to changes such as retrofits
- performing more than one retrofit at a time will introduce uncertainties in the evaluation of their individual effect.

Some general criteria for performing a good experiment should also be taken into account by the researcher. They are contained in the following quotation:

"The requirements for a good experiment are that the ... comparisons should as far as possible be free from systematic error, that they should be made sufficiently precisely, that the conclusions should have a wide range of validity, that the experimental arrangement should be as simple as possible, and finally that the uncertainty in the conclusions should be assessable" (Cox 1958).

Further details will be described in ch. II a. See also general texts on engineering experimentation (e.g. Schenk 1961)

- <u>planning of the experiment</u>

In this section an outline of the whole planning of the experiment will be presented. The discussion below will be restricted to problems associated with the <u>scientific methodology</u>. Questions concerning <u>project management</u> in a broad sense will only be touched upon in a short way, as the reader of this Report is expected to be a researcher with some experience of performing field experiments.

It would seem logical to start the experiment by considering first the <u>workplan</u> for the scientific part of the project, and from this draw conclusions about the <u>resources</u> in time, money and people necessary for the realization of the project. In reality, the situation is very often the opposite; it is not convenient to make any detailed plans for the experiment before the available resources for the project are known. However, the decision that the project has to be performed may be received by short notice and it is therefore essential that the project manager has in advance a hierarchy of alternative plans about how the experiment should be performed, related to what resources will be allocated. Due to inevitable modifications in the available financial budget and changes in the time schedule, the plans should be flexible. The time schedule should also be flexible, but some fixed deadlines for important stages of the project should be established.

The team performing the experiment and the equipment are the two major resources needed. At different stages of the project, the team may include technicians for the desigh of the measurement equipment, computer specialists for writing the data collection programs, a monitoring crew for the installation, surveillance and maintenance of the equipment, psychologists and social scientists for the evaluation of the behaviour of the occupants, scientists for the analysis of the results and for the writing of the final report, and finally project managers. For further details about this topic see Day, 1983.

The experiment can be considered as consisting of eight connected steps, the most relevant of which will be further discussed in ch. IIa, IIIa and IIIg:

1 - task
2 - aim of the investigation
3 - evaluation of the problem
4 - description of the system
5 - design of the experiment and choice of the model
6 - planning of measurements
7 - measurement campaign
8 - analysis of data

1. Task

The first step in the procedure will often be a request made to the experimenter by a customer (an administrative authority, a superior, a public utility etc.) to solve a general problem as "what is the energy saving which can be achieved through a certain retrofit?" This request will establish the main limitations, and objectives, of the investigation in detail. The financial budget and the available time will generally be proposed by the customer at this stage. The task assigned to the researcher will consist of questions requiring target-directed, practical and generalizable answers, according to the customer's purpose.

2. Aim of the investigation

The problem, qualitatively defined at the previous stage, has now to be clearly defined. Although the problem has been presented in general terms, it is now necessary to choose, a specific sample, if this has not been chosen previously. Practical circumstances will limit this choice. Nevertheless, the object(s) of the investigation should be chosen so that no large systematic errors are introduced in the experiment. Different approaches are possible. The two extreme cases are:

- a single apartment, house, or building can be chosen, representative of a certain population of buildings and occupants
- a larger sample can be used to minimize the influence of uncontrollable variables

The smaller the sample to be investigated is, the more complex the experimental apparatus will have to be.

3. Evaluation of the problem

At this stage the experimenter must check if he can solve the problem using existing knowledge. If the reply is affirmative, there is no need for an experimental evaluation. Otherwise, he will have to make a rough estimate of the energy savings using a simple, static model, neglecting the effect of occupants, making use of typical meteorological data and taking into account the characteristics of the control system. Once a rough estimate of the energy savings has been made, it should always be verified whether the uncertainties are still so large as to require an experimental evaluation.

4. Description of the system

The next step is to construct a descriptive model of the system to be investigated. First of all, the system boundaries must be defined. The energy flows across the boundary and those coming from internal sources are desribed. Their importance will depend on weather factors (W), on the required indoor climate (I), on the thermal performance of building components (B), and on energy related activities of the occupants (O). Therefore, the researcher must now decide what interactions have to be considered between B, O, W, I and what building components are involved in the energy dynamics. For further discussion of this topic see ch. IIa.

5. Design of the experiment and choice of the model

The design of the experiment and the choice of the model are the very heart of the planning of the experiment. The design of the experiment is the procedure used to compare the retrofitted and non retrofitted buildings. It should reduce the influence of some uncontrollable factors, such as O or W, on the energy evaluations. The design of the experiment is limited by practical reasons, such as time and money.

Along with the design of the experiment a model is constructed. In it, the energy flows of the system are formally described by a set of equations. If the relations appearing in the model are well known, and reliable records of O-or W-related factors already exist, a theoretical calculation would be preferable to an experiment.

If, on the other hand, only one building component is involved in the model and the influential factors can be reproduced under controlled conditions, a laboratory experiment can be performed.

Otherwise a field experiment will be preferable. The time resolution, the required accuracy and the resolution of the measurements are decided at this stage, as well as the course and duration of the experiment. For further discussions, see ch. IIa and IIIa.

6. Planning of the measurements

At this stage the technical questions related to the measurements have to be solved. The measurable quantities pertain to different disciplines (meteorology, engineering, social sciences etc.), and therefore different methods of measurement, such as direct measurements, observations, surveys, etc., have to be employed (see Chapter IIIa). Furthermore, the determination of the quality of craftmanship during the implementation of the retrofit, should be planned at this stage.

The whole measurement system from transducers to data storage has to be planned (see ch. IIIg). The sensors will be chosen along with installation rules and techniques (see ch. IIIg). The accuracy of the measurement chain can now be established and compared with the expected resolution of the model. If it turns out to be insufficient to match the model requirements, other measurement techniques should be chosen, or the model should be modified.

At this point, programs for on-line elaboration and surveillance of data should be prepared, data storage planned and the sampling time for every measured quantity chosen.

7. Measurement campaign

The first action in the measurement campaign will be the instruction of the monitoring crew. Then, the monitoring equipment should be installed in situ, without causing unnecessary disturbance to the occupants activities. The occupants will have to be instructed about what to do in case they unintentionally damage the apparatus or detect a malfunction.

The whole system should be tested before starting the measurement campaign. The monitoring crew should be given time to learn how to operate the measurement equipment and collect experience on how to treat frequently occuring malfunctions, there should be a "running- in and learning period" for the monitoring crew.

If all the previous steps have been carefully considered, during the measurement campaign only routine operations should be required, aiming at the prompt detection of any possible system malfunctions. These should be expected in this kind of experiment because of the complexity of the experimental apparatus and due to the fact that the occupants interfere with it.

Once the measurement campaign has started no alterations "a posteriori" of the previous points 5. and 6 should be made.

8. Analysis of data

After the measurement campaign has been terminated, every experiment requires the analysis and the interpretation of data, without which the whold procedure is meaningless.

First of all, bad data, stemming from previously undetected malfunctions, should be rejected from the data collection. The reasonable data should be used to estimate the numerical value of the parameters of the model. The model in its turn, is validated by checking the consistence of the values of the parameters with those provided by previous experience or knowledge. If all *checks are positive, it will be possible to use the model as a predictive model* and therefore to apply it to other - similar - buildings.

The experimentar should always write a report describing how he faced and solved the questions posed at each stage of the experiment and how the data were collected.

The results should be presented by using graphs and equations, as well as tables or statistical figures. If the task was to establish the retrofit effect, the model should now be used to correct the result from the effect of uncontrolled variables.

- Example

The following example will cover, step by step, the procedure described in the previous section: it has no other particular aim than the description of the suggested procedure.

1. Task: evaluate the energy saving by installing thermostatic valves.

2. Aim of the investigation: The aim is to evaluate the energy savings obtained by installing thermostatic valves having a 20°C set point on the radiators of a water-fed gas-fired heating system. The object is a multifamily building in a suburban area.

3. Evaluation of the problem: From previous knowledge on similar buildings, the average indoor temperature is estimated to 22°C. Therefore, if a previous energy bill Q. and the related degree-days DD_x are known, the retrofit effect R could be estimated by:

$$R = Q_c \, (1 - DD_{x-2}/DD_x) \qquad \text{(Ia - 2)}$$

where

x is the reference indoor temperature for the calculation of the degree-days

4. Description of the system: The energy flows in the system which are *taken into consideration are:*

- the heat delivered to the building from the heating system.
- the heat introduced in the building by solar radiation impinging on the windows facing south.
- the energy introduced by occupants through their presence, use of appliances, and opening of windows.
- the transmission heat loss through the building envelope.
- *the heat loss due to air infiltration*
- the heat stored in the building structure

5. Design of the experiment and choice of the model: Since the effect of occupancy variations has to be avoided, an experiment is chosen in which the same building is examined before and after the retrofit (before- after design of experiment, see ch. II c). The assumption is made that occupancy is independent of time, but that it may be influenced by the retrofit. The chosen model is, according to step 4.:

$$a*Q_c + b*Q_s + c - d*(\bar{T}_i - \bar{T}_o)\, n - e*\Delta T_{int} = 0 \qquad \text{(Ia - 3)}$$

where:

a represents the average efficiency of the boiler over the period

b is a constant of proportionality to southwards vertical solar radiation

c is the "energy effect of occupants"

d is a constant of proportionality to inside-outside temperature difference, taking into account transmission and infiltration losses

e is the heat capacity of the building

n is the length of the time interval between two measurements

Q_c is the energy corresponding to the amount of gas burned, V_g

Q_s is southwards vertical solar radiation

T_i is indoor air temperature

T_o is outdoor air temperature

T_{int} is the average temperature of the building structure

ΔT_{int} is the difference in T_{int} between two readings

The minimal time resolution (n) of the model is one hour

6. Planning of the measurements: the quantities to be measured are

T_{int} with a time step of one hour

T_i, T_o with a time step of ten minutes
Q_s, V_g with a time step of one minute

- e is measured once by letting the temperature drop after the heating system has been switched off
- a and b are known from previous experience
- c and d are parameters to be determined by a fit to data

On-line integration is required for T_i, T_o, Q_s, V_g. Data are recorded with a time step of one hour. The experimental apparatus will be composed of

- a gas flow meter for the measurement of V_g
- resistance thermometers (RTD) measuring the average temperature of the building structure (RTD's are placed in internal walls)
- RTD's for the measurement of indoor air temperature (in the living room of every dwelling)
- solarimeters (pyranometers) placed on the wall facing south

7. Measurement campaign: After the "running - in and learning" - period of the monitoring crew, the experimental apparatus is installed and tested. The first measurement period starts and goes on for a whole heating season. Before the next heating season begins the thermostatic valves are placed in every room. The experimental apparatus is tested again. The second measurement period starts and continues for the whole heating season.

8. Analysis of data: During and after the first campaign the parameters of the model are assessed by a fit to experimental data, the model for the non-retrofitted building is therefore:

$$a*Q_{c1} + b*Q_{s1} + c_1 - d*(\bar{T}_{i1}-\bar{T}_{o1})*n - e*\Delta T_{int,1} = 0 \qquad \text{(I a- 4)}$$

the terms without subscript are assumed to be constant during the measurements
After the second measurement campaign we will find:

$$a*Q_{c2} + b*Q_{s2} + c_2 - d*(\bar{T}_{i2}-\bar{T}_{o2})*n - e*\Delta T_{int,2} = 0$$

If the value of the parameter d is different from that of the non- retrofitted building, this is an indication that the model is not a good one. From the eq. I a- 4 we get:

$$Q_{c1} = (-b*Q_{s1} - c_1 + d*(\bar{T}_{i1}-\bar{T}_{o1})*n + e*\Delta T_{int,1}) / a$$

similarly, from eq. I a- 5 we get

$$Q_{c2} = (-b*Q_{s2} - c_2 + d*(\bar{T}_{i2}-\bar{T}_{o2})*n + e*\Delta T_{int,2}) / a$$

Therefore, define

$$Q'_{c2} = (-b*Q_{s1} - c_2 + d*(\bar{T}_{i2}-\bar{T}_{o1})*n + e*\Delta T_{int,1}) / a$$

Finally, the retrofit effect R is given by:

$$R = Q_{c1} - Q'_{c2} = (c_2 - c_1 + (\bar{T}_{i1}-\bar{T}_{i2})*n) / a$$

It should be observed that this result coincides with the rough estimate in eq. I a-2, provided the variation in the influence from the occupants is neglected.

CHAPTER Ib

Interaction between building and external environment

Contents

Keywords

absorptivity
air flow coefficient
air humidity
air temperature
atmospheric radiation
building energy budget
emissivity
infiltration
meteorological factor
solar radiation
terrestrial radiation
thermal parameters of building
thermal transmittance
transmission heat loss
transmissivity
U-value
wind direction
wind velocity

I b Interaction between building and external environment

- general introduction

The external environment exerts different kinds of influence on a building, such as acoustic, mechanical, thermal, hygienical, etc. Here we are interested in those external factors which modify the thermal budget of the building and/or the thermal comfort of its occupants. These factors are referred to as the meteorological factors. The set of meteorological factors defines the outdoor climate.

On the other hand, the indoor climate will be defined by the human requirements for thermal comfort (see ch. Ic for an introductory discussion and ch. IIIc for the measurement of indoor climate).

The difference between indoor and outdoor climate produces mass and energy flows across the building envelope, the magnitude of which will in general depend on the climate difference and on the performance of the building envelope.

There are other contributions to the thermal budget of a building, such as the heat produced by household appliances, cold and hot tap water use and the metabolic heat released by the occupants (see ch. Ie and Part IV). The heating system contribution is, of course, the most important one of the factors influencing the thermal balance (see ch. Id and IIIf).

This chapter is devoted to a general description of the interactions between the building and the external climate. Measurements will be dealt with in ch. IIIb.

A building can be considered as an open thermodynamic system, the boundaries of which coincide with the building physical envelope. The heat transfer across the envelope is determined by a combination of all the three components of heat transfer:

- radiation from internal and external surfaces of the envelope to the surroundings

- convection to indoor and outdoor air
- conduction through the envelope

Mass flow takes place both in the form of air flow and water flow across the building enclosure. Air flow, naturally induced or artificially forced into the building, will result in an enthalpy flow, thus contributing to the energy budget of the system. The same applies to water flowing in the sanitary plant.

- *meteorological factors*

The meteorological factors can be divided into two components: the first is strongly deterministic and somehow predictable, being linked to the relative motion of the Earth and the Sun, while the second one, superimposed on the first one, is highly stochastic though of the same order of magnitude as the other. For instance, one can easily recognize the deterministic component in air temperature records obtained as an average of a great number of days or years, as the stochastic component is removed by the averaging procedure. On the other hand, the deterministic component will hardly be recognized if the records for a *single day or year are analyzed.*

Only a few typical weather parameters are generally used in the thermal design of buildings, but when trying to simulate the thermal behaviour of a building, a large number of meteorological factors turn out to be influential. Similarly, a number of meteorological factors should be monitored when trying to assess experimentally the energy budget of a building.

We will here give a list of influential meteorological factors, along with their definition and reciprocal relations:

- *air humidity* (AH)
- air temperature (AT)
- atmospheric pressure (AP)
- atmospheric radiation (AR)
- cloudiness and precipitation (CP)
- solar radiation (SR)
- wind (W)

These factors are generated by the complex interaction between solar radiation and the Earth and, therefore, primarily depend on such geographic and astronomical factors as the local latitude, the time of the year (i.e., the Sun declination) and the time of the day (i.e., the Sun hour angle). Other factors are the physical characteristics of the atmosphere (optical thickness, thermal capacity, etc.) and the ground (reflectivity, thermal capacity, etc.).

Air humidity can be defined as the water vapour content of the ambient air. It is usually measured and expressed as the ratio of the actual water vapour content to the water vapour content that would saturate the air at its actual temperature and pressure (relative humidity). Moist air diagrams showing the relations between relative humidity, mass water content per unit of air mass (absolute humidity), air temperature, atmospheric pressure, and air enthalpy are used in two main versions: the Mollier moist air diagram and the socalled Carrier moist air diagram.

Air temperature is the most important meteorological factor from the point of view of effects on the building thermal budget. It shows a strong seasonal as well as daily variation, reflecting its origin, that is the convective heat transfer from the ground, heated, in its turn, by the Sun rays. Due to the thermal capacity of the atmosphere, a certain delay appears when comparing the seasonal and daily trends of air temperature and global horizontal solar radiation. The yearly fluctuations of air temperature are also responsible for the weak yearly oscillations of ground temperature.

Atmospheric pressure is defined as the weight of the air contained in an infinitely high vertical cylinder with its base on the ground. Its effect on the thermal budget of buildings in only indirect, therefore no further attention will be paid to this topic in this chapter.

Atmospheric radiation is the longwave radiation impinging on the Earth surface. Its origin can be explained as follows: the Earth surface emits an amount of radiation which, according to Stefan-Boltzmann's law, is proportional to the fourth power of its absolute temperature, and to its emissivity. Part of this radiation is reflected, or absorbed and the re-emitted, by the air in all directions. The part which is reflected or re-emitted downwards is called atmospheric (terrestrial, longwave) radiation. It is contained in the region of the spectrum ranging from 4 to 100 μm. The spectral atmospheric radiance is discrete under clear sky conditions and more continuous under heavy overcast conditions. Sometimes the value of atmospheric radiation is expressed through the "effective sky temperature", that is the temperature of a blackbody in *radiative equilibrium with the sky.*

Cloudiness is defined as the fraction of the sky covered by clouds. There are three general types of clouds: cumulus, stratus and cirrus. These can be distinguished, at a microscopic level, according to the size, shape, and state of their constituents, i.e. water particles. A cloud touching the surface of the earth is called fog. Another characteristic of clouds is their height above ground.

Precipitation is defined as liquid (rain or drizzle) or solid (snow, hail, etc.) water falling onto the ground.

Solar radiation constitutes all of the radiative exchanges between the Sun and the Earth in the short wavelength region of the spectrum. It consists of three components:

- direct solar radiation, coming directly from the Sun disk
- diffuse solar radiation, coming from the sky vault
- reflected solar radiation, coming from the surroundings

The direct component is determined by the extinction of the atmospheric layers (depending in its turn on air humidity, cloudiness, etc.) and by the air mass crossed by the Sun rays (i.e., by the Sun altitude). The diffuse components is due to atmospheric scattering, diffusion and reflection. The reflected component is the amount of solar radiation reflected by the surroundings on a given surface. The shortwave reflectivity of the ground is often referred to as albedo. Direct+ diffuse+ reflected radiation on a given surface yields the global solar irradiance, usually, but not correctly, called global solar radiation.

Wind is defined as the horisontal motion of the air. Wind can be caused by large scale pressure gradients, by the uneven heating of land and sea, and by orographic factors. In all cases the driving energy comes from the sun, either directly or indirectly. Wind is described by its velocity and direction.

An overview of the relations between meteorological factors is given in Table I b-1. The relations are expressed in a purely qualitative way.

TABLE Ib-1

Relations between meteorological factors

			INFLUENCED FACTORS						
			AH	AT	AP	AR	CP	SR	W
INFLUENCING FACTORS	Air humidity	(AH)		X		X	X	X	
	Air temperature	(AT)	X		X	X	X		X
	Atmospheric pressure	(AP)					X		X
	Atmospheric radiation	(AR)		X					
	Clouds and Precipitation	(CP)		X		X		X	
	Solar radiation	(SR)	X	X	X		X		X
	Wind	(W)					X		

- influence of meteorological factors on the building energy budget

Air humidity does not directly affect the heating demand of a building, but has rather to be considered in air conditioning problems. Whatever the value of the relative humidity during the heating season, the absolute humidity is always very small and so are its variations. Outdoor air, heated to about 20^{o}C, will always have, when introduced into the building, a very low relative humidity. Activities performed by people at home, such as cooking and use of hot water, and perspiration, will however increase the indoor water vapor content.

Air temperature (AT) exerts its influence through two mechanisms:
- heat transmission through the building envelope
- enthalpy flow across the building envelope

A temperature difference between indoor and outdoor air separated by walls, gives rise to a heat flow ($\dot{q}$) which, in the steady-state regime, is proportional to the air temperature difference ΔT, the wall area A, and the overall heat transfer coefficient U (sometimes called transmittance) of the wall, according to the well known equation:

$\dot{q} = U^* A^* \Delta T$ (Ib-1)

The U-value itself depends on the conductance of the wall and on the surface (or film) heat transfer coefficients. These, in their turn, depend on the temperature of the air and of the surrounding surfaces, and on the wind velocity and direction. ΔT influences that part of the film coefficients which depends on natural convection, and this is of interest mainly for the film coefficient on interior surfaces. Experimental results are generally expressed in terms of equations involving the Nusselt, Grashof and Prandtl numbers. A simplified expression can be used for air at atmospheric pressure (Mc Adams, 1954):

$h_c = A^*(\Delta T/L)^b$

where

h_c is the film coefficient

ΔT is the temperature difference between the surface and the air

L is the height (for vertical surfaces) or the side length (for horizontal surfaces facing up)

A, b are constants

Another effect of the temperature difference between inside and outside air is the thermally driven air infiltration ("stack effect"). Temperature differences between the inside and the outside cause differences in air density. This leads to pressure differences across the building envelope which are given in terms of air density, or air temperature, by:

$\Delta p = (\rho_0 - \rho_i)^*g^*z = a^*z^*p^*(1/T_0 - 1/T_i)$ (I b-2)

where

Δp = pressure difference

ρ_i = indoor air density

ρ_0 = outdoor air density

g = gravitational acceleration

z = height coordinate in system with origo at the level where the pressure difference is zero (neutral level)

p = atmospheric pressure (Pa)

T_i = internal air temperature (K)

T_0 = external air temperature (K)

a = constant, whose value is equal to 0.0342 (K/m)

The air flow through any kind of opening depends on the pressure difference, induced by temperature differences or by wind pressure, across the latter. Empirical relations have been expressed in various ways depending on the kind of opening. For flow in long regular pipes and ducts the flow is in general expressed in terms of a power of the pressure difference as

$\dot{Q} = C*A*\Delta p^{\beta}$ (I b-3a)

where

$\dot{Q}$ = flow rate of air

C = proportionality constant

A = cross-sectional area of opening

Δp = pressure difference across the opening

β = flow exponent

It has been shown that the value of the exponent β may depend on Δp (Honma 1975). The value of β is known exactly only for laminar or fully developped turbulent flow in long smooth channels. It then takes respectively a value of 1 and 1/2. For flow through orifices it is common to express the flow rate as

$\dot{Q} = C * \Delta p^{1/2}$ (I b-3b)

where C, the discharge factor, in general depends on the Reynolds number.

Strictly speaking, none of the expressions I b-3a and I b-3b can be applied to describe the flow rate through a small opening in the building envelope. This is due to the complexity of such openings; rough walls, varying cross section, bends, non- stationary flow, entrance effects etc. However, from a practical point of view, it is necessary to use some model to describe the flow through openings in building envelopes. It has then become common to use the expression I b-3a with an exponent having a value between 1/2 and 1.

Atmospheric radiation is probably the most neglected of all the previously mentioned factors. It is nevertheless responsible for large amounts of energy losses. Empirical models of the atmospheric radiation relate its value to the values of air temperature, air humidity and cloudiness. A number of relations have been reported for clear sky conditions (see e.g. Kondratijev 1969, Sellers 1965, Monteith 1975, Paltridge and Platt 1976 or Oke 1978). Some examples which involve only the temperature and not the humidity are:

$G_0 = 1.2*\sigma*T^4 - 171$, $G_0 = 208 + 6.*T$, $G_0 = 0.94*\sigma*10^{-5}*T^6$

where

G_0 = atmospheric radiation for clear sky (W/m^2)
T = air temperature (K)
σ = *the Stefan-Boltzmann constant*

For cloudy sky Kondratijev reports the following relation (developed by Boltz, see also Geiger 1965)

$$G = G_0*(1 + k*n^2)$$

where
G = atmospheric radiation (W/m^2)
n = cloud cover (parts of unity)
k = constant depending on type of cloud (k = 0.04 for cirri, k = 0.17-0.20 for cumuli, k = 0.24 for strata)

The difference between radiation emitted by a "gray" surface and atmospheric radiation, generally positive, is given by:

$$R = F*(\varepsilon *\sigma* T_s^4 - G)$$

where
F = the view factor of the surface to the sky (for isotropic sky $F = 0.5*(1 + \cos\theta)$, θ = tilt angle of the surface)
ε = the emissivity of the surface
T_s = the surface temperature

When the sky is clear, during cold winter nights, and the surface is horizontal, R can attain a value of 200 W/m^2.

The influence of cloudiness on buildings in only indirect. Therefore it will not be discussed here.

It is a hard task to relate precipitation to the energy requirements of a building. Driving rain and snow can moisten the walls, thereby increasing their U-value. Snow will affect ground reflectivity (albedo), thus increasing the global solar radiation on non-horizontal surfaces. It will also reduce the U-value of roofs, and produce an increase of ground temperature.

Solar radiation gives a major contribution to the building energy budget, minor in importance only to air temperature. Many analytical and/or empirical models have been constructed for clear sky conditions. They are based on Beer's Law of atmospheric monochromatic extinction. The corresponding equation integrated over the spectrum can be written in the form used by Lunelund (1936) and ASHRAE (1977):

$I_n = A*\exp(-B/\sin\beta)$

where

I_n = direct normal radiation (W/m^2)

β = altitude angle of the Sun

A,B = parameters depending on the day of the year

For <u>diffuse radiation</u> it has been proposed (ASHRAE 1977) that the diffuse horizontal radiation is proportional to I_n with a proportionality constant depending on the day of the year. Solar radiation has two effects on the energy budget of buildings:

- it is absorbed by opaque walls
- it is transmitted across transparent walls

One way to take into account the first effect in calculations is to use the <u>sol-air temperature</u>, defined as the air temperature which would cause a convective heat transfer from the wall surface equal to that actually caused by radiation and convection together. Sol-air temperature is defined as:

$T_{sa} = T_o + (a*I - R)/h_o$

where

T_{sa} = sol-air temperature

T_o = outside air temperature

a = absorptivity of the wall surface

I = global solar radiation on the wall surface

R = net longwave radiation leaving the wall surface

h_o = outside film coefficient

The second effect produced by solar radiation is even more important. The amount of solar radiation transmitted through a unit area of a non-opaque medium (e.g. window glazing), is proportional to I with a proportionality constant τ, the transmissivity of the glazing, which depends on, among other things, the angle of incidence.

Solar radiation represents a positive factor in the heat balance of a building, but to take advantage of it requires a suitable design of the building and the control system, as well as a certain skill on the part of the occupants.

The wind also plays a great role in the energy consumption of buildings. It acts in two different ways:

- modifying the outside film coefficient
- producing a pressure difference, and consequently an air flow, across the building enclosure

The outside convective heat transfer coefficient h_{oc} is strongly related to the air velocity (forced convection). Non dimensional empirical relations linking the Nusselt, Prandtl and Reynolds numbers can be employed to give relations between h_{oc} and the wind speed. Unfortunately such relations cannot be easily employed because the local air velocity varies widely over the wall. Correlations with a reference wind velocity measured, e.g., over the roof, will yield different values of h_{oc} on different walls and even at different points of the same wall (edges, centre, etc.) (Ito et al. 1972). The parameter h_{oc} is often neglected compared to the thermal resistance of most components of an external wall, possibly with the exception for windows. Generally, the variation of the convective coefficient will not greatly change the thermal resistance of a low conductance wall, for common wind speeds it will reduce it by only a few per cent. In calculations of the heat balance it is common to simulate the influence of h_{oc} by giving it a fixed value, independent of temperature and wind speed.

The wind has a more important effect on air infiltration: it will cause a pressure difference between the inside and the outside of the building envelope. The wind pressure is found to vary over the envelope. This is often expressed through the introduction of the dimensionless pressure coefficient C_p defined from

$$\Delta p = C_p * \rho * v^2/2 \qquad \text{(Ib-4)}$$

where

ρ = density of air

v = reference wind velocity

Δp = difference between the pressure at a point on the building facade and a reference pressure

The reference wind speed and reference pressure are generally defined as the wind speed and static pressure in the free stream at a height equal to that of the building. These entities are easily determined in model studies in a wind- tunnel and possibly in field measurements involving only an isolated building, but are less easily determined in field measurements in an urban or sub- urban setting.

Pressure coefficients are mostly available only for isolated buildings, exposed to wind from all directions, which is a situation rarely encountered in practice. Surrounding buildings may drastically change\ the wind pressure distribution over a building (see fig. I b-1), and thus also the infiltration losses (Wirén 1983).

The wind speed varies with height, and the vertical profiles of wind velocity vary with the roughness of the terrain over which the wind is passing. Several relations describing the wind speed variation with height have been proposed. Relations of this kind are difficult to employ in calculations of the building heat balance, possibly with exception for use in studies of isolated high- rise buildings. In an urban or sub- urban setting they are not even approximately valid below a height which is several times the average height of the buildings in the neighbourhood of the building studied. However, relations of the kind above are sometimes employed when extrapolating wind data from a meteorological station to the building site (see ch. III b). Extrapolations of this kind are always uncertain, and meteorological experts should be consulted.

A second type of wind-induced ventilation through an opening is due to turbulence and a varying flow separation. These factors are very complex because the pulsating ventilation flow will depend on the frequency of the external pressure fluctuations. It has been estimated (Handa 1979) that this factor may increase the natural ventilation by up to 30 per cent, compared to the case when the turbulance intensity is small, depending on the turbulance intensity and the correlation between the pressure on the windward and leeward facades of the building. Model studies of this effect have also been performed (Cockroft and Robertson 1976)

- thermal performance of buildings

In the previous section a number of equations have been given, relating the outdoor and indoor thermoclimatic factors (temperature, pressure, etc.) to the energy or enthalpy flow across the building envelope. The parameters, which are used in these equations, quantitatively describe the thermal performance of the building. Some parameters have been derived from physical teories and can be

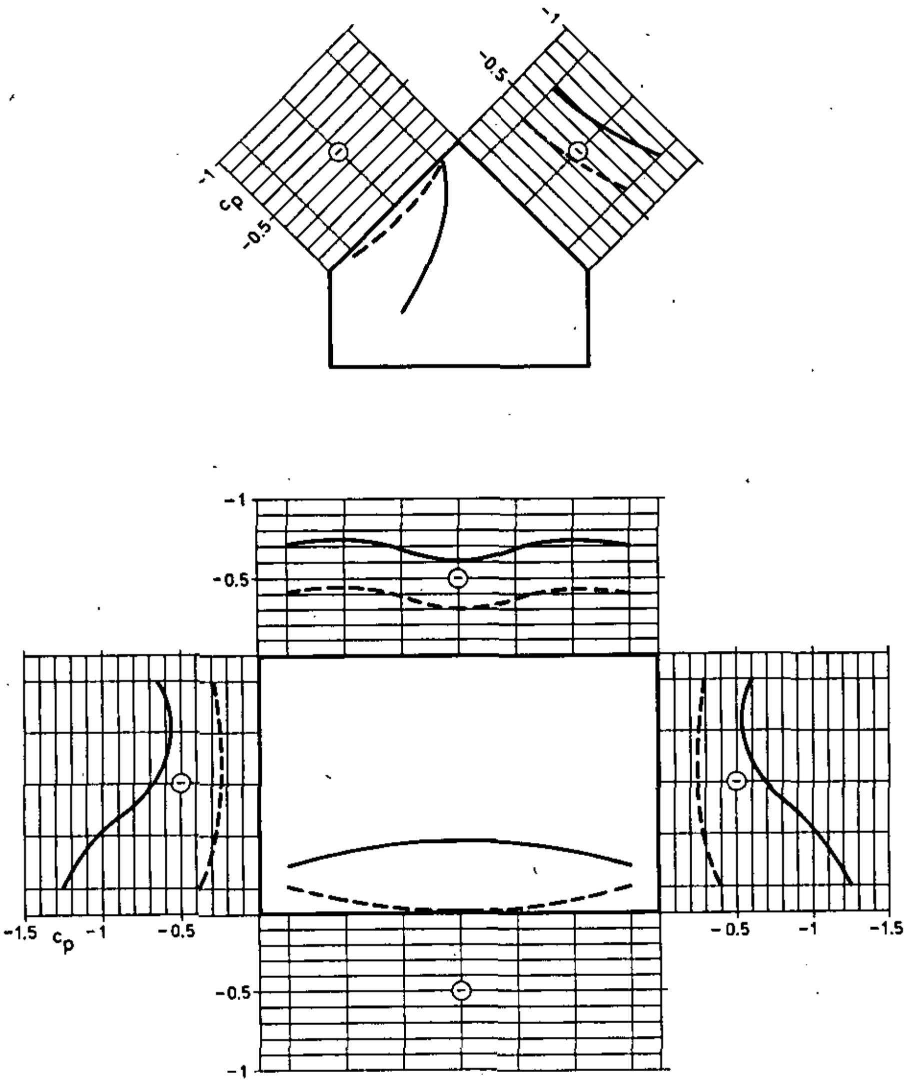

Fig. I b-1 Pressure coefficient C_p as measured at mid-height of exterior walls and on the roof of a two- storey house. The full-drawn lines are for an isolated, exposed house and the hatched lines for an identical house in a very densely built sub-urban setting. (after Wirén 1983) computed analytically, others are empirically determined and cannot be theoretically calculated.

When dealing with field experiments, the measurement of thermal parameters is convenient if:

1) it can be performed quickly, simply, and accurately
2) the model in which the parameters are used is reliable

Otherwise a direct measurement of energy flows should be performed. Building thermal parameters can also be determined using model calculations combined with field measurements. The main areas for field measurements are then:

i) infiltration
ii) heat transfer through the walls
iii) radiative heat transfer
iv) determination of thermal building parameters

i) infiltration

If a building is considered as having a certain porosity with an overall leakiness such that the flow through all openings can be described by, e.g., the eq. I b-3a, the natural ventilation can be estimated provided the internal pressure is known. This can be done using the mass conservation law, which states that the sum of air flows into the building must equal the sum of air flows out of the building. This law can be used to calculate the interior pressure of the building if no internal resistance to air flow is present. If this is not the case, the building interior has to be divided into cells with no internal resistance. The law of mass conservation then has to be applied to each cell separately, taking into account also the air flow between cells.

The rate of air change will, directly or indirectly, be dependent on:
- the pressure distribution over the building facade
- the temperature difference between the indoor and outdoor air
- location of openings (often far from a uniform distribution)
- bypass inside the building (shafts etc., connecting one part of the building to another)
- internal flow resistance

As the internal pressure in the case above has to be calculated by a time-consuming numerical iteration, simpler models and methods are often used to assess the rate of air change in buildings.

Using data on leakiness provided by the pressurization *method* (see ch. IIIe), one can attack the problem of comparing leakiness from one house to the next. One attempt in this direction has been to make such comparisons for a number of houses using the parameter $\dot{Q}/A$ (flow/surface area), and then derive a relationship between pressurization tests and natural air infiltration (Kronvall 1978, 1980).

Another line of attack is to make a number of simplifications in the modeling of infiltration to allow predictions of air infiltration from pressurization measurements (Sherman and Grimsrud 1980). Surface pressures are estimated from knowledge of terrain and weather. These surface pressures and leakage functions (and geometry) are then used to calculate air infiltration. This method provides good results, considering the simplicity of the model.

When the building is equipped with a mechanical ventilation system, other methods must be used. An example is a method including a calculation scheme and model (Nylund 1980). The method consists of the analysis of a driving power system (wind, thermal effects and fans), and a leaking system (the building envelope and penetrations including ventilation ducts). The air exchange rate is the sum of the desired and uncontrolled ventilation. Numerical values can be obtained for individual houses with varying tightness and a variety of ventilation systems.

The so-called "crack method", as one means of estimating air infiltration, emphasizes leakage rates associated *with windows and doors, which, however,* constitute a minor fraction of the overall leakiness in many instances.

Methods of measurement of air infiltration are reported in ch. III e.

ii) heat transfer through the walls

Heat conduction in a material is defined by Fourier's equation, which states that the heat flow rate is directly proportional to the temperature gradient and to the area of the surface normal to the flow; the constant of proportionality is called thermal conductivity. In one dimension we have:

$\dot{q} = - \lambda * A * dT/dx$ (I b-5)

where

$\dot{q}$ = heat flow rate

λ = thermal conductivity

A = area of the surface normal to the flow

dT/dx = temperature gradient in the direction of the heat flow

Fourier's law can be combined with the energy conservation law: assuming that there is no internal energy generation and that thermal conductivity is constant in all directions, the three-dimensional heat conduction equation becomes:

$\partial^2T/\partial x^2 + \partial^2T/\partial y^2 + \partial^2T/\partial z^2 = (\rho * c/\lambda) * \partial T/\partial t$ (I b-6)

where

x, y, z are the three space coordinates

ρ is the density of the material

c is the specific heat of the material

t is time

The quantity $\lambda/(\rho c) = \alpha$ is called the thermal diffusivity of the material, it describes the unsteady- state behaviour of the material: the larger the value of α, the faster will heat diffuse through the material.

Calculations of heat transfer through building components are generally only performed in one dimension. Even so, Fourier's equation is still rather complex to solve for multilayer walls because of boundary conditions varying with time. In this case, the rigorous analytical approach leads to a simple solution only for steady-state conditions.

The integration of Fourier's equation, when thermal conductivity is considered constant with temperature (this hypothesis is justified if the variations in wall temperature are small), yields:

$\dot{q} = C * A * (T_{si} - T_{so})$ (I b-7)

where

$\dot{q}$ = heat flow

T_{si} = inside surface temperature

T_{so} = outside surface temperature

C = conductance of the wall, defined as $C = 1/(\Sigma\ s_i/\lambda_i)$

s_i = thickness of the i-th layer

λ_i = thermal conductivity of the i-th layer

When also surface heat transfer is considered, eq. I b-7 becomes eq. I b-1 and the overall heat transfer coefficient, U, is calculated from

$U = 1/(1/h_i + 1/C + 1/h_o)$
where
h_i = inside surface heat transfer coefficient
h_o = outside surface heat transfer coefficient

Transient heat conduction in building walls is always connected with variable convective + radiative boundary conditions at the inside and outside surfaces. Therefore, even for regularly shaped solids such as multilayer walls, an analytical solution can not often be found. In this case the problem is best handled by numerical techniques such as

1) finite-difference approximation (forward and backward differences) (see, e.g., Arpaci, 1966)
2) finite- element method (see e.g., Wilson and Nickell, 1966)

When the time series of outdoor temperature and heat flow can be developped in a Fourier series, the Fourier tranform method can be used (see e.g., Cali and Sacchi, 1976). For every frequency ν considered in the thermal oscillations, the inside and outside surface temperatures and fluxes are related through four complex quantities $A\nu$, $B\nu$, $C\nu$, $D\nu$, according to the expression:

$$\begin{pmatrix} T_{i\nu} \\ \dot{q}_{i\nu} \end{pmatrix} = \begin{pmatrix} A_\nu & B_\nu \\ C_\nu & D_\nu \end{pmatrix} \begin{pmatrix} T_{o\nu} \\ \dot{q}_{o\nu} \end{pmatrix} \qquad \text{(I b-8)}$$

where
$T_{i\nu}$ and $T_{o\nu}$ = inside and outside component of surface temperature at frequency ν
$\dot{q}_{i\nu}$ and $\dot{q}_{o\nu}$ = inside and outside component of surface flux at frequency ν
The four coefficients must satisfy the condition $A\nu * D\nu - B\nu * C\nu = 1$.

The response factor method (Mitalas and Stephenson 1971), relates the heat flux at a given time t to the hourly time series of inside and outside surface temperatures and to the time series of heat fluxes previous to time t, according to the equation:

$$\dot{q}_t^{(i)} = \sum_{j=0}^{\infty} c_j * T_{t-j\Delta}^{(i)} + \sum_{j=0}^{\infty} b_j * T_{t-j\Delta}^{(o)} + \sum_{j=1}^{\infty} d_j * \dot{q}_{t-j\Delta}^{(i)} \qquad \text{(I b-9)}$$

where
upper index (i) and (o) refer to indoor and outdoor
lower index denotes the time at which the entity is evaluated
Δ is the time interval between each evaluation of the entity

Sets of b, c, d coefficients for a great number of walls and roofs structures can be found in ASHRAE, 1977. Methods of measurement of heat transfer through the building envelope are described in ch. III d.

iii) radiative heat transfer

Experience shows that the amount of radiation emitted by a body depends on its temperature, on the state of its surface (roughness and colour) and on the area of the surface. When radiation encounters a body, part of it is reflected, part of it is absorbed, and if the body is transparent, part of it is transmitted. The reflected fraction of incoming radiation is defined as the reflectance ρ, the absorbed fraction as the absorptance α, and the transmitted fraction as the transmittance τ. These three components must add up to unity: $\alpha + \tau + \rho = 1$

For an opaque body, $\tau = 0$. For a blackbody, being opaque as well as non reflecting, $\tau = \rho = 0$, and hence $\alpha = 1$. The blackbody is taken as reference for the radiation of real bodies, whose emittance ε is by definition the ratio (less than one) of the radiation flux, to the radiation flux of a blackbody having the same temperature. Kirchhoff's law states that, at equilibrium, $\varepsilon = \alpha$.

The coefficients (α, ρ, τ) are independent of the temperature of the body, but they are strongly related to the wavelength, which leads to the definition of the monochromatic quantities, α_λ, ρ_λ and τ_λ.

Transmission, absorption, and reflection, as well as emission, is of great practical interest. For example, the importance of the wavelength of radiation may be illustrated by the example of a greenhouse. Window glass transmits radiation in the range of wavelengths from about 0.15 to 3 µm, as shown in fig. Ib-2. It is almost opaque to radiation of longer wavelengths. Most of the radiation which reaches the earth from the sun is within this range, and solar radiation therefore passes through the glass to the topsoil in the greenhouse.

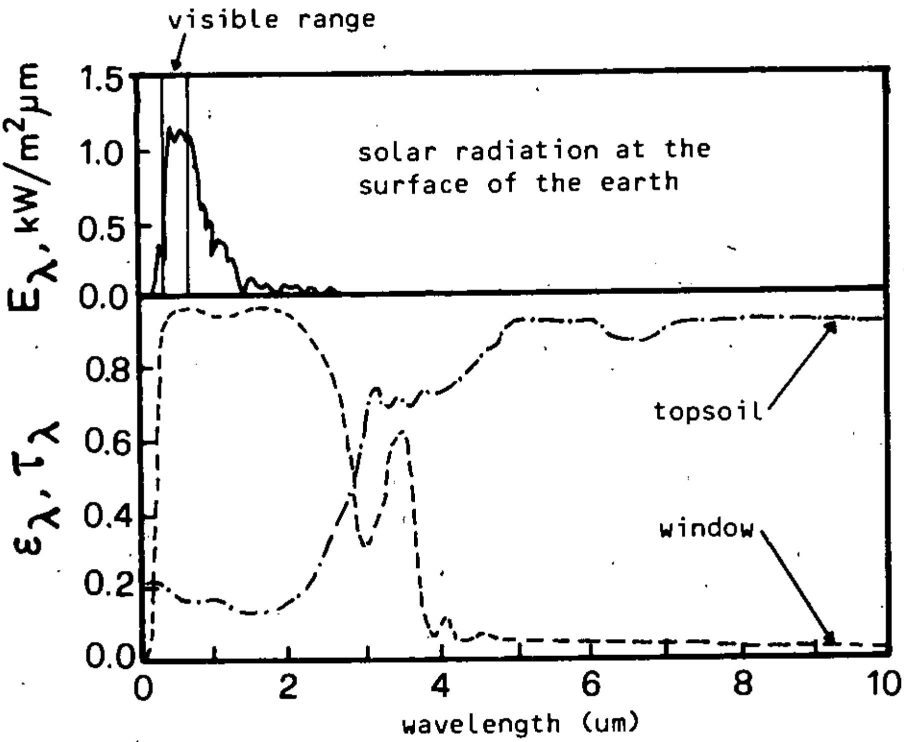

Fig. I b-2 Spectrum distribution of solar radiation, emissivity of top soil, and transmissivity of glass

On the other hand, the topsoil radiates mainly in the longer wavelengths, and reradiation from the topsoil to the surroundings is unable to pass through the glass. The heat transferred by solar radiation is therefore trapped in the greenhouse, and causes the temperature to be higher than that of the surroundings.

iv) determination of thermal building parameters

When analyzing the dynamical thermal behaviour of buildings, interacting with the outdoor climate, it is often convenient to make use of non-deterministic models whose parameters have to be assigned a value by a fit to numerical data. In these models, the building thermal mass is either treated as a whole, or is divided into a small number of components (air, furniture, building fabric etc.) (Billington 1965). Each of these components is considered as a lumped parameter system having a certain "equivalent" heat transfer coefficient, and thermal capacity or thermal time constant (TTC). The models are in general linear in the parameters. Models of this kind have been used in several studies of the building energy balance (see, e.g., Sonderegger 1977 and Steinmüller 1982).

When the building thermal mass is considered to consist of the components "air" and "building fabric", the equivalent thermal parameters (ETP) are for instance:

- the equivalent heat transfer coefficient (EHTC) between room and outdoor air
- the equivalent EHTC between room air and the building structure
- the EHTC between room air and an environment of constant temperature, describing the basement and adjoining dwellings
- the equivalent thermal capacity of the building or
- the equivalent TTC of the buiding
- the equivalent solar window area, defined as the area of a perfectly transparent and insulated opening on the southern facade that would allow for the same degree of indoor solar heating as what is actually obtained

Once the model has been constructed, the ETP's are determined by a fit to experimental data. From the above it is obvious that, in this case, one would have to monitor variables like indoor and outdoor temperatures, solar radiation, energy from heating systems, ventilation etc. It is of importance to control all contributions to the building energy balance. For this reason it is more convenient to operate in an unoccupied building. One then also has the possibility to "speed up the procedure" by introducing supplementary electric heating (Sonderegger 1977).

The dispersion of points from a straight line in the daily energy consumption- temperature plot is only partially due to the presence of driving forces other than the indoor- outdoor air temperature difference; if the model time resolution is of the same order of magnitude as the TTC(e.g. one day), the dispersion is also produced by unsteady state effects. In a simplified method for the evaluation of the TTC, one shows that energy consumption is approximately a linear function of an "equivalent temperature", calculated as (Drusiani and Negrini 1979):

$$\tilde{T}_i = K^* T_i + (1-K)^* \tilde{T}_{i-1}$$

where

T_i = average outdoor temperature of day i

$\tilde{T}_i$ = "equivalent temperature" of day i

Using this method, one has to monitor only the daily energy consumption and the daily average outdoor temperature. By letting the parameter K vary from 0 to 1, in the daily energy consumption- "equivalent temperature" plots, the best fitted value of K can be determined, leading to a reliable estimate of the average TTC of the sample through the relation:

$$TTC = - 24/ \ln(1-K) \ (h)$$

An analysis of this kind has been performed to evaluate the average TTC of a group of buildings through information about the daily heating gas consumption.

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CHAPTER I c

Physical indoor environment factors affecting man

Contents

I c Physical indoor environment factors affecting man

- general introduction

Every dwelling should be constructed so that a climate suitable for human beings can be created. This is achieved by shielding the dwelling from the influence of the external climate by a suitable design of the building envelope and if necessary by using energy to keep the interior of the dwelling at a temperature different from that of the outdoor air.

The indoor air should be kept at a temperature comfortable for the occupants, taking into account their clothing and their activities at home. The temperature of the interior surfaces should not differ too much from that of the indoor air. There should not be any large temperature gradients inside the dwelling.

The moisture content of the indoor air should be kept within certain limits if the indoor climate is to be a comfortable one. The moisture content of the indoor air will in general be different from that of the outdoor air due to the outdoor- indoor air temperature difference and the use of water by the occupants inside the dwelling.

The heating of the dwelling and activities performed by the occupants will result in the adding of pollutants to the indoor air. The indoor air may also be contaminated by gaseous constituents dissipating from the building fabric.

There should not be any draught in the dwelling, a sufficient degree of lighting should be provided and the demand for privacy should also be considered.

All factors mentioned above are of importance for the physiological wellbeing of the occupants. Their behavioural response to the indoor climate can be very complex. Only on rare occasions will the occupants experience a single factor like air temperature, radiant temperature of walls and windows, indoor humidity, draught, illumination, ventilation, or level of noise as inadequate. In general they will experience a combination of these factors through the senses of vision, hearing, smell, touch, and thermal sensation. If at, most, two of the factors mentioned above are involved, experience from psycho- physical experiments under controlled laboratory conditions in many cases tells the limits of the comfort range of these factors for a certain clothing.

Retrofitting a residential building will often result in a change in the indoor climate. When performing a retrofit this should therefore be taken into account and not just the energysaving effects of the retrofit. This can often be done in a qualitative manner. However, it is sometimes of interest to be able to do this in a quantitative manner. The thermal environment of the occupant can then be described by the use of a so called comfort index. This topic is treated in the first section of this chapter, "thermal environment". This is followed by two sections treating questions related to air contaminants and lighting that are of interest when performing a retrofit of a residential building.

- thermal environment

i) physiological basis: heat balance and metabolism of the human body

Heat is produced continuously in the human body at a rate that is strongly dependent on the activity being performed. Fuel is required for producing this heat, and air to burn it. In these respects the human body does not differ from the furnace that maintains the temperature of a building at the required temperature. The fuel we burn, or metabolise, is food. The caloric value of the food eaten , less the mechanical work performed, is equal to the heat produced in the body. It must all be dissipated . The body can tolerate only small and relatively brief changes in temperature, unlike houses, that can store heat from warm days to cold nights or even over periods of several days. Houses need not maintain their internal temperature so exactly as we do, neither are they subject to the five-fold alterations in rate of heat production that we impose on our bodies as we engage in different activities.

The average rate of heat production for a 24 hour period has been calculated as 102 watts for women and 126 watts for men. These figures are based on food intake for an average-sized person, not engaging in any of the more active occupations or pursuits. Large people will eat more food and produce more heat. It is usual to normalize these figures by dividing by the body surface area, a good measure of the size of a person and a critical factor in heat balance, as outside wall area is for a house. Since, e.g., women in Northern Europe have an average body surface area of 1.6 m^2, men 1.8 m^2, the 24-hour average rates of heat production are 64 and 70 W/m^2, respectively. Ignoring sex differences gives an average of 67 W/m^2.

The 24-hour average is a useful concept for calculating the heat contribution from occupants to a house, but it conceals large and systematic differences at different times of day and is therefore inadequate even for calculating contributions to the heat balance of a room. However, as we shall see below, it provides a surprisingly good basis for calculating the average required room temperature in different clothing ensembles. In most cases, however, it is necessary to allow for different rates of heat production for different activities: sleeping 40 W/m^2, sitting quietly 55 W/m^2, standing still working 78 W/m^2, light house work 110 W/m^2. Much higher rates of working occur occasionally in the home, corresponding to medium heavy industrial work 150 W/m^2 heavy manual work 200 W/m^2, but are seldom maintained for long.

Rate of heat production is governed by the activity in which we engage. It is therefore to a very large extent under conscious control during leisure time in the home. This is not the case during working hours. Rate of heat loss is governed by 5 principal factors: clothing insulation, air temperature, radiant temperature, air velocity and air humidity. These have been listed in descending order of importance for heat balance in normal dwellings and for normal activities. Humidity is in last place because it affects mainly the rate at which sweat can evaporate. Sweating is something we try to avoid during normal occupation of the home, for hygienic reasons as much as for the fact that it is the last line of defence. Similarly, shivering is a heat balance mechanism we try to avoid. Dwellings should be planned so that only in freak weather conditions is it necessary for the body to use these strategies. In hot countries this may be an unrealistic goal, and if so humidity at once becomes an important factor in heat balance. Sweating can save enormous amounts of energy used for summer air conditioning in advanced hot countries, but this specific form of energy conservation will not be dealt with here.

ii) indoor temperature

The permissible range of temperature is given by the restraints imposed upon the other 5 factors governing the heat balance of the body - activity, clothing, radiant temperature, air velocity, humidity. Under nonsweating conditions even very large differences in relative humidity, between the extremes at which humidity becomes a nuisance in itself , 20% to 70% , can be compensated thermally by a change of only 1 K in the air temperature. Air velocity becomes a nuisance by causing local cooling of the body above 0.2 m/s, and blows paper about. It is usual to limit air velocity to 0.1 m/s in rooms occupied by sedentary people for this reason. Under these conditions the air - and the radiant- temperature affect heat loss to about the same extent. The "operative temperature" can be taken as the arithmetic mean of the two and used to characterize the temperature of the space. TableI c-1 sets out the maximum and minimum air temperatures for the activities whose heat production rate has been discussed above, as a function of clothing (or bed-clothing) insulation value. At these limits sweating or shivering, respectively, must occur in the steady state. They have been calculated on the basis of the heat flow from the centre of the body at 37^{o}C, to the room, taking account of the minimum and maximum insulation afforded by the body tissues when fully vaso-dilated and vaso-constricted, respectively. The insulation value of the clothing worn is a parameter of Table I c- 1. The insulation value of the air is a function of its relative velocity taken here to be 0.1 m/s except in the case of light house-work where 0.3 m/s is assumed. A small amount of uncertainty is introduced by the dependence of clothing insulation on air velocity, but since effective clothing insulation can be altered much more in an adaptive way, by opening or closing buttons, for instance, this can probably be neglected.

Clothing and activity, the parameters of Table I c- 1 , may be seen to have very large effects on the permissible range of room temperature. They naturally affect also optimum temperatures, which for the present purpose can be taken to mean optimally comfortable temperatures and to lie mid way between the limits set out in Table I c-1. It is a common observation that preferred temperatures vary seasonally, diurnally and between countries. Many field studies have documented these differences, without normalizing clothing and activity. Had they done so it is probable that the undoubtedly large and systematic differences in clothing and activity that occur between seasons, between times of day and between countries, would have accounted for the differences in preferred temperaure. Fanger (1970) has performed extensive studies of preferred temperature in standard clothing, sitting still in a laboratory, and has never found any variation due to the above factors. It seems therefore adequate to assume that by taking account of the clothing and activity likely to occur in a given place at a given time, Table I c-1 values may be used to give the permissible range of room temperature without further correction for the so-called seasonal, diurnal and geographical bias. The only exception, already

TABLE I c-1

Permissible temperature range

A. Minimum temperature without shivering

Activity	Metabolism W/m^2	Clothing (clo) 0	0.5	1.0	1.5	2.0	3.0
Sleeping	40	30	28	26	24	21	17
Sitting	55	27	24	21	18	15	
24-hour average	67	25	22	18	14		
Housework (standing)	78	23	19	15			
Active housework	110	20	14				

B. Maximum temperature without sweating

Activity	Metabolism W/m^2	Clothing (clo) 0	0.5	1.0	1.5	2.0	3.0
Sleeping	40	32	30	28	26	23	19
Sitting	55	30	27	24	21	18	
24-hour average	67	29	25	21	18		
Housework (standing)	78	27	23	19			
Active housework	110	26	20				

excluded from the present treatment but worth reiterating, is when sweating is socially acceptable or economically necessary in hot countries. Table I c-1 upper limits do not then apply, other heat stress equations must be used and heat acclimatization must be considered *qualitatively. This will introduce* marked seasonal and geographical variation. Table I c-1 is based on an equation for dry heat balance by Humphreys (1976), assuming that 0.7 of the total heat loss is non-evaporative, that the air velocity is 0.1 m/s except in active housework, where 0.3 m/s relative air velocity is assumed, and that the permissible temperature range is given by the limits of vasoconstriction and vasodilation, beyond which shivering and sweating occur, respectively.

Thermal gradients occur in both space and time. Horizontal thermal gradients are experienced as temperature swings in time by occupants who move through them. Temperature swings, the factors influencing their perception and their effects on comfort, performance and behaviour have been studied extensively by Wyon et al. (1971, 72, 73, 77). Their results may be summarized for the present purposes as showing *a surprising lack of hysteresis during the* relatively slow temperature swings occurring in dwellings - dynamic effects may be neglected and occupants assumed to respond to the actual temperature, regardless of its past variation.

Vertical thermal gradients have been insufficiently studied. A correct treatment of criteria should be based on a quantitative understanding of physiological response. This is available for total heat balance in a uniform environment but not yet for an environment that varies between different parts of the body. It has been found good practice, however, to limit vertical thermal gradients to 2 K/metre. This requirement is included in building regulations in several countries. Larger gradients are likely to occur only with such marked convective circulation of air that draughts and cold floors will cause problems *rather than the thermal gradient per se. It is worth noting* that such thermal gradients are always positive, the temperature increasing with height above the floor. Although very few thermal comfort studies have asked for multiple judgements of thermal comfort referred to different parts of the body, Wyon et al (1968) showed that thermal preference is for a negative thermal gradient. (In other words, people prefer to keep a cool head rather than get cold feet). Most heating systems can achieve at best a small positive thermal gradient in air temperature. However, radiant systems can easily create a negative gradient in operative temperature. The limits applicable in this case are discussed in the following section.

iii) surface heat radiation

The operative temperature in a room is affected to the same extent by the surface temperatures as by the air temperature. The mean radiant temperature at any point in the occupied zone must be calculated in order to be able to estimate the overall heat balance of the human body. Table I b-1 may then be used to give the permissible range of operative temperature. It is necessary to define the occupied zone quite closely in this connection, for the solid angle subtended by a given surface area whose temperature differs from the air temperature determines its contribution to the mean radiant temperature. This becomes unreasonably large if the occupied zone is taken to extend right up to walls and windows.

Building regulations often define the occupied zone as extending to within 1 metre of the walls or window, and to 0.5 metres of an outside wall without a window for the special purpose of calculating the plane radiant temperature. High density occupation will require that the occupied zone in practice extends into the last metre excluded above. Real health risks can thereby occur, for example when occupants must sleep right up against cold outside walls.

Increasing insulation standards are reducing these risks, but it is worth considering whether extra floor space would not in some situations be justified economically by the high alternative cost of meeting building regulations for thermal environment if the occupied zone must extend to the walls.

In addition to satisfying the above requirements for overall heat balance, surface temperatures must not cause excessive heat loss from the body. If radiation exchange with a cold surface causes a particular part of the body to be colder than it would be in the absence of the surface, the sensation and effect is identical to that caused by a cold draught or excessive air velocity. As stated above, the underlying physiological model for response to such asymmetric thermal loads is lacking. It has been found good practice to require in building regulations that the plane radiant temperature must be calculated or measured in the occupied zone, and to introduce the concept of the plane operative temperature, analogous to operative temperature. This quantity should not be less than 18°C anywhere, nor should differences in plane operative temperature within the occupied zone exceed 5 K. In practice the extreme points are usually 1 metre from the centre of a radiator below the window and 1 metre from the centre of the window. Observe that the plane operative temperature at the latter point will be lower than at the former. An occupant seated or standing in front of the window will experience a negative gradient in plane operative temperature, provided that the radiator is fulfilling its other function of preventing down-draught by creating upward convection. Whereas the radiant heat exchange of the body as a whole with window and radiator, as reflected by the conventional calculation of mean radiant temperature or measurement of globe temperature, may show acceptable operative temperature values, care must still be taken to ensure that the asymmetric radiant field does not cause too much local heat gain or loss from different parts of the body. The above criteria have been found adequate even under severe winter conditions with present-day windows. With increased insulation standards for outside walls and windows leading to reduced radiator size and surface temperature, the asymmetry will be reduced and it will be easy to meet the above criteria except in special cases of very large windows or high temperature radiant sources.

iv) air velocity (draught)

Air velocities that are too high can cause excessive local cooling of parts of the body. They can cause discomfort by drying the mucous membranes of the eyes, nose and mouth, particularly in dry winter conditions. Some people are particularly sensitive to the latter effect. Older women often fall into this category and account for a large proportion of complaints of draught. Even the former effect is highly dependent on the clothing worn and the exact way clothing insulation is distributed over the body surface. Sex differences in clothing lead to sex differences in complaints of draught. Women tend to wear less clothing on the legs, ankles, shoulders and arms than men do and are therefore more likely to be affected by draughts. Thus draught susceptibility is a highly individual matter. Although work has been done on minimum temperatures for avoiding complaints of draughts at a given air velocity, providing the means for individual adjustment of this is better than raising the temperature. These velocities can then be increased in hot weather to provide increased cooling, local or general, but reduced to avoid draughts or to raise the effective temperature in cold weather. Raising the temperature to avoid draughts is not conducive to energy conservation.

It is good practice to limit the general air velocity in an occupied zone to 0.1 m/s but provide the means to increase air velocity when required. The general effect of air velocity on the heat transfer coefficient for whole body heat balance is discussed below, but in dwellings is unlikely to be a major source of variation.

v) combined effects of air temperature, radiation and draught on the human body

There have been many attempts to predict quantitatively the effects of the thermal environment on the human body. Over 20 different indices of thermal stress have been used in different connections. All have their limitations: some take account only of certain thermal factors, neglecting others in order to simplify the measurement of thermal climate in a particular situation. They lead to widely different predictions of thermal stress even in theory and therefore cannot predict reliably any relevant measure of thermal strain in practice, except in the particular conditions under which they were derived. Most such indices attempt to predict equivalent combinations of extreme thermal stress that produce the same limiting physiological strain, e.g. maximum permitted heart rate, sweat rate, or central body temperature. They do not lead explicitly to a predicted numerical value for these relevant parameters, however, but to an arbitrary value of "thermal stress". Strain parameters must be linked to this dimension experimentally. Since there is always a statistical distribution of physiological response even under identical conditions, the selection of a reassuringly exact number on the thermal stress dimension conceals a very large degree of uncertainty on the strain dimension. Only when the measure of physiological strain is the proportion observed to die of heat stroke has the exact shape of the distribution been studied with any close attention.

These indices of extreme thermal stress are of limited use in assessing conditions in dwellings. They are all based on experiments where sweating was profuse and discomfort considerable.

Another set of indices are based on subjective responses to comfort questionnaires. They equate thermal conditions in terms of the thermal discomfort they produce. Their weakness is that complaints of discomfort depend very much on what people are trying to do, in spite of the heat or the cold, and in almost all of the experiments on which comfort indices are based, the subjects were not trying to do anything. Although quite successful in equating different combinations of thermal conditions giving optimum comfort for sitting quietly, they provide a rather inadequate basis for the two kinds of assessment required for energy conservation decisions, which are:

1) to determine the limits of the reasonably comfortable zone beyond which it is justifiable to use energy to improve the thermal environment

2) to provide a thermal environment in which it is possible for the body to maintain thermal balance in a way that does not hinder the performance of specified activities.

Most comfort indices take no account of clothing, activity or the adaptive mechanisms of the body. They therefore neglect the most important factors that can extend the comfort zone. The only basis they could provide for (1) above is to predict some *arbitrary "unacceptable" degree of discomfort or percentage* uncomfortable, while giving no information at all on (2). Table I c-1 shows how inadequate this simplification would be. Fanger (1970) made an important step *forward by taking account of clothing and activity* level. His equation can show the conditions providing ideal comfort for a given activity level and clothing, ideal comfort being a particular state of thermal balance as defined by the mean skin temperature and sweat rate of subjects in exact thermal comfort. A comfort zone defined by acceptable clothing changes would be much narrower than required for (1), as it would not utilize the adaption of which the body is capable. Fanger treats deviations from ideal comfort on a statistical basis, predicting the number of people not in ideal comfort rather than the consequences for an individual in terms of the adaption his body would be required to make. It is therefore not possible to address (2) at all by using Fanger's equation.

Humphreys (1976) introduced a much simpler equation for the heat balance of the human body which enables assessments (1) and (2) to be made. It is an equation for the heat flow from the central body core at *37 °C to the* surroundings, taking account of the three insulating layers that govern this flow: that of the body tissues, of the clothing and of the surrounding air. *For continuous occupation, the heat flow must be equal to the heat produced in* the body, otherwise a stable central body temperature could not be maintained. The temperature differences across these three layers of thermal resistance are expressed by three terms of the equation and together equal the temperature difference between body core and air temperature:

$$T_a - T_b = M/A*(R_b + R_c + K/(4.2+13\ u^{1/2})\ )$$

where:

T_a = Body core temperature, 37°C

T_b = Air temperature, °C

M/A= Metabolic rate of heat production per m^2 of body surface, W/m^2

K = Proportion of metabolic heat dissipated by means other than evaporation, about 0.7 indoors.

R = Thermal resistance of body tissues, m^2,K/W

R = Thermal resistance of clothing, m^2,K/W (Popular unit:1 clo= 0.155 m^2,K/W)
u = Air speed, m/s
$1/(4.2 + 13u^{1/2})$= Thermal resistance between clothing and surroundings, m^2,K/W

Using Humphrey's limiting values for body tissue resistance, R_b = 0.04 m^2,K/W at onset of sweating and R_b= 0.09 m^2,K/W at onset of shivering, this equation allows the calculation of conditions that permit stable adjustment of skin temperature to the prevailing air temperature. It is convenient to select fixed values of metabolic rate appropriate to a given activity, and fixed clothing resistance, in order to allow the calculation of maximum and minimum room temperatures. Table I c-1 was prepared in this way. Air velocity should not be assumed to be less than 0.1 m/s. Thermal radiation can be included by using the operative temperature instead of the air temperature, i.e. by replacing T_a by the arithmetic mean of air temperature and mean radiant temperature. This approximation is appropriate for all normal indoor air velocities.

Assessment (1) required for energy conservation decisions can be made quite simply from the above equation, in the following way: for a given room and time of day, a number of activities are to be expected. A judgement must be made as to what it is reasonable to be able to do without sweating or shivering, and what are the reasonable limits for clothing for these activities. These judgements will vary greatly between countries. The equation will then give maximum and minimum temperatures, enabling the engineer to calculate frequency diagrams showing the number and duration of occasions during a typical year that given activities at given times of day will inevitably lead to discomfort. The consequences of refusing to adapt clothing can be calculated in terms of the increased frequency and duration of discomfort then predicted. Alternatively, the benefits of increased energy consumption can be expressed either as a reduction in the frequency and duration of periods of discomfort or in terms of a reduced need to adapt clothing or to reschedule activities to other rooms or other times of day.

Assessment (2) required for energy conservation decisions can be made by considering the consequences of adjusting the body's heat balance to cope with unsuitably high or low temperatures. A general rule is that activities requiring mental concentration cannot be adequately performed when fully vaso-dilated, i.e. when at the limit of reduced thermal resistance of body tissues, 0.04 m^2,K/W, close to the onset of sweating. For such activities, a lower limit of 0.065 m^2,K/W should be assumed. It is better to be slightly cool than slightly too hot. For social intercourse, too, it is unpleasant to be on the verge of sweating: it discourages animation and induces lethargy. On the other hand, it is not pleasant to be cold either. The region 0.075 to 0.055 m^2,K/W is probably acceptable for pleasant, active relaxation. If skilled manual work is to be performed, it will be hampered by too great a degree of vasoconstriction. A maximum value of 0.07 m^2 ,K/W should be assumed for sewing,writing,typing, playing musical instruments, etc.

The above approach allows of great flexibility in energy conservation decisions. Occupant behaviour can be assumed to be adaptive or inflexible, as appropriate, and the consequences can be calculated quantitatively. Occupant decisions can be predicted. The effects of energy conservation on activities of various kinds can be estimated. The degree of approximation introduced by the assumptions is no greater than that inherent in using group experimental results to predict individual reactions.

- air contaminants

One of the most common measures when retrofitting a residential building in order to cut down the energy consumption, is to increase the heat resistance of the wall by adding an extra layer of insulating material. This measure in addition often leads to an increased air-tightness of the building. This may cause problems, especially for buildings with natural ventilation, because the ventilation rate can be diminished to an unacceptable level.

We will now discuss some of the major air pollutants separately. Carbon dioxide (CO_2) is a pollutant the concentration of which has been used as a measure of the quality of the air in a dwelling for more than 100 years.

A concentration of CO_2 lower than 0.5% by volume is often considered as acceptable. For a resting person an air supply rate of 12 m^3/h is required to keep a concentration of 0.15% at an equilibrium. For a living area of 60 m^2 and a volume of 150 m^3containing five persons this leads to a required air change rate of 0.4/h. At higher concentrations than 0.15% the air starts stinking. This is not because of the CO_2 concentration, but because of associated pollutants. The CO_2 concentration must attain a value of 3% by volume before physiological reactions like breathlessness and headache become noticeable. This concentration corresponds to an air exchange of 0.6 m^3/h and person and is only one twentieth of the air supply rate required to keep a concentration of 0.15% constant.

The problem of excessive moisture content in residential buildings, mostly caused by excessively air-tight constructions or ventilation systems with an inadequate efficiency, has become more important in recent years. This problem may occur in buildings where the rate of ventilation has been decreased in order to save energy, or have been retrofitted by adding extra insulation to the walls.

A seated person will expire about 40 g of water per hour. For a family of five persons this leads to an increase of the moisture content in a dwelling by 200 g/h. Drying of laundry by itself will take about one day. Laundry after spin-drying will contain 50 -100 % of water by weight. Thus, laundry with a dry weight of 4 kg will contain 2-4 kg of water. Assuming the emission of moisture from drying laundry to be constant during 24 hours leads to an increase of the moisture content in a dwelling by 80-160 g/h from 4 kg drying laundry.

Adding to this the contribution from the occupants and a smaller contribution from cooking, the estimated increase of moisture content in the living area will be about 300 g/h. For the example used here of a 5-person family in a living area of 60 m^2 with a volume of 150 m^3, we have plotted in fig. I c-1 the required air-change rate to keep the indoor relative humidity at a constant level for some different outdoor temperatures. The calculations have been performed for an outdoor humidity of 85 % . Assuming that this family is at home only 16 hours a day will reduce the required air-change rate by 25%. In this case an air-change rate of 0.5/h will in any case suffice to keep the indoor relative humidity below 60% during the heating season.

A high indoor humidity may bring problems of a different kind. Condensation may occur on cold surfaces such as windows. Humidity can give rise to serious hygienic disadvantages and the air can stink. Dust mites can flourish and be a threat to the health especially for allergic persons. High humidity can also cause rot and the growth of dry rot with serious economic and hygienic consequences.

High concentrations of formaldehyde has recently become a problem in buildings where particle board has been used in the construction. Certain types of furniture also contain particle board. The formaldehyde is contained in certain types of glue used at the fabrication of particle board. Allergic

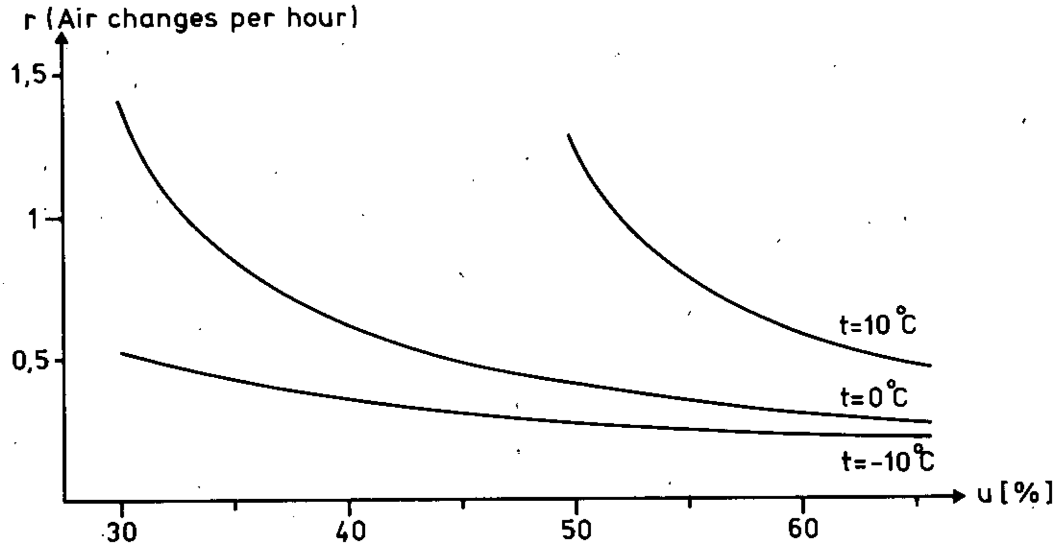

Fig Ic - 1 Required air change rate, r, to keep indoor humidity, u, constant for different outdoor temperature, t is the outdoor temperature. Calculation performed for dwelling described in text (5-person family, living area 60 m^2, volume of dwelling 150 m^3).

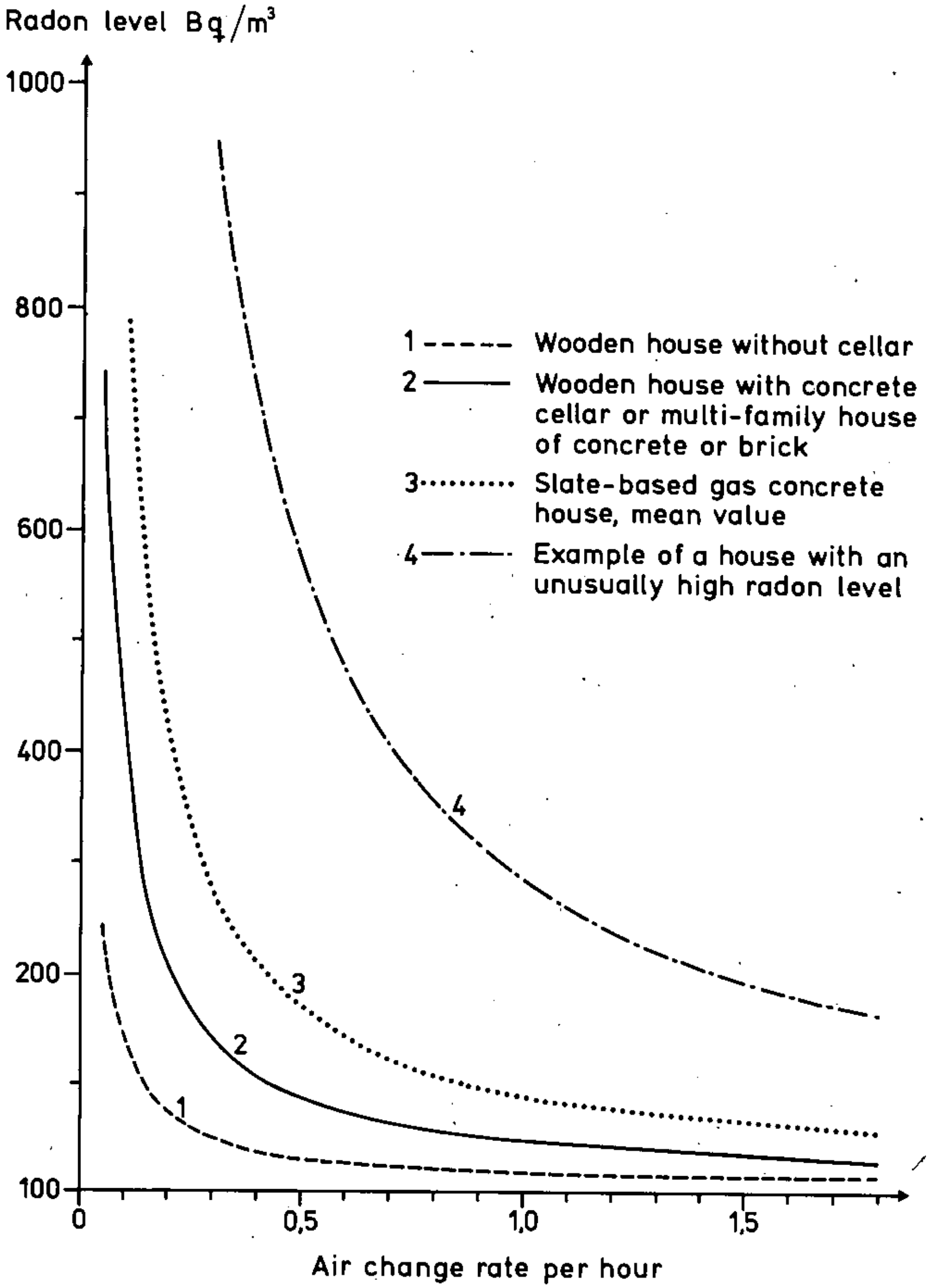

Fig Ic - 2 Radon concentration versus air change rate from some case studies of buildings (Radonutredn. 1979) persons may react to concentrations as low as 0.1 ppm. In some recently built houses concentrations of 2 ppm have been measured. In some cases increasing the airchange rate from 0.5 to 1/h only lowered the concentration from 1 to 0.7 ppm, due to imperfect mixing of the air . This problem can not therefore be solved by an increase of the ventilation, but has to be solved by elimination at the source.

Radon is a radioactive substance emitted from the radium existing in certain rocks . In some building materials the concentration can be relatively high. If the ventilation rate is too low, a constant exposure may after 15-40 years cause lung cancer. An air change rate of 0.5/h is considered sufficient to eliminate this risk. In fig. I c-2 we give as an example the concentration of radon as a function of the air change rate as measured in some case studies of buildings of different kind.

The examples discussed here indicate that an airchange rate of 0.5/h is sufficient to fulfil all hygienic ventilation requirements. For the purpose of this Report the hygienic problem of air contaminants need not be considered as long as one does not encounter a residential building where the airchange rate may fall below 0.5/h.

- lighting

Windows, and consequently daylighting, is a fundamental part of rooms in dwellings. The size of the windows and their performance have to be considered in the calculation of the heat balance of the building.

In many countries the building regulations contain minimum requirements for window sizes. These requirements are often expressed as minimum daylight factors, to some extent based on studies of preference. The use of windows depends on such things as view, demand for privacy and climate.

Differences in cultural traditions and fashion are reflected in the use of curtains, blinds, flowers and plants. This has a great influence on the amount of daylight entering the room and consequently on the need for electric light.

The electric light used in dwellings is mainly incandescent light with a few exceptions, for instance Japan, where flourescent lighting is dominant.

Flourescent lighting is in some countries used mostly in kitchen lighting. The electricity used for lighting in dwellings is relatively small compared to the total energy consumption.

There are very few stated requirements for electric lighting in dwellings. However, for stairs there is often a requirement of 50-150 lux. For most other rooms there should be sufficient number of electric outlets to make it possible to arrrange a suitable lighting allowing for individual choice .

For a fuller treatment of these questions see Hopkinson- Petherbridge-Longmore (1966) and deBoer-Fisher (1978).

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CHAPTER I d

Influence of the heating system on energy consumption

Contents

I d Influence of the heating system on energy consumption

- general introduction

Energy used to heat a building or domestic hot water is normally in the form of primary energy as oil, gas or solid fuels, or secondary energy as electricity. Renewable energy sources like sun radiation and energy contained in ambient air, ground water, earth etc. can be utilized with the help of solar collectors or heat pumps.

A heating system of a building is often divided into four sub-systems or components: the heat generator (the heat production unit), the heat distribution system, the heat terminals (radiators etc.), and the control system. There are heating systems which do not contain all these four components.

The most common heat generators are based on the above mentioned primary or secondary energies. Table I d-1 gives examples of types of energy; heat distribution media, and heat terminals.

Warm air furnaces are the oldest space heating equipments. The development of heating systems has resulted in efficient combustion boilers and furnaces, more efficient electric boilers, furnaces and space heaters and even more efficient thermodynamic heat generators as heat pumps.

Heat distribution systems are water- or airbased. Heat terminals are radiators, convectors, baseboard and finned tube terminals, dual duct and induction terminals etc. Floorheating systems are designed for low temperature systems as solar or heat pump systems. Control systems can be anything from manual radiator valves to computer based central feed-back control systems. The control system must be such that it can match the requirements on the heating system. Thus, a certain control system is only efficient in combination with certain heating systems.

The success of energy conservation depends on the knowledge of building behaviour, heating and ventilation systems behaviour and the coupling between building and installation systems. The interaction between building and heating

Table I d-1. Residential heating systems

	Forced air	Hydronic	Zonal
Primary energy	Gas Oil Solid fuels Electricity: -resistance -heat pump	Gas Oil Solid fuels Electricity: -resistance -heat pump	Gas Solid fuels Electricity: -heat pump -resistance
Heat distribution medium	Air	Water, steam	-
Heat distribution system	Ducting	Piping	-
Heat terminals	Diffusers Registers Grillers	Radiators Fan coil units Floor heating	Included with product

Table I d-2. Heat generators

Fuel or electricity	*Heat generators*	*Heat distribution medium*
Gas Solid fuels Oil	Combustion boilers Combustion furnaces	Air Radiation Water
Electricity	Electric furnaces Resistance space heater Heat pump	Air Radiation
	Electric boiler Heat pump	Water

system is analyzed in the last section of this chapter.

The efficiency of a heating system is often defined as the product of the efficiencies of its components. The efficiency of the heat generator and the heat distribution system can be unambiguously defined in terms of the thermodynamical properties of these components. The efficiency of the heat terminals and the efficiency of the control system, the control efficiency, are less easily defined. For these components there do not exist any generally accepted definitions of the efficiency.

- heat generators

Fuel or electricity is transformed to heat in a device called heat generator, whose construction depends on the type of fuel and heat distribution medium. In Table I d-2 most common types of heat generators are listed.

A combustion boiler is a pressure vessel designed to transfer heat (produced by combustion) to a fluid. Boilers may be designed to burn coal, wood, various grades of fuel oil, various types of fuel gas, or to operate as electric boilers. A boiler designed for one specific fuel may not be convertible to another type of fuel. Some boilers can be adapted to burn coal, wood, oil, or gas. Some boilers have two separate combustion chambers, one for solid fuel and one for oil. Several designs allow firing with oil or gas by burner conversion, or by using a dual fuel burner.

Warm air furnaces are of two types, gravity and forced air. Forced warm air furnaces use a motor-driven blower to circulate air over the heat exchanger and through the ducts. A draft hood is attached to the outlet of the furnace and replaces the barometric damper.

Conversion burners are complete burners and control units designed for installation in existing boilers and furnaces. Conversion burners for domestic application are available in sizes ranging from about 10 to 100 kW capacity.

Space heaters are used for heating a single room or a limited area. They differ from central heating equipment in the extent of distribution system incoporated. Both natural convection and forced circulation warm air systems are used.

An oil burner is a mechanical device for preparing fuel oil to combine with air under controlled conditions for combustion. Two methods (atomization and vaporization) are used for the preparation of fuel for the combustion process. Air for combustion is supplied by natural or mechanical draft. Ignition is generally accomplished by an electric spark, gas pilot flame, or oil pilot flame. Burners of different types operate with luminous or nonluminous flame. The operation may be continuous, intermittent, modulating, or high-low flame. Residential oil burners ordinarily have a fuel consumption rate from about 0.5 to 5 ml/s.

A gas burner is a device for the final conveyance of the gas, or a mixture of gas and air to the combustion zone. Burners are of the atmospheric injection, luminous flame, or power burner types. Residential gas burners may be classified as those types designed for central heating plants or those designed for room application. Gas burners and conversion burners are available for several kinds of central systems and for other applications, where the units are installed in the heated space. Central heating appliances include warm air furnaces and steam or hot water boilers.

A mechanical stoker is a device that feeds a solid fuel into a combustion chamber. It provides a supply of air for burning the fuel under automatic control and, in some cases, incorporates a device for automatic removal of ash. Coal, wood, and pellets can be burned more efficiently by a mechanical stoker than by hand firing because the stoker provides a uniform fuel feed rate, better distribution in the fuel bed, and positive control of the air supplied for combustion.

Most oil-fired burners, and many gas-fired residential boilers are equipped with an internal tankless heater coil. The boiler/heater is a water to water heat exchanger, used to supply domestic hot water. By definition, a tankless heater uses no storage tank: the only heat storage is the volume of heated boiler water surrounding the heater coil. A storage tank for domestic water may be added to supply peak loads and thus to allow a reduction in boiler capacity. A circulation pump is usally needed to circulate water between boiler heater and storage tank.

Electric heating systems are either centralized hydronic or warm air systems or consist of room units such as space heaters, radiators, or convectors. Hydronic systems often use an electric boiler which is a pressure vessel designed to transfer heat from electric resistance elements to a fluid.

Electric boilers are nearly 100% efficient in transferring heat within the boiler. Losses from electric boilers are heat lost from the external boiler surface and piping connections. Depending on location, the heat losses can contribute to the heating of the dwelling during the heating season.

A heat pump is a device that with help of work can transfer heat from a lower temperature level to a higher level. The vapor-compression cycle, electrically driven, is the most common working principle for heat pumps. Heat pumps are normally classified according to heat source and sink and heating and cooling distribution fluid. The most common type is the air-air heat pump mostly depending on traditions from air-conditioning. The use of air-water and water-water heat pumps is increasing in Europe as well as in the U.S and Canada.

- heat distribution

Water systems can be of the forced type, where water is circulated by a pump, or gravity systems where the thermal head is created by the difference in temperature and weight between supply and return columns of water. Gravity systems are seldom used today.

The heated fluid is distributed throughout the residence by a system of piping to cast-iron or steel plate radiators and cabinet convectors or fan-coil terminals located in each room. Basic piping arrangements are series loop, one-pipe, two-pipe reverse-return and two-pipe direct return (see fig. I d-1).

Losses of energy e.g. by water leaks are common. Firing rates higher than needed reduce efficiency and increase energy waste. Radiant and convective heat losses from heat generators and piping are unrecovered if the heat is delivered to the outside air rather than to the spaces where heat is desired. Energy saving is accomplished by insulating the surfaces of all heating system components which have a temperature appreciably above that of the surrounding air and which do not contribute heat to the design load.

Air central systems are rarely used in apartments, since it is generally considered undesirable to mix return air from more than one apartment. In single-family dwellings forced air systems are widely used in the U.S. Heated air is distributed throughout the residence by metal and/or fiberglass air ducts. The heat losses from an air system are mainly due to air leakage and bad

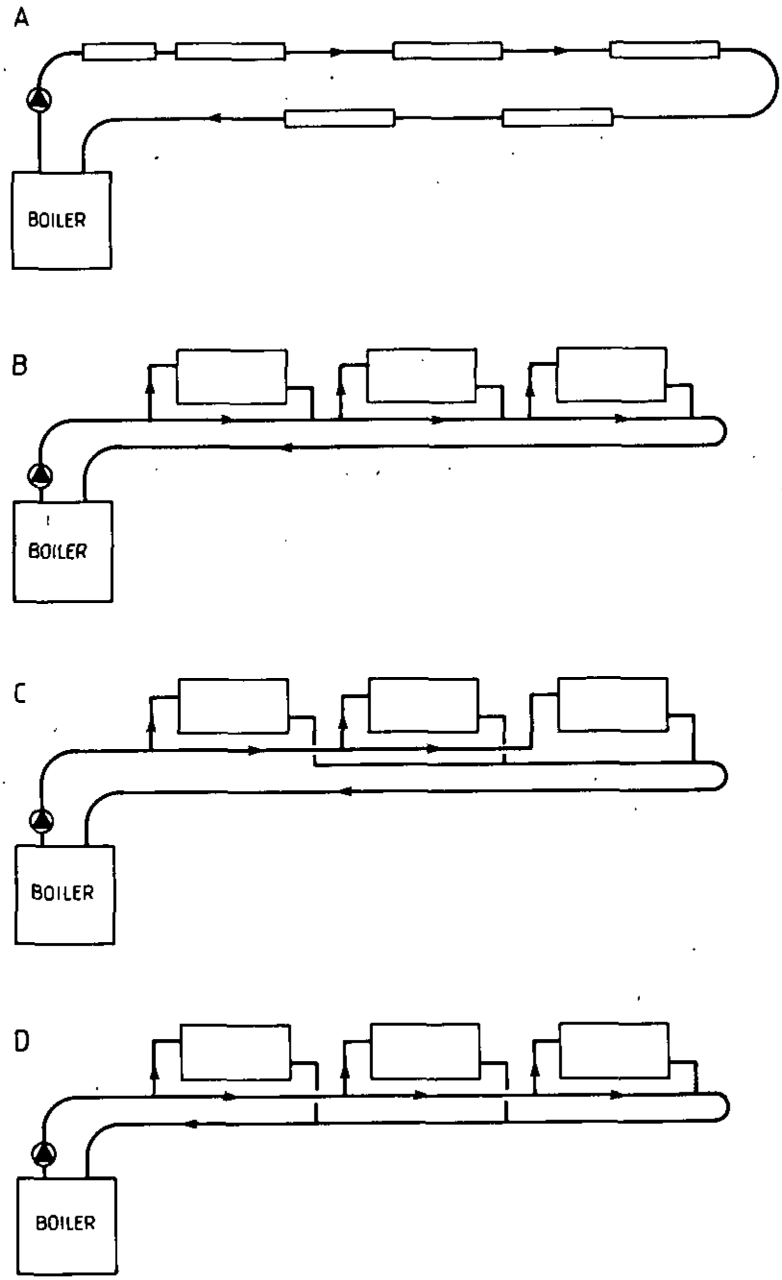

Fig. I d-1 Examples of piping systems
A = serie loop system
B = one-pipe system
C = two-pipe reverse return system
D = two-pipe direct return system

insulation of the ducts.

It is important that the heating system is well adjusted. Otherwise some areas might become overheated when other areas are too cool. A bad system can also lead to oversized fans and oversized furnaces.

- heat terminals

The term radiator is generally confined to sectional steelplate or cast iron radiators of column tubes or steel plate panel radiators. The heat emission from a radiator is partly radiation and partly convection. The heat emission from a radiator depends on:

- the size of convective surface
- the height of the radiator
- air flow conditions
- water temperature and flow
- temperatures and radiation coefficient of room surfaces
- furniture
- air movement in the room
- curtains
- the position of the radiator
- the distance radiator- wall and radiator- floor
- casing

The heat emitted by the radiator is not proportional to the temperature difference between the radiator surface and the ambient temperature, but is rather proportional to some power of this temperature difference. The numerical value of the exponent is in general around 1.3. The surface temperature of the wall section behind a radiator is much higher than on other parts of the wall. The heat losses through the wall behind the radiator can be as much as three times the losses through other parts of the wall. As the wall is primarily heated by radiation,a simple radiation shield can be attached to the wall.

The term convector refers to a heat terminal that operates with gravity-circulated air and has a heating element with a large amount of secondary surface containing two or more tubes. The heating element is surrounded on all sides by an enclosure having one air inlet opening below and one above the heating element. The heat emission from convectors depends on:

- the water temperature
- air flow over convector surfaces
- the degree of dirt on convector surfaces
- contact between pipes and seconday surfaces
- the size of inlet and outlet openings

The term baseboard heater refers to heat terminals designed for installation along the bottom of walls. They operate with gravity-circulated room air. The term finned tube refers to heat terminals fabricated from metallic tubing with metallic fins bounded to the tube. They operate with gravity-circulated room air.

The term dual duct refers to a heat terminal consisting of a "mixing box" with two air supply connections, one with air of a temperature below and one with air of a temperature above that of the room air. The box mixes the two air streams so the resulting air stream has the wanted temperature.

In an induction terminal conditioned supply air is mixed with room air passing over a heating coil (steam,hot water or electric type). The temperature of the mixed air is controlled by regulating the output of the heating coil.

Room fan-coil units contain a small motor-driven centrifugal fan and a finned coil heat exchanger. They operate on all recirculated air, or take a proportion of fresh air through an external wall, or takes the air from a central plant. The finned coil is often heated by hot water.

There are hydronic or electric heating systems where the floor or the ceiling is heated by a piping system or electric resistent straps. Heat is emitted by radiation.

- control systems

The functional requirement of control in a heating system is to alter the system variables in such a way that the equipment capacity is changed to meet the load. Different heating systems require different kinds of control systems. A certain control system may only be efficient in combination with a certain heating system. Essentially, there are two types of control loops present in modern heating systems: open loop and closed loop.

1) A feed-forward control (see fig. I d-2a) is an open loop control because it is anticipating the effect on the system of an external variable which is characteristic for the open loop control. An outdoor thermostat arranged to control heat flow to a building in proportion to the load, varying with outdoor temperature, is an example. The actual room temperature has no effect on this controller. If the load of a room is decreased because of some kind of free heat, the room temperature will rise with effects on comfort and on energy consumption. Many occupants open the windows to avoid overheating. Thermostatic valves are often used in combination with feed- forward control systems to avoid overheating.

2) The central feed-back control (see fig. I d-2b) is an example of a closed loop control. In this type of system the controller measures the actual changes in the controlled variable and activates the controlled device to offset such variation. An example is a room thermostat that controls the amount of heat being distributed from the heating system. A room thermostat controlling the heat distribution to a building must be located in the most representative room according to indoor temperature.

A modern control system has an outdoor thermostat to control the supply temperature of the heat distribution medium and a room thermostat to control the amount of heat distributed.

A local automatic control is a device that controls room temperature only in the room where the control is placed. The control device may consist of

- a thermostat controlling an on-off switch on electric space-heaters
- a thermostatic valve controlling water flow through a radiator or other water based heat terminals
- a thermostat controlling a damper designed to control the flow of air

The performance of local manual control depends on the operator, who in most cases will be the occupant of the dwelling. In buildings with a water system the manual control mostly operates on the water flow.

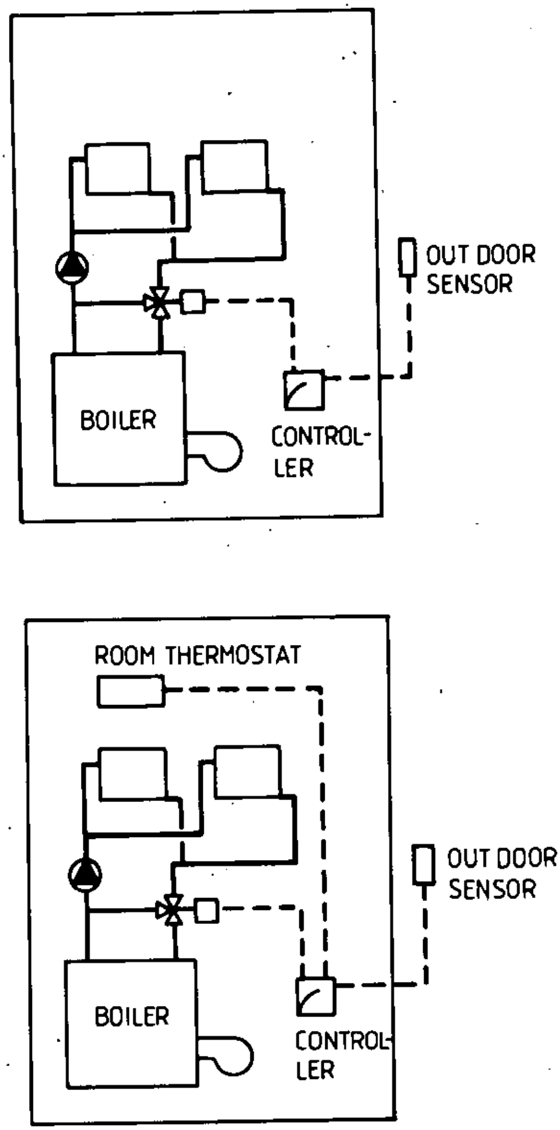

Fig. I d-2 Examples of central heating control systems
Feed forward system (top) and
Feed back system (bottom)

- efficiency of heating systems

The definition of efficiency is seldom unique or commonly accepted. In general efficiency can be defined as the ratio between "useful energy" and "consumed energy". For complex systems such as heating systems, which consist of a number of components, the efficiency of the system can be expressed either in terms of the efficiency of each separate component, or in terms of the system efficiency.

A heating system can be divided into
- the heat generator
- the heat distribution system
- the heat terminals
- the control system

The control system should influence the performance of, and the interaction between, the other three components so that the actual indoor climate is as close as possible to the desired one.

The energy flows of the heating system are listed below (see fig. I d-3). Note that here the chimney is not included in the heating system.

Q_i = heat content of the supplied fuel (calorific value)
Q_j = convective and radiative heat losses to the environment from the heat generator
Q_ℓ = convective and radiative heat losses to the environment from the heat distribution system
Q_u = convective and radiative heat losses to the environment from the heat terminals
H_a = enthalpy of the air entering the boiler
H_f = enthalpy of the flow gases and vapour in the flue gases
H_4 = enthalpy of the heated fluid entering the boiler
H_1 = enthalpy of the heated fluid leaving the boiler
H_2 = enthalpy of the heated fluid entering the heat terminal
H_3 = enthalpy of the heated fluid leaving the heat terminal
W_v = work performed by the burner
W_p = work performed by the circulation pump

The energy conservation equation of the components in steady state conditions

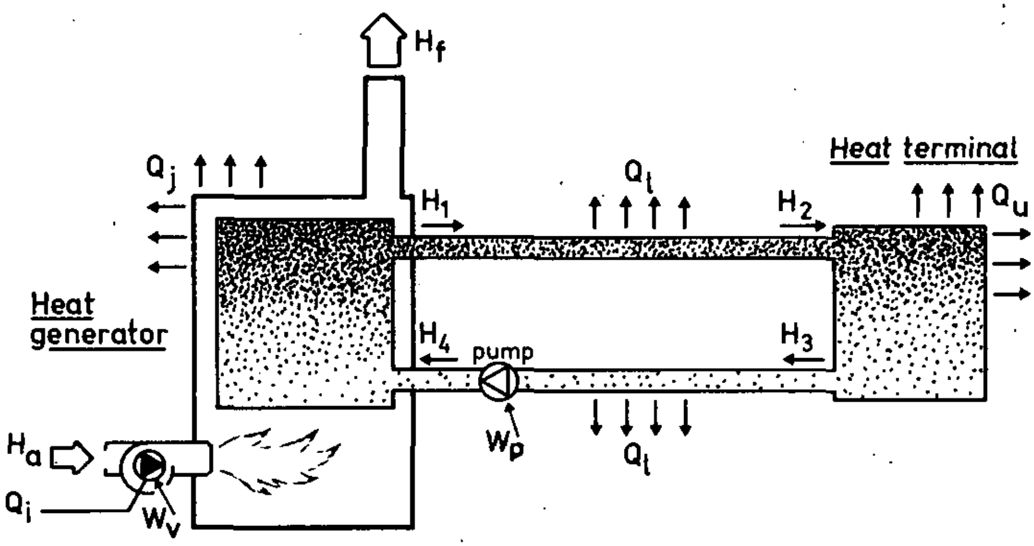

Fig. I d-3 Generalized picture of energy flows in a heating system consisting of heat generator, heat distribution system, and heat terminal (the chimney is not included)

Q_i = heat content of fuel

Q_j = radiative and conductive heat losses from the generator (jacket losses)

Q_l = heat losses from the distribution system

Q_u = heat given off by the terminals

H_a = enthalpy of air entering burner

H_f = *enthalpy of smoke gases and vapour entering* the chimney

H_1 = enthalpy of heated fluid leaving generator

H_4 = " " " " entering "

H_2 = " " " " entering terminal

H_3 = " " " " leaving "

W_v = work performed by burner

W_p = work performed by pump or fan

is then for the heat generator:

$$-Q_j + W_v + Q_i + H_a - H_f + H_4 - H_1 = 0 \qquad \text{(I d-1)}$$

for the heat distribution system:

$$-Q_\ell + W_p + H_1 - H_2 + H_3 - H_4 = 0$$

for the heat terminal

$$-Q_u + H_2 - H_3 = 0$$

and for the whole system

$$-Q_j + Q_\ell + Q_u + W_v + W_p + Q_i + H_a - H_f = 0$$

The efficiences can then be defined as the ratio between "useful energy" and "consumed energy". It is then common not to include the work required for the process in the "consumed energy", but to include only the heat content of the fuel. The hypothesis is made that W_v and W_p can be disregarded. One can then define the efficiencies of the heat generator:

$$\eta_g = (H_1 - H_4)/Q_i = 1 - Q_j/Q_i - (H_f - H_a)/Q_i \qquad \text{(I d-2)}$$

of the heat distribution system:

$$\eta_d = (H_2 - H_3)/(H_1 - H_4) = 1 - Q_\ell/(H_1 - H_4) \qquad \text{(I d-3)}$$

of the heat terminal

$$\eta_t = Q_u/(H_2 - H_3) = 1$$

and of the whole system

$$\eta = Q_u/Q_i$$

It is easily verified that

$$\eta = \eta_g * \eta_d * \eta_e = \eta_g * \eta_d$$

In practice, the term "energy conversion efficiency" of a boiler (or a furnace) can refer to two different definitions of efficiency as this one often varies with the load:

1) the steady state efficiency at a fixed load (defined as in eq. I d-2)
2) the average or cyclic efficiency (the average efficiency over a period. The variation in the load with time must then also be defined)

The steady state efficiency is in general experimentally determined in one of two ways:

- the direct balance method
- the indirect balance method

These topics are treated in more detail in ch. III f.

It should be noted that part of the radiative and convective heat losses of the heat generator and the heat distribution system and part of the flue losses may also contribute to the heating of a building. This has not been taken into account in the definitions of efficiency given above. Alternative proposals for the definition of efficiencies have been made. The efficiency of the heating system has been defined as the product of the efficiency of the heat generator, the efficiency of the heat distribution system, the efficiency of the heat terminals and the control efficiency (Uytenbroeck 1981), but no precise definitions of the efficiency of the heat terminal or the control efficiency are given in this case. The efficiency of the heat terminal has been defined as the ratio between the minimal energy required to provide a certain indoor climate and the actual energy output by the heat terminal (Guillaume-Gengoux 1981). This then requires a quantitative evaluation of the energy required by an ideal heat terminal to guarantee a certain indoor climate. This evaluation is not easy to perform, due to the complexity of the interaction between the terminal, the ambient air and the surrounding walls.

The control efficiency can be defined in terms of the deviation of the controlled variable from the set- point (provided there is only one control variable). If the control variable is the indoor temperature, and one denotes by:

T_i' = the actual indoor temperature
T_i = the wanted indoor temperature
ΔT = the temperature difference $T_i'-T_i$
the control efficiency η_{cs} can be defined as

$$\eta_{cs} = 1 - \int (\Delta T)^2 \, dV \, dt / \int T_i^2 \, dV \, dt$$

where the integration is over the heated building volume, V, and over time, t. The temperatures T_i and T_i' (in degrees Kelvin) may refer to the indoor air temperature or to a weighted average of the indoor air temperature and the surface temperatures of a room (an operative temperature). The temperatures T_i

and T_i' may be functions of space and time. If η_{cg} refers to the instantaneous efficiency, the integration over time should be omitted. If T_i and T_i' take the same value everywhere in the heated volume of the building, the integration over V may be omitted. In a feed- forward control system, where the heat supplied to the heat distribution system is not affected by the indoor temperature, the control efficiency may be defined in terms of the supply temperature instead of the indoor temperature.

If the heat demand for a certain outdoor temperature is expressed in terms of the dependence of the required supply temperature on the outdoor temperature, one obtains a heat demand curve like in fig. I d-4. The shape of this heat demand curve will depend on the kind of heat terminals that are used. For an air system the curve will be approximately linear, for a water system the curve will be more convex. Depending on the amount of free heat (solar radiation, household electricity etc.), the curve may be translated along the abscissa of fig. I d-5. The magnitude of this translation will vary with the time of the year if solar radiation makes a significant contribution to the free heat. The heat demand curve is an intrinsic property of the building and the heating system, and is not influenced by the control system.

For a control system where the supply temperature is determined by the outdoor temperature only, the dependence of the supply temperature, determined by the control system, on the outdoor temperature is given by the characteristic curve of the control system. For most control systems this curve is either approximately linear or slightly convex (see fig. I d-5).

The best control efficiency is achieved if the heat demand curve and the characteristic curve of the control system coincide. This can, however, never be the case if the two curves do not have the same curvature. The best that can be achieved in practice is, in general, that the two curves cross for two values of the outdoor temperature. For other values of the outdoor temperature, the supply temperature will not be the optimal one. The control efficiency may be bad if the curvature of the heat demand curve and the characteristic curve of the control system are very different.

For control systems that do not use the outdoor temperature as the only input, the situation may be analogous, but more complex. In this case the control efficiency cannot be illustrated by just comparing two curves.

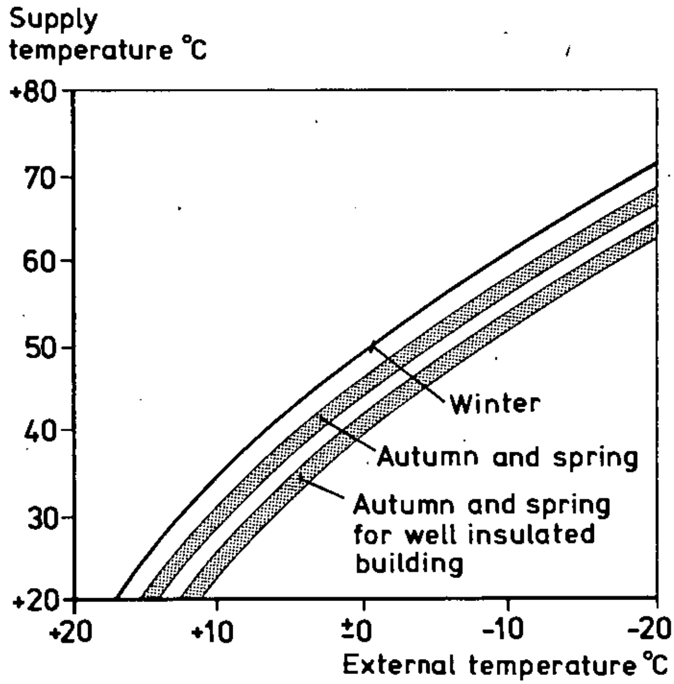

Fig. I d-4 Example of the dependence of supply temperature on the external temperature (heat demand curve) before and after increasing insulation of exterior walls

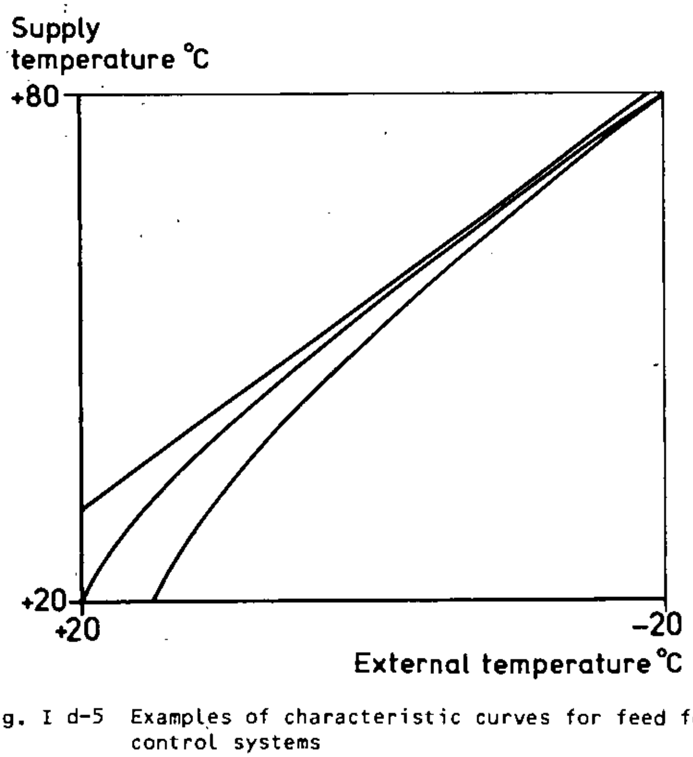

Fig. I d-5 Examples of characteristic curves for feed forward control systems

For heat pumps one uses instead of the efficiency other terms to describe the performance, the coefficient of performance (COP, also called the cooling energy ratio), and the seasonal performance factor (SPF). The COP is the ratio between heat output and energy demand (mostly electricity). The COP of heat pumps depends on the temperatures of heat source and sink. The wider the span in source-sink temperature, the smaller the efficiency. The theoretical COP for well defined conditions (the Carnot COP) is defined as

COP(Carnot)= T(cond)/(T(cond)-T(evap))
where
T(cond) = condensing temperature, K
T(evap) = evaporating temperature, K

Practically, 45-60% of the COP(Carnot) can be reached, but one should take into account that the condensing temperature must be higher than the sink temperature, and the evaporating temperature must be lower than the source temperature, thus increasing the temperature span..

Depending on the heat distribution medium fans or pumps are needed, which must be considered when calculating the seasonal performance factor (SPF). SPF is defined as the ratio between the total heat output (heat pump heating and supplementary heating) and the total energy demand (to heat pump and supplementary heating) during one year. The SPF depends on the building heat demand, size and type of heat pump and type of supplementary heat.

- building and heating system coupling

The overall efficiency of a heating system is determined by how well the heating system is adapted to the building. The most important factor is the design heat output of the heating system. A building of heavy construction may require another heating system than a building of light construction. For a building of heavy construction variations in indoor temperature should be allowed so that solar gains can be exploited. This is not so important for buildings of light construction as only small amounts of heat can be stored in the building structure.

A heating system can respond quickly or slowly to a change in heat demand. Forced air systems and electric heaters in general have a quick response, while water systems in old buildings with large tubes and radiators in general respond slowly. In new buildings with well adjusted water systems, the volume of the water in the system is often small and the response may therefore be quick. The ability to exploit free heat from people, sun, and household electricity depends on the response time of the heating system.

In a tight building an air to air heat exchanger or a forced air heating system will work better than in a leaky building. The ventilation will remain balanced even if there is a strong wind. Heating systems require a number of penetrations through the building envelope for ducts and pipes. This has an impact on the tightness of the building.

When a building is retrofitted, the heat demand will in general decrease. This means that also the average load of the heat generator will decrease. As the efficiency of most heat generators decreases with the load, this means that oversized heating systems may become less efficient after a retrofit.

It is not possible to give a full treatment of the complex interaction between building, heating system, and heating control system within the framework of this Report. We will therefore only illustrate the above dependence by regarding a building with a rather simple system, a water system controlled by a central feed- forward control system. It will be seen that, even for this rather unsophisticated control system, the interaction between the building, heating system and heating control system can be very complex.

For the system described above, there are two main requirements that have to be fulfilled for the heating system to be efficient from an energy point of view:

- the distribution of heat must be as even as possible between different rooms
- the room temperature must be kept within certain limits independent of the swings of the outdoor temperature

If the first requirement is to be fulfilled, the heating system must function as expected. This can be achieved by adjusting the heating system, i.e., presetting of valves so that the distribution of water between radiators is such that the temperature difference between rooms is small. The requirement for a certain indoor temperature everywhere will then mean that the coldest room will determine the energy consumption.

Even if the heating system has been adjusted according to the above procedure, there will often still be a need for a post-adjustment of the heating system to detect the "weak points" of the heating system. In a multi- family residential building this can be achieved by lowering the supply temperature until complaints by the residents are received. In practice, this will often lead to detection of "weak points" of the ventilation system and the thermal insulation of the building as well.

Retrofits like improved thermal performance of exterior walls and windows, or decreased ventilation, changes the energy demand by an amount that varies from one room to another. A post- adjustment of the heating system might therefore be necessary.

In a building with thermostatic valves, these have to be adjusted if one wants to lower the indoor temperature of every room to a value below the preset value of the thermostatic valves. After the adjustment, the supply temperature can be lowered. The return temperature will then fall.

The second requirement listed above was that the indoor temperature must be kept within certain limits. This can, in principle, be achieved by letting the supply temperature be determined by the outdoor temperature. It has already been noted that, for water systems, the dependence of the supply temperature upon the external temperature is a non- linear one, and the dependence is not the same for different periods of the year. One would then like to have the possibility to shift the characteristic curve of the control system parallel to the abscissa of fig. I d-5. This is, however, not possible with most control systems. Instead, the curve can be shifted parallel to the ordinata and it is also in general possible to change the curvature of the characteristic curve of the control system.

We then have the situation described in the previous section: the supply temperature will be the correct one only when the heat demand curve and the characteristic curve of the control system cross.

When the outdoor temperature is changing slowly, the supply temperature will be the one determined by the characteristic curve of the control system. However, when there are rapid changes of the outdoor temperature, there will be a time lag between the required and the actual temperature, and the amplitude of

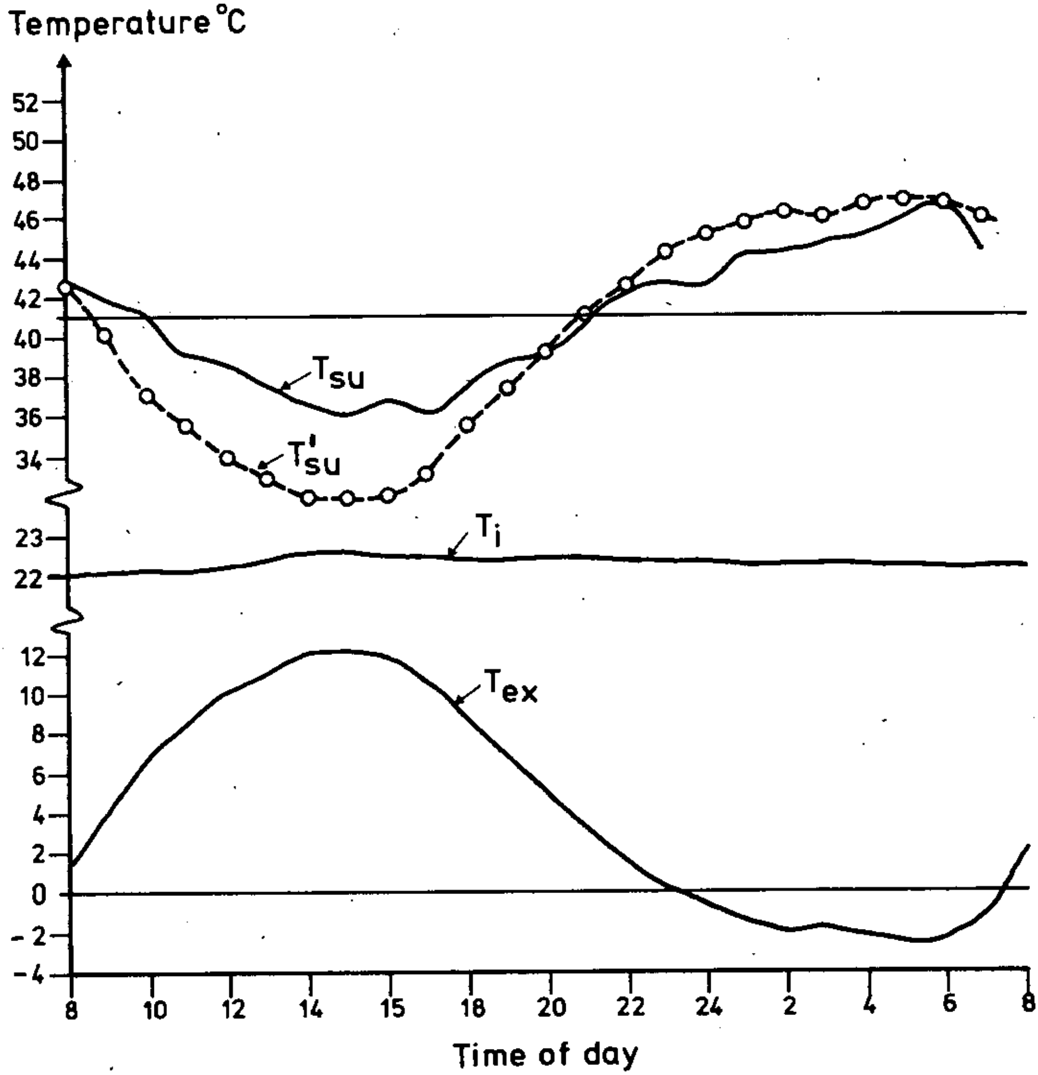

Fig. I d-6 Example of recorded supply temperature and external temperature during a clear day along with the "theoretical" supply temperature that the control system should have produced for the actual external temperature

T_{su} = actual supply temperature

T'_{su} = "theoretical" supply temperature

T_i = internal temperature

T_{ex} = external temperature

the supply temperature will be smaller than the amplitude required to counteract the change of the outdoor temperature (see fig. I d-6). The cause of this is that the reading of the external temperature sensor is influenced by the surface temperature of the external wall. The damping of the supply temperature amplitude will in general not affect the indoor temperature because of the thermal inertia of the building. The reading of the external temperature will also be affected by solar radiation, wind, and air humidity. The above factors may be important when night temperature set-back is used.

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CHAPTER I e

The occupants influence on the energy consumption

Contents

I e The occupants influence on the energy consumption

- operations by the occupant affecting energy consumption

The operations and activities of an occupant can be viewed as caused by physiological needs, or social and cultural norms, or by a combination of these factors.Most of the daily activities of an occupant are probably caused by such a combination of factors and, therefore, it will only exceptionally be useful to try to ascribe a certain behaviour or activity of an occupant to a single factor.

By human behaviour we do not here mean the whole spectrum of behaviour, habits, and actions performed by the occupant in a residential building due to cultural, social and physiological driving forces. Here we will deal with such behaviour of occupants in residential buildings that influences the domestic energy consumption.

For a better understanding it may be useful to split up the complex of behaviour, habits and activities of the inhabitant into single operations and determine the impact of each one of these on energy consumption. A distinction can then be made between

1) operations by the occupant involving consumption of energy in a direct form
2) operations by the occupant aiming at control of the indoor climate

1) Some operations involve the consumption of energy in a direct form, often associated with the use of domestic appliances. Energy will then be consumed directly in the form of electricity, gas, oil or hot tap water.

Operations of this kind include cooking, use of TV, refrigerator and illumination, clothes-washing, clothes-drying, washing up dish, and taking a bath or a shower. If an occupant needs to perform an operation of this kind, he can only indirectly influence the amount of energy that is consumed.

The amount of net energy will be determined by the appliance, by the kind of energy that is used and the conversion factor from primary to net energy. Some appliances are used by the occupant to save time and to reduce the amount of manual work needed to perform an operation (e.g. the use of a dish-washer). Often this also means that the amount of required primary energy is reduced.

Other appliances, like illumination and TV, are not used to replace manual work. The use of these appliances will always increase the total energy consumption. The total energy consumption will, however, not increase by the same amount as is needed for the operation of the appliances. Much of this energy will contribute to the heating of the dwelling. The magnitude of this contribution will depend on the need for ventilation when the appliance is used, the thermal inertia and the heating system of the dwelling and where, in the dwelling, the appliance is situated.

A break-down of the total energy into constituents representing the energy required for the performance of operations of the kind discussed here will in general not be necessary if one is interested only in the total consumption of domestic energy. It can usually be read off directly from a meter once a month or year. The purpose of a break-down of the energy consumption is to calculate the contribution to the heating of the dwelling from the energy by appliances when there is no way to measure it directly.

A discussion on operations of the kind discussed above, data on what amount of energy is used when they are performed and how to perform measurements of this energy consumption are found in Part IV.

Data on when operations of this kind take place are scarce. But some can certainly be performed only when the occupant is at home. Therefore knowledge about when the occupant is at home and how he spends his time there can be useful (see ch. IV c).

2) Other operations than those discussed above do not directly require an energy source, but are operations performed by the occupant in order to control the indoor environment. Some of them can only be performed when the occupant is at home. For some it is very difficult to determine the impact on the energy consumption. When and if they are performed depends on the occupant's attitude towards the prevailing indoor climate. The extent to which some operations of this kind are performed is also more directly influenced by social and cultural norms. These topics are discussed in ch. IV c.

An example is the choice of or demand for a certain indoor temperature. The difference between inhabitants of different countries is often reflected in national recommendations and building regulations regarding the permissible indoor temperature. The average indoor temperature has increased steadily during this century (see e.g. Hunt-Steel 1980) and there has been, at least until the energy crisis in the seventies, a tendency of different national recommendations and regulations to converge towards an indoor temperature well above 20 °C. This convergence can be regarded as a reflection of the fact that residential buildings in different industrialized areas are becoming more alike independently of the climatic zone. The demand for a higher indoor temperature is probably linked to the tendency to wear lighter clothing at home. It is also common today that the occupant tries to keep a comfortable temperature in all rooms of the dwelling.

Another example of this kind of behaviour is the habit of keeping the bedroom windows open during the night, influenced by the opinion that fresh air is very important. If the dwelling is equipped with a mechanical ventilation system, the notion that fresh air is of great importance for health and well-being may lead to an excessive ventilation. In these cases there can probably be large differences in behaviour between different countries.

A third example is that shutters and blinds can be used to control the amount of sunshine and daylight penetrating into the living area. Electric lighting will be used if there is not sufficient daylight. The use of shutters and blinds at night is to a large extent determined by the demand for privacy.

The choice of, or demand for, a certain indoor temperature in different countries is either well known or prescribed in some code and it is in any case comparatively easy to measure. The choice of ventilation in bedrooms and the use of shutters and blinds at night have been very little investigated. To obtain further knowledge in this field will require a rather extensive amount of research.

If the occupant does not feel comfortable with the prevailing <u>indoor climate</u>, he will try to <u>modify</u> it in the required direction. What action he will take will depend on the means at his disposal. If it is too cold he might turn on an electric stove rather than change his clothing. If it is too warm he might open a window.

If the residential building does not contain equipment giving the individual occupant the possibility to modify at least the indoor air temperature and the ventilation, the resulting behaviour of the occupant may be very unpredictable. He may try other means to control the indoor climate, means that from an energetic point of view might be very uneconomical. Such a behaviour may easily affect the energy consumption to such an extent that all calculation schemes for the prediction of the energy consumption can become useless (see ch. IV c).

Some investigations (see ch. II e) indicate that most of the variation of energy consumption in nominally indentical buildings can be explained by a variation in the behaviour of the occupants.

It is therefore important not to regard the occupant as a passive consumer of energy but to take into account the interaction between environment, building and occupant.

A factor that should not be forgotten is the attitude of the occupant towards energy saving. If the occupants can not understand the reason why a residential building is retrofitted, he may act in such a way that the purpose of saving energy is not achieved. In some cases the occupants will ultimately understand and accept the reason, but if they become involved in a research programme running for only one heating season, they may still be in the process of adapting to the new situation and this may influence the outcome of the research programme. This effect has been noted in some investigations.

- variation in energy consumption due to variation in indoor temperature and use of appliances

In many discussions about the effect of occupancy on energy consumption it should be kept in mind that data refer to an "average behaviour" of the occupants. The scatter around every such "average" will be large. The cause of this scatter is rather complicated. Attempts to correlate energy consumption to different factors such as the size of dwelling, family size, income, education, occupation, or age have been only partly or not at all successful.

In most experiments one has found that the standard deviation of the total energy consumption in a group of "identical" houses lies between 10 and 30 % of the average total energy consumption. In a group of houses that are really of an identical construction, this standard deviation may sometimes be as small as 10 - 15 % (Solum and Songe-Moller 1974, Socolow 1978). In a group of houses that are similar, but not really identical, the observed standard deviation is more typically of the order of 20 %. Two typical examples of the distribution function for the total energy consumption in a group of similar houses are given in fig. Ie-1.

One major source of the variation in energy consumption is the variation in the average indoor temperature between dwellings. In studies of the indoor temperature one often finds that the standard deviation of the average temperature in a group of dwellings is close to 2 K, even if the average indoor temperature may vary from one country to another. Some examples are given in fig. Ie-2. Here the data for Sweden and Italy may be considered as representative of the stock of residential buildings of these countries. How much of the variation in total energy consumption that can be explained by this variation of the indoor temperature will of course depend on the average indoor-outdoor temperature difference and the degree of insulation of the dwelling. In fig. Ie-3 we give an example where about half of the variation in total energy consumption can be explained by the variation of the indoor temperature.

The variation in the consumption of household energy is then superimposed on the variation in the indoor temperature. Here one often finds that the standard deviation of a certain kind of household energy consumption is as large as 50 % of the average total energy consumption. As an example we give in fig. Ie-4 the distribution function of the use of hot tap water from investigations in some countries. Here the distribution function from the french investigation may be considered as representing the national variation in consumption of hot tap water.

Very few studies have been performed where a break- down of the energy consumption has been made in such a way that the variation in different kinds of energy consumption can be studied. In fig. Ie-5 we give an example where the standard deviation of the total energy consumption is rather small, while the variation in the energy consumption for different household activities is much larger. The energy consumed for heating of the dwelling in this case probably constitutes the major part of the total energy consumption.

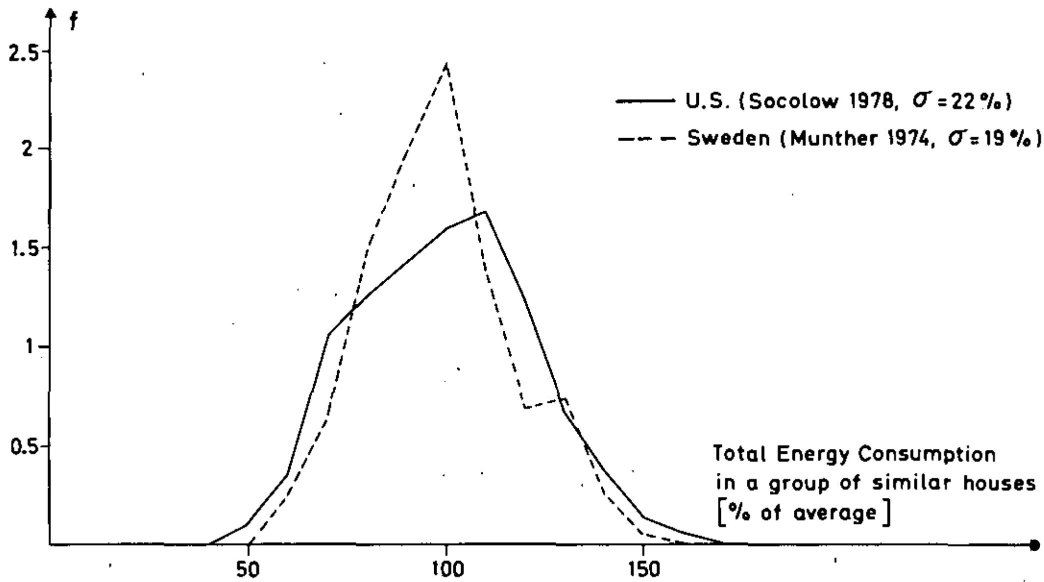

Fig Ie - 1 Distribution function f of the variation of total energy consumption in a group of similar houses. σ is the standard deviation

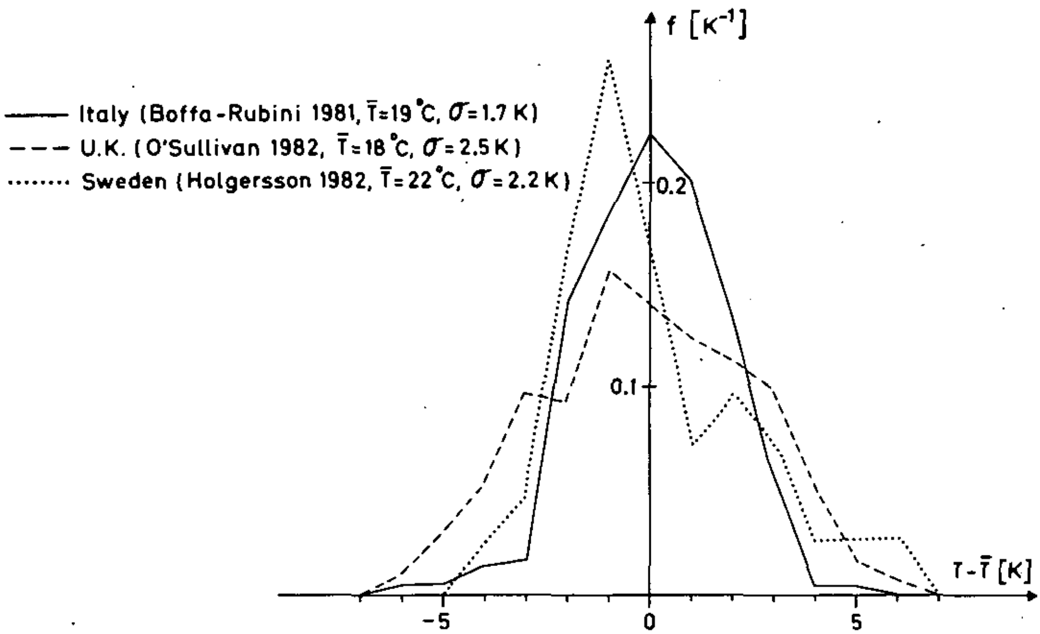

Fig Ie - 2 Distribution function of the variation of indoor temperature in dwellings, T. $\bar{T}$ is the average indoor temperature for all kind of dwellings included in the experiments, σ the standard deviation. The data for Sweden and Italy can be considered as representing a national average of all kinds of dwellings

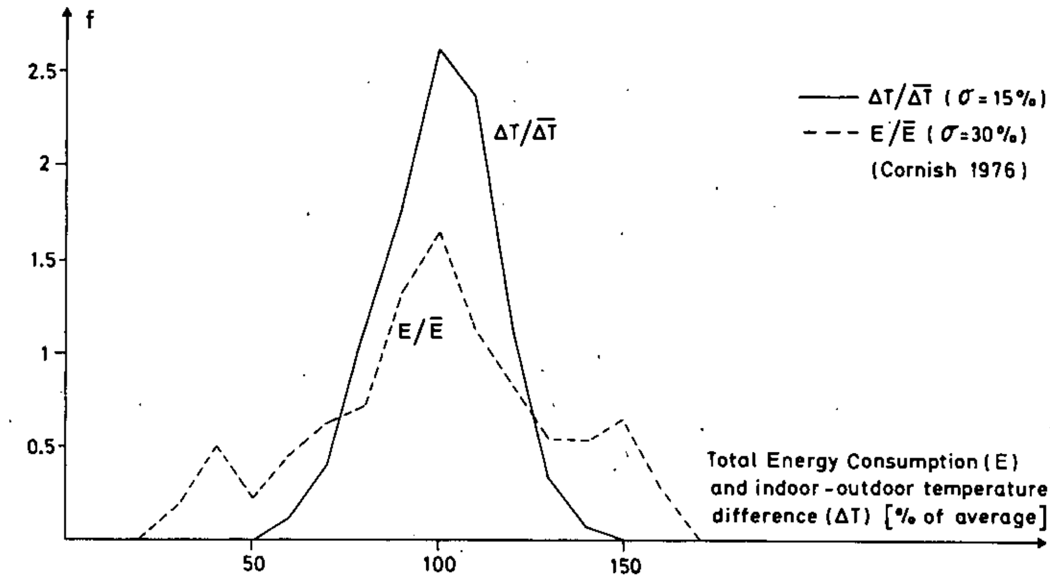

Fig Ie - 3 Distribution functions of the relative total energy consumption, E/$\overline{E}$ and the relative indoor-outdoor temperature difference. σ is the standard deviation

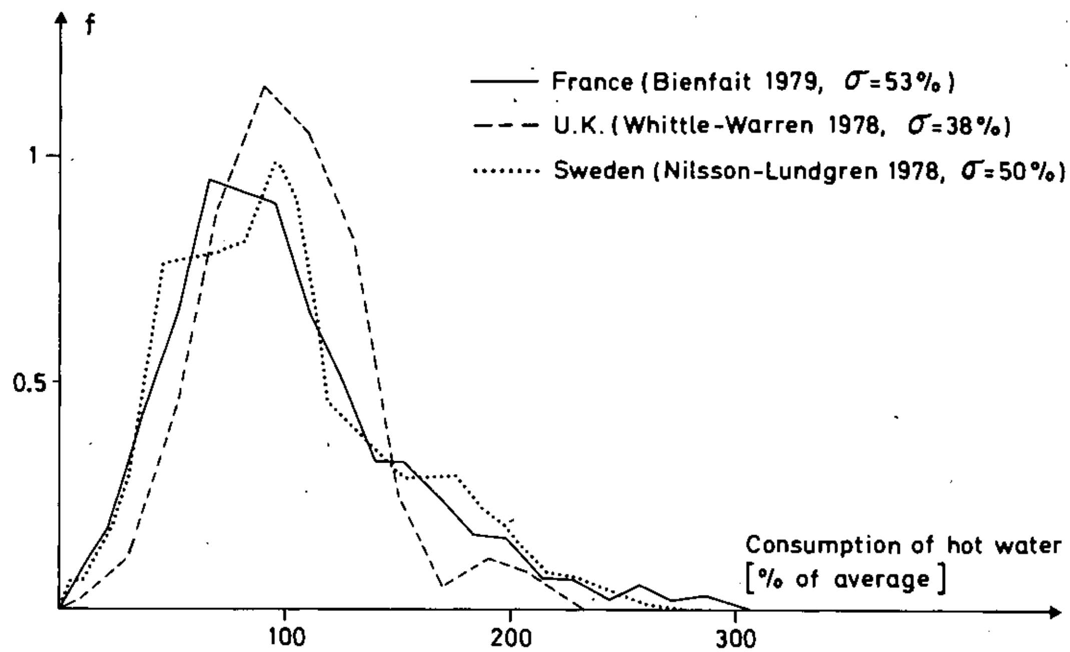

Fig Ie - 4 Distribution function of the consumption of hot tap water of a class of buildings relative to the average consumption of that class. The distribution functions of several classes of residential buildings have been added. σ is the standard deviation

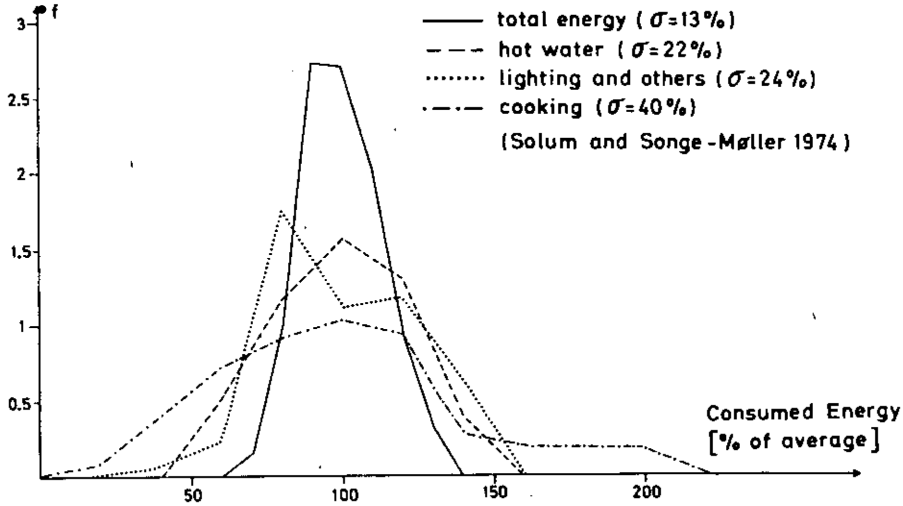

Fig Ie - 5 The distribution functions of the relative energy consumption for total energy consumption, hot tap water consumption, cooking and lighting and other consumption for a group of identical, electrically heated single family houses in Norway, σ is the standard deviation

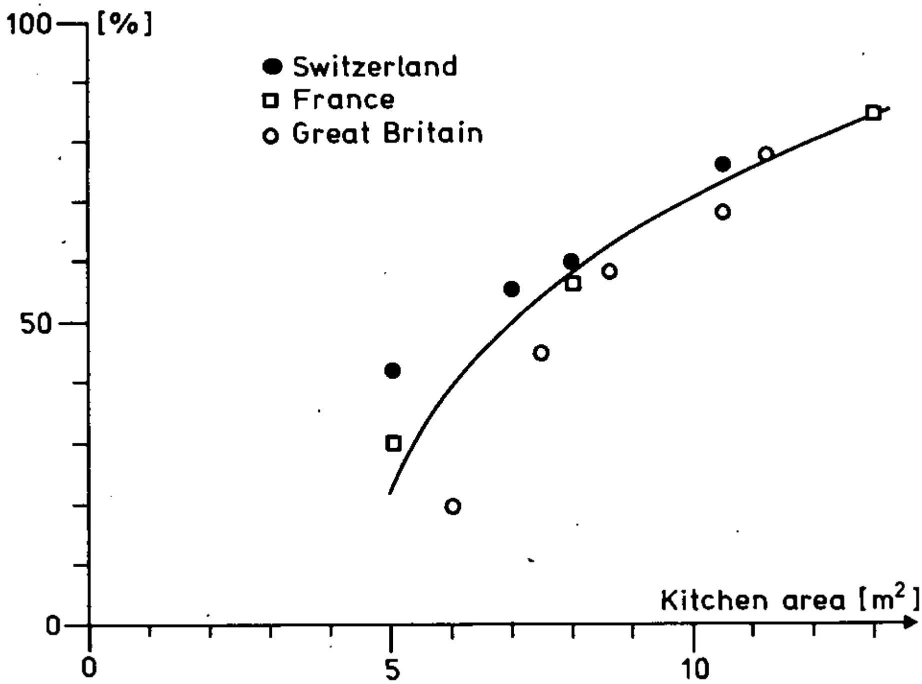

Fig. Ie - 6 Percentage of meals taken in the kitchen versus kitchen area in three countries

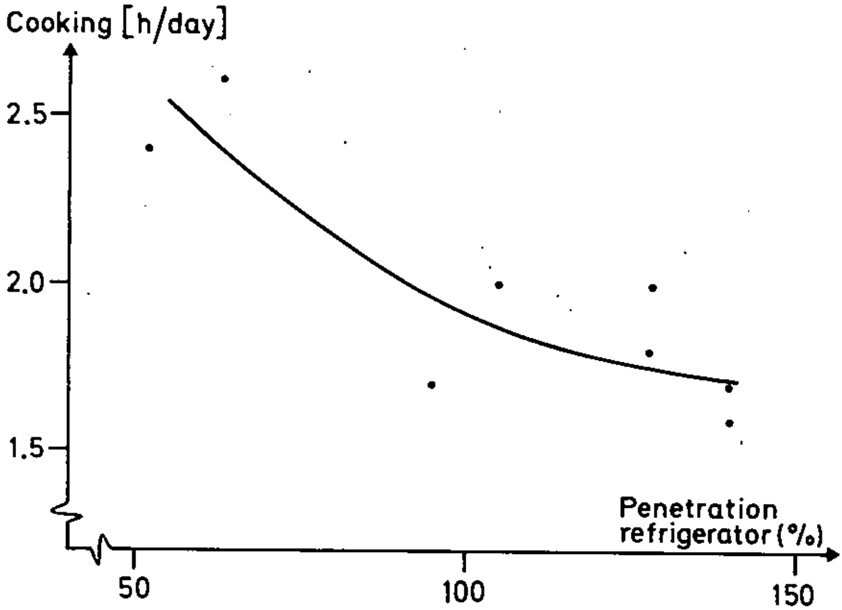

Fig Ie - 7 Average time spent on cooking by women versus penetration of refrigerators and freezers in some Western European countries

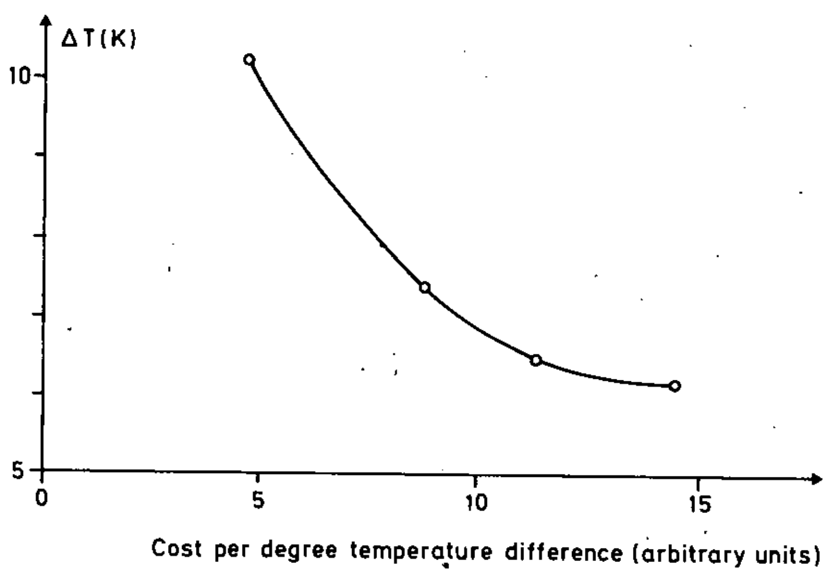

Fig Ie - 8 Occupant s choice of indoor-outdoor temperature difference (ΔT) versus relative cost for keeping this indoor temperature (after Weston 1950)

Most examples given above do not represent any national averages, but are merely case studies, and should therefore not be made the basis for generalizations of any kind. Distribution functions of the kind found in fig. Ie- 1 through 5 are often compatible with being log- normal.

It is difficult to find illustrations of the variation in other habits of the occupant that may affect the energy consumption. It is, however, obvious that the size and other characteristics of the dwelling and the presence or absence of certain appliances will influence where, when and how the occupant will perform certain activities. Two examples of this are given in fig. Ie-6 and Ie-7.

The price of energy will of course also affect the energy consumed by the occupant. This can be of great importance in experimental situations. If the energy consumed by the occupant participating in an experiment is subsidized, the result may be that he prefers a higher indoor temperature than he would have done under normal circumstances. This is illustrated in fig. I e-8.

It should then be obvious that in any study of the effect of a retrofit one should take into account the interaction between environment, building and occupant.

- *variation in energy consumption* due to behaviour and attitudes

Much of the discussion on energy saving by retrofitting residential buildings has been about purely technical measures. However, it should be realized that an equal amount or even more energy would be saved if the behaviour of the occupants could be changed, or if every occupant was really motivated to save energy at home.

Research on the behaviour of occupants at home has often used sociological methods, combined with detailed surveys of houses. One should not draw any hasty conclusions from details of the data. Data have been obtained by different researchers using different methods of investigation and in many cases the sample of questioned occupants has not in a true sense been representative of the whole population of a country. However, the major features of data certainly reflect the behaviour of the occupants.

The criteria of human thermal comfort must always be examined. Traditionally they have been used to optimize on fuel and thermal insulation ratios for the design of heating, ventilation and air-conditioning system. Thermal comfort has become a commodity produced by the service industries and marketed and sold by the heating, ventilation, air-conditioning and insulating engineers (Fanger 1972).

In the past, individuals relied upon clothing to maintain thermal equilibrium, while recent trends depend upon the production of artificial interior climates. Thermal insulation is therefore purchased more expensively from the building services engineer rather than from the tailor (O'Callaghan 1978).

Make the hypothetical assumption that clothing habits changed to what they were a hundred years ago, so that the interior temperature could be lowered to less than 15°C. This alone would save more energy than any other single measure that has been proposed to cut energy consumtption. The importance of the behaviour and attitudes of the occupant for the level of energy consumption can be illustrated by some examples.

In an investigation forming part of the Twin Rivers project the energy consumption in about 200 town houses was studied. It was found that more than two thirds of the variation in energy consumption for heating in nominally identical buildings could be explained by occupant related consumption patterns (Sonderegger 1978).

In other studies it has been observed that if occupants are subjected to an intense energy-saving campaign, the result may be a heavy reduction of the energy consumption.

In an energy saving study the occupants were informed how to reduce the consumption of hot tap water (Adamson et al 1975). This led to a 40% decrease in the consumption of hot tap water. However, a few months after the end of the energy-saving campaign, this reduction had entirely disappeared. This indicates that an intensive information campaign can reduce the energy consumption for a short period of time, but probably have no lasting effects.

The importance of feedback to the occupant about the results of his effort to save energy has been the subject of a study (Seligman - Darley 1977). The results show that providing home-owners with feedback information about their rate of energy consumption can be an effective strategy for saving energy.

Another feed-back study (Becker 1977) was conducted to test the *hypothesis* that feed-back would lead to more energy conservation if occupants were asked to adapt to a difficult conservation goal rather than an easy one. The result shows that feed-back is especially effective if the occupants are motivated to save a considerable amount of energy.

The attitude towards energy saving may be more important than the *technological possibility of saving energy.* In a study in California (Hamrin 1979), it was found that people in houses with the greatest technological potential for savings actually made fewer conservation efforts than did people in conventional houses of a comparable nature. In this case the probable explanation was that the residents in the former category of buildings regarded these as a "technical fix", a device that would let them save energy without requiring them to change the way they lived. In contrast to this, the residents of the conventional houses were mostly concerned with saving money on their fuel bills.

It is important to realize that the behaviour and attitudes of the *occupants may change with time.* *In many* studies of the effects of retrofits it has been found that energy saving has been great at the beginning of a programme, but then it has gradually faded away. One has, however ,also noted the opposite effect. In retrofits, including the introduction of more complex systems into the building, sometimes no energy has been saved during the first heating season, but a substantial reduction in energy consumption has taken place during the second heating season after the retrofit. The probable explanation, in this case, is that it has taken the occupant quite a long time to learn how to handle the new system. It may therefore be an advantage if, in studies of the retrofit effect, the occupants can be given time to adapt to the new living conditions before the measurements start. This is often referred to as a "*running- in and learning period*".

The effects described above will obviously be of special importance in cases where the measurements are only performed during one heating season after the retrofit. In this case it would be an advantage if one could follow at least the total energy consumption of the building during still another heating season to make sure that the effect described above is not relevant.

In experiments involving inhabited residential buildings it is important that the occupants are informed in advance about the research programme, what measures are going to be taken and what changes in the indoor climate are to be expected. If possible, changes should be introduced gradually to give the occupants the possibility to adapt to the new environment. The result may otherwise be complaints, and a negative attitude of the occupants towards the research project that may affect the outcome of the investigation.

In many research programmes for the study of energy savings in residential buildings, the indoor temperature has been lowered too much and too rapidly. The result has often been that things previously unnoticed by the occupants, like draught, temperature differences between different rooms of the dwelling, temperature gradients and indoor temperatures, changing by the hour, have become apparent. This has led to complaints from the occupants which have necessitated a revision of the research programme, and an increase of the indoor temperature (an example of this is given in ch. IV c section "control of ventilation and airing by occupant").

On the other hand, there is a danger that the occupants may become too enthusiastic about the research project and be willing to do anything to save energy. This attitude will probably not last longer than one heating season. If this happens to be the period when the investigation is performed, the conclusions that are drawn from the results of the experiment may be erroneous.

The impact of the behaviour and attitudes of the occupant on the outcome of an investigation may be of particular importance if the investigation is performed using the test-reference design (see Part II). Here it may be possible to ascertain that the test and the reference building are identical except in one respect and that the test and the reference population are identical with respect to social variables. It can be more difficult to ensure that the behaviour and attitudes of the two populations are not affected in different ways by the information they receive about the investigation, by the procedures of the investigation or by different alternations of the interior environments.

In this case it can be of worth to have access to experts with experience from physiological experiments to evaluate factors like those described above.

In any case the members of the two populations must be informed in ways as similar ways as possible.

- *effects of occupancy on the energy balance of a building*

Below we have tried to sum up the influence of the occupants on the energy consumption of a building. We have used the data given in Appendix IV.

Compare the energy balance of the same residential building when it is unoccupied and when it is occupied, assuming that the average indoor temperature is the same (see fig. Ie-9). In the unoccupied case, the energy input stems from the heat plant and from solar radiation. If the building is occupied there is an extra net energy input from electric appliances, cooking, hot water generation, and from the occupants themselves. The energy input from solar radiation may be different due to the occupants´ use of shading devices at the windows.

In the unoccupied case, the energy losses consist of transmission, infiltration, and ventilation losses. If the building is occupied, there are in addition losses caused by airing, and losses corresponding to the increased heat content of the discharge water. The transmission losses by long- wave radiation through windows may not be the same in the two cases, due to differences in the covering of windows.

The effect of airing and covering of windows on energy consumption is treated in ch. IV c. Here we will estimate the difference between the net energy input from appliances, cooking, human heat and hot water generation, and the energy losses due mainly to the discharge of water.

The following assumptions have been made:

1) all of the net energy used for illumination, TV, refrigerator, freezer and minor electric appliances is converted to heat inside the building
2) 25 % of the net energy used for cooking is lost through kitchen flue, and steam losses
3) 25 % of the net energy used for heating of tap water is transferred to the building by losses from the hot water storage and the plumbing
4) 20 % of the heat content of the hot tap water relative to the indoor

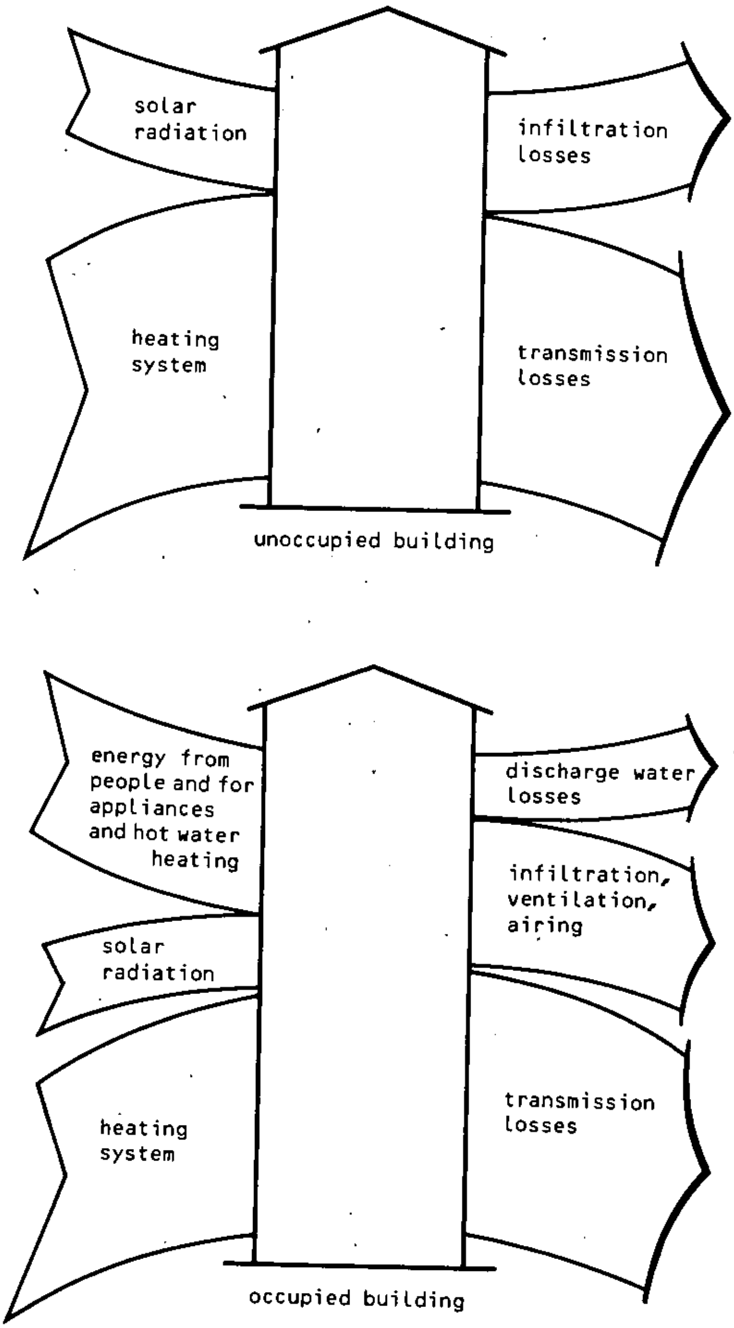

Fig Ie - 9 Energy balance of a residential building if unoccupied and occupied temperature is lost to the building before discharge

5) 20% of the net energy used by clothes- and dish-washers is lost to the building interior
6) cold water takes a temperature just between that of the of indoor air and that of the inlet water before discharge. The temperature of the inlet water is close to the yearly average air temperature.
7) human metabolism has been assumed to be 90W and employed occupants are assumed to be at home on the average 14 hours a day, non-employed 20.
8) the appliance efficiency of hot tap water appliances has been assumed to be 60 %.

For a discussion on the background of these assumptions see the section of App. IV where the specific topic is treated. In Table I e- 1 we give the estimated net energy input from appliances, cooking, human heat and energy used for the heating of hot tap water, the contribution to the heat balance from this net energy input, the cold water losses, and the resulting contribution to the heat balance of the building. This resulting contribution is in most cases considered here between 50 and 60 % of the net energy input. For a further discussion of this question see Romig-Leach (1977).

This calculation has been performed assuming static thermal conditions, and it has not been considered where, in the building, the heat has been released.

The calculated resulting contribution to the heat balance of the residential building constitutes therefore only an upper limit for how much the energy consumption for space heating can be reduced, due to these contributions from appliances, cooking, hot water generation, and human heat. Still, it gives some indication about how the size of these contributions can vary between different countries.

TABLE I e- 1

Estimated net energy input from appliances, cooking, human heat and energy used for hot water generation, the contribution of this net energy input to the heat balance of the building, the energy losses due to use of cold water and the resulting contribution to the heat balance of the building from these factors (MJ/dwelling and day during the heating season)

		Net energy input	Useful for heating	Cold water losses	Resulting heat contribution (% of net energy)
BELGIUM:	Antwerpen	53	40	7	33 (62 %)
	Brussels	"	"	4	36 (68 %)
DENMARK:	Copenhagen	70	47	5	42 (60 %)
	National	"	"	7	40 (57 %)
FINLAND:	Helsinki	65	45	13	32 (49 %)
	Lahti	"	"	8	37 (57 %)
FRANCE:	Paris	54	39	7	32 (59 %)
	Paris area	"	"	8	31 (57 %)
FRG:	Hamburg and Munich	57	41	8	37 (65 %)
ITALY:	Torino	52	34	13	21 (40 %)
	Rome	"	"	8	26 (50 %)
NORWAY	Oslo	78	55	9	46 (59 %)
	Baerum	"	"	15	40 (51 %)
SWEDEN	National	77	51	8	43 (56 %)
SWITZER-	Basel	66	46	11	35 (55 %)
LAND	Zurich	"	"	10	36 (54 %)
UK	National	75	54	6	48 (64 %)
US	New York	119	90	18	72 (60 %)
	Washington D.C.	"	"	15	75 (63 %)

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APPENDIX I

Definitions of measurement and energy terms

Contents

Appendix I Definitions of measurement and energy terms.

In this appendix we have collected the definitions of some terms that are used in this Report. These definitions are divided into three groups:

- measurements
- models
- energy

- definitions of measurement terms

A measurement is a procedure to give a numerical value to a conceptual quantity representing a physical observable. It is assumed, that in the measuring procedure the relation between this quantity and the measured entity is exactly defined and that it is described precisely under what circumstances and in which way the measurement can be performed.

As all measurements are approximations in the sense that it seldom is possible to tell exactly what has been measured, a measurement is not very interesting if the measured numerical value is not given along with an estimate of the error of the measurement.

It is common to make a distinction between two kind of error, statistic errors and systematic errors. A statistic (accidental or random) error is the scatter in the result of several repeated measurements depending on parameters over which one has no control, even if in principle the conditions should be identical at two measurements. By a systematic error is meant the error that remains after correction for all other known errors. Consequently an error of this kind is in principle unknown. There are, however, ways of estimating systematic errors, e.g., using different methods of measurements. Errors can also be classified according to where in the measuring procedure they appear or according to their origin.

In a classification according to where in the measuring procedure the errors appear, one can distinguish between:

1. errors in the measured object- when something else than intended is measured

(the environment and the measuring procedure affect the measured object)

2. errors in the measuring apparatus (e.g., calibration errors, environmental parameters etc.)

3. errors produced by the observer (he is influenced by the environment or has a preference for a certain result)

4. errors in the calculations (the measurement is founded upon an erronueous theory, certain values are disregarded as being false,values are rounded off too early in the calculation etc.)

In a classification according to origin one can distiguish between:

1. errors in the measuring method (the method is based on an erroneous theory, influences the measured object, the measurement apparatus is subjected to an unallowed strain).

2. errors in the instrument (faulty calibration, aging, used under conditions different from those prevailing at the moment of calibration etc)

3. the environment affects the result of the measurement through the measured object, the measuring apparatus or the observer.

The measurement must fulfil many requirements. To characterize them several terms have been in use (reliability,congruence, precision, objectivity, constancy, validity, relevance, accuracy, resolution, reproducibility, discrimination, sensitivity, drift, stability etc.) There is no common agreement upon the exact meaning of these terms. Below is an attempt to define them.

1. the measuring procedure is required to be operationally definable, i.e., it must be possible to tell exactly how the measurement is to be performed.

2. a second demand is reliability (the terms reproducibility or precision are sometimes used instead with the same meaning). This means that,once defined, a measuring procedure shall give results which agree reasonably well if more than one measurement is performed. The demand for reliability can be further divided into:

- congruency: degree of agreement between results from different measuring methods

- precision: degree of agreement between results from repeated measurements
- objectivity: degree of agreement between results obtained by different observers
- constancy: degree of agreement between results from measurements performed at different times

3. also required is validity (the words relevance or accuracy are sometimes used instead with the same meaning). By this is meant the degree of consistency between what is measured and what has been the intention to measure. It may be worth noting, that a good validity requires a good reliability, not vice versa

For the requirements on the measuring apparatus one uses terms as

1. accuracy - degree of agreement between the value read off an instrument and "the true value". Sometimes is meant the ratio between the difference of the two values and "the true value". A better term is then relative accuracy or relative error.

2. precision - which with the definition above is a measure of how small the accidental error is (but says othing about the systematic error). Precision refers not to the measured value but to the error.

3. resolution (or discrimination). This is a measure of how small a change in the input can be and still be resolved by the instrument.

4. sensitivity refers to the ratio between the least possible change in the value read of the instrument and the change of input required to cause this

The above terms describe the performance of an instrument (at a certain moment. Terms relating to the performance of an instrument during a longer period of time are :

5. drift - the maximal deviation in the measured value due to the instrument during a prescribed time period.

6. drift rate - drift per unit of time

7. stability - the reproducibility of the average value of a great number of

measurements under prescribed conditions at different times.

- definitions of model terms

By a model we mean an abstraction or mapping of an object, real or *imagined, where only the components and relations necessary for the model to* fulfil its purpose have been taken into account. There are many ways of classifying models. For our purpose it will suffice to mention the following ways.

I. The purpose of using the model

a) descriptive model (answers a question)
b) explaining model (e.g., gives analytic relations between dependent and independent variables)
c) prognostic model (explaining model where the relations can be extrapolated into the future).

II. Technique of solution (for mathematical models)

a) analytic model
b) *simulation model*

III. Time dependence

a) static models
b) dynamic models
c) continuous variables
d) discrete variables

IV. Degree of precision

a) deterministic (the result is completely determined by input data)
b) non-deterministic
c) stochastic (the result depends on random factors

- definitions of energy terms

- primary energy is the gross calorific value of the fossil fuels coal, oil and natural gas or the equivalent of nuclear and hydro-electricity.

- secondary energy is that which is contained in coal-gas, coke, electricity or any other form of energy manufactured from a primary energy source.

- net energy consumption of a particular consumer is the real amount of energy received by that consumer.

- gross energy consumption of a consumer is the total primary energy equivalent required to produce and deliver their net consumption.

- useful energy is the energy needed to perform a required task and differs from the delivered energy by an amount equal to the flue and other losses of the appliance. The term "useful energy" is mainly used in the discussion of space heating loads. For loads such as cooking, where losses may be recovered as fortuitious gains to the heating system,the concept is less easily defined

- final user or end user is a consumer who does not produce energy for others but uses it for his own purposes.

The definitions given above are the ones given at the 1976 CIB Symposium by Leach and Desson. We will here also give the definition of an important term used in this document, the retrofit effect.

- the retrofit effect is the amount of energy saved by a retrofit if everything is kept constant except for the retrofit itself, and changes in the behaviour of the occupants induced by the retrofit.

The retrofit effect is not to be confused with the observed change in energy consumption. This one will be influenced by differences in external climate, indoor climate, and changes in the behaviour of the occupants not due to the retrofit. The retrofit effect is the saved energy when a correction has been made for all these differences between the retrofitted and the non retrofitted building.

PART II

THE DESIGN OF THE EXPERIMENT

Keywords

analytical approach
before- after experiment
building system
choice of model
component
design of experiment
descriptive model
generalization of results
heat flows
interaction
predictive model
on- off experiment
parameters of model
simulated occupancy experiments
simplicity
statistical approach
status of system
system
test- reference experiment
time- plan
variable

CHAPTER II a

General introduction, experimental design and models

Contents

II a General introduction, experimental design and models

- general introduction

In Part II methods for the evaluation of the effect of a retrofit on the energy consumption of a building are described. This chapter corresponds to two steps of the procedure outlined in ch. I a, namely "description of the system" and "*design of the experiment and choice of the model*".

These are also the titles of the first two sections of ch. II a which are followed by two sections dealing with more specific topics of experimental design, "common experimental designs" and "use of models".

Ch. II a is followed by four chapters describing in more detail the most common experimental designs in retrofit studies. The titles of these are: ch. *II b* On- off experiments, *ch. II c* Before- after experiments, *ch. II d Test-*reference experiments and, the last ch. II e Simulated occupancy experiments and Movers and Stayers. Movers and stayers refers to an experimental method which is of great interest for the assessment of the impact of occupancy on energy consumption.

Part II is ends with an appendix on statistical methods of interest for the design of experimental studies on retrofit effects. After this, a bibliography and a reference *list* follow.

In the literature there does not exist any exhaustive and simultaneous description of the different experimental designs discussed here. We therefore have to refer to the examples given in the text.

Illustrations of the use of these experimental designs can also be found in research reports where the methodological question has been taken seriously, see the bibliography. A general discussion on the use of models can be found in Saaty and Alexander (1981). Examples on models can be found in e.g. Sonderegger and Garnier (1982), Wiltshire (1981), and Steinmüller (1982). The properties of some large computer models have been evaluated in a Report from IEA Annex III Subtask A (Källblad 1983). Statistical methods of interest here can be found in Cox (1958) and Hahn (1977).

- description of the system

When the aim of the investigation on the effects of a retrofit has been formulated in a precise manner (see ch. I a), and it has been decided that measurements are to be performed, one should proceed with the design of the experiment. It is then of great importance to realize that in this case one is not dealing with a controlled experiment where the experimenter can at will change the physical status of the building, or isolate it from its surroundings. Instead, one is dealing with a system where the building, the exterior climate, and the occupants interact in a complicated manner.

It might then be advantageous to regard this system as consisting of components. Examples of components related to the physical building structure are the external walls, ceiling, basement, windows, heating system, ventilation system, cold and hot tap water systems, domestic appliances etc. The occupants can be regarded as other components of the system. All these components will not operate independently of one another. In general there will be some kind of interaction between at least some of them. An example is the occupants' use of domestic appliances and their manipulation of the set points of the heating system. Another example is the internal energy balance of the building, determined by radiative, conductive and convective heat transfers between components.

The status of the system is described by the instantaneous value of variables. Some variables are associated with the physical status of the building interior, e.g. the indoor air temperature, the temperature of the external walls, the temperature of the hot tap water, the energy output from the heating system, the rate of air exchange produced by a ventilation system, the moisture content of the indoor air, etc. Variables do not necessarily take a uniform value throughout the building interior.

Other variables describe the outdoor climate, e.g. the outdoor air temperature, wind speed and direction, air pressure on the building envelope, outdoor humidity, global and solar radiation etc. Variables related to the occupants are e.g. the age and occupation of the occupants, the occupants' knowledge of the heating system, the occupants' demand for comfort and a certain indoor climate, their habits with regard to airing, the frequency in the use of different domestic appliances etc.

Here one is not interested in all aspects of the above complicated system, but in those features of it that are relevant to the study of the effects of a certain retrofit. It may then be natural to start with considering the <u>energy flows</u> of this system. These energy flows can be divided into

1) conductive, convective and, radiative energy flows
2) heat flows emanating from work
3) enthalpy flows

Examples of conductive, convective, and radiative energy flows are heat losses through the building envelope, heat transfer to the building interior by the heating system, heat produced by the human metabolism, heat produced by solar radiation impinging upon the building, and heat flows through internal partitions. An example of energy flows emanating from work are, e.g., heat transfer to the building interior by domestic appliances. Examples of enthalpy flows are heat losses due to infiltration, energy losses caused by the use of cold and hot tap water, and deliveries of fuel to the building.

The energy conservation equation for a thermodynamic system (as a building) states that the sum of the energy flows, due to conduction,convection and radiation, the mechanical work, and the enthalpy flows, due to mass transfer through the building envelope, must be zero.

All energy flows may not be of interest for the evaluation of the effects of a certain retrofit. Energy flows that are not affected by the retrofit can often be neglected. The first task of the experimenter is, therefore, to identify the relevant energy flows. This will require at least some knowledge of where, and how, heat is produced inside the building, and by what mechanisms heat is dispersed to the exterior of the building. It will also require an understanding of how the retrofit will influence the components of the system. One should not at this stage choose to neglect energy flows about which one has no previous knowledge.

When the energy flows of importance for the study of the effects of the retrofit have been determined, the experimenter should identify the components of the system which take a part in the production of, or affect, these energy flows.

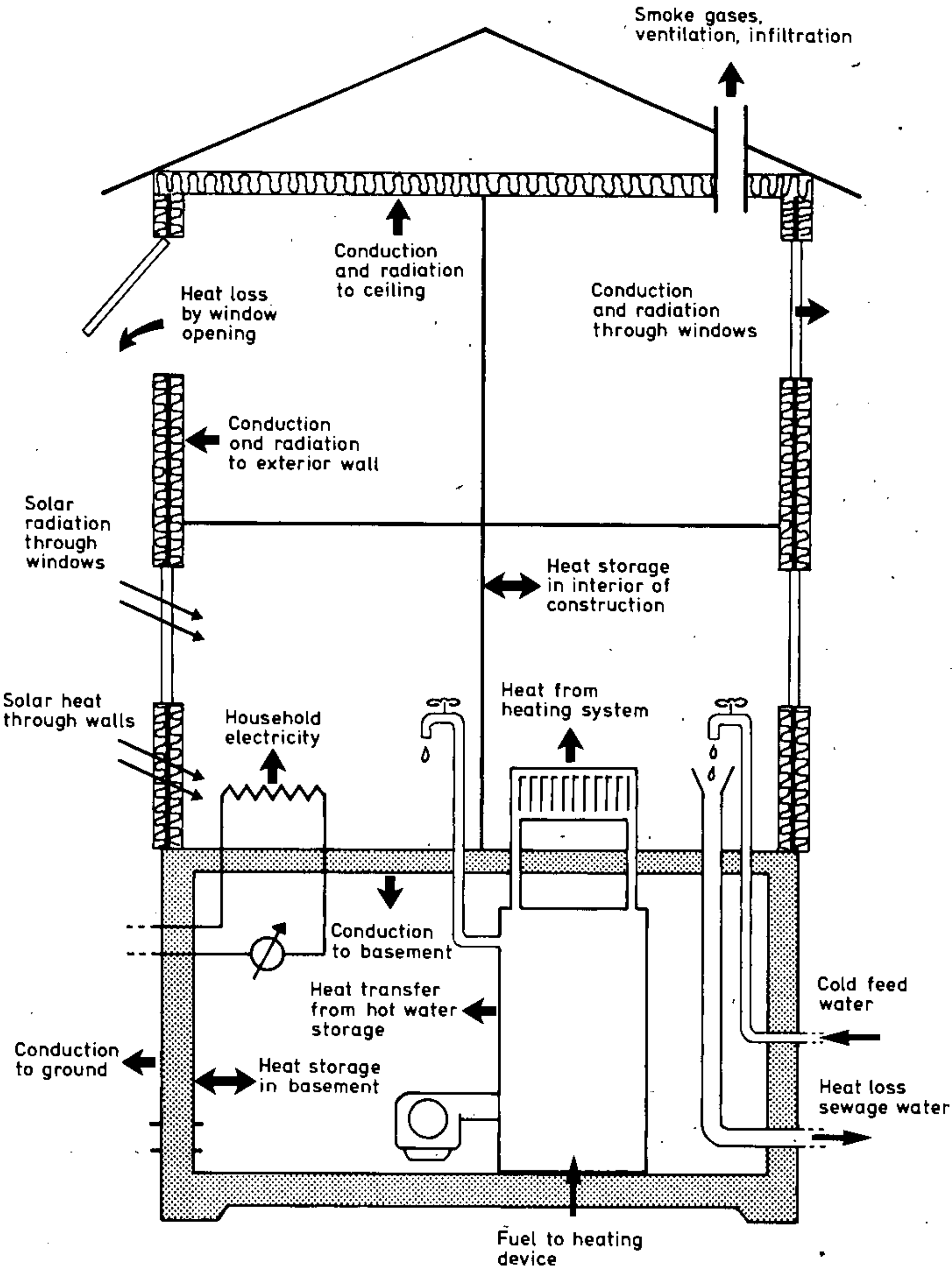

Fig. IIa-1. Examples of heat flows in a simple descriptive model.

At this stage the experimenter will have reduced the initial complicated system to a more tractable one, including only the energy flows and components relevant to the study of the retrofit in question. The experimenter has constructed a qualitative or descriptive model of the initial system. It is often useful to present this model in a graphic form. An example of this is given in fig. II a-1.

The experimenter has thus completed one step of the planning outlined in ch. I a, the step "description of the system".

- design of the experiment and choice of the model

In the previous section one step of the planning, "desription of the system", was discussed.The experimenter can now proceed to the step "design of the experiment and choice of the model". This step is a complicated one, and it can seldom be performed in a chronological order according to some scheme. However, it is often advantageous to start by a more detailed analysis of the energy flows.

It is still possible to further reduce the number of energy flows that have to be considered. Some of them may be very small compared to the retrofit effect. In the model there must be included those residual energy flows that are greater than, or of the same order of magnitude as, the retrofit effect. If there are several energy flows about one order of magnitude smaller than the retrofit effect, these will in general also have to be taken into account. However, in most cases it will not make any sense to include in the model energy flows that are even smaller compared to the retrofit effect.

To make the above comparison between the retrofit effect and the magnitude of different energy flows, it will be necessary to estimate these magnitudes. A crude estimate of the retrofit effect has already been obtained when the evaluation of the problem was performed (see ch. I a).

An estimate of the heat losses through the external walls can be obtained, e.g., if one has some information about the average indoor- outdoor temperature difference, as well as about the transmittance of the external wall. One has to know physical properties of some components of the system, or to assign a numerical value to certain parameters. In the above example, the transmittance is considered as a parameter (the "U- value") describing a physical property of a component, the external wall. In other words, the experimenter has to construct a model or describe a procedure, whereby the magnitude of the energy flows can be estimated, provided the value of some parameters (in this case the U- value), and some variables (in this case the temperature difference across the external wall) are known.

The above procedure of deciding what energy flows are to be included in the model is important, because the magnitude of the energy flows that one chooses to neglect will have a great impact on the resulting accuracy of the determination of the retrofit effect.

Before proceeding with the description of how to select the model, it will be necessary to know what experimental designs can be applied by the experimenter. A short description of the differences between some common experimental designs is given in the section "common experimental designs".

Some possibilities of reducing the number of energy flows in the model have been considered above. These possibilities have not yet been exhausted. By choosing a suitable experimental design the model of the system can be simplified. In general, one is interested in getting rid of energy flows that are either difficult to measure, or influenced by variables describing the exterior climate, or the behaviour of the occupants.

From the analysis done in the following section "common experimental designs", it is clear that in most designs there are underlying assumptions which have to be verified. This will seldom be the case in practice. It is then possible to proceed along one of two lines:

1) it is possible to include in the study a sufficient number of buildings so that the resulting average error becomes statistically insignificant compared to the retrofit effect (the statistical approach). Even this procedure can be doubtful if nothing but the energy consumption is measured. It can, e.g., be difficult to verify whether the indoor climate of the retrofitted building is the same as that of the non- retrofitted one

2) one can further proceed with the construction of a mathematical model of the system. It may then be possible to take into account the difference in energy consumption due to differing weather conditions or indoor climate (the analytical approach). One can monitor a few buildings very precisely, measure a

lot of variables and use a sophisticated model to describe the findings. One will then know very accurately the retrofit effect for the buildings studied. It will probably be difficult to include in the model variations in the behaviour of the occupants due to the retrofit or to factors other than the climatic ones.

At this stage the experimenter has also to consider practical questions related to what experimental design to choose and what model to use

- what buildings is it possible to include in the study?
- for how long (how many heating seasons) is it possible to use the building for measurements?
- is the retrofit reversible?
- are there occupants in the buildings?
- what is the cost if a certain experimental design is used and how much money will there be left for measurements?
- how are the results to be generalized?

A statistical approach will require a large number of buildings and/or households. The exact number is determined by the estimated retrofit effect and the variation in the energy consumption among the households or buildings to be studied (see App. II and ch. I e). The resulting error can be reduced if some simple measurement other than that of the energy consumption is performed. The effect of the different indoor temperatures before and after the retrofit can be evaluated, e.g., by the use of some simple model of the thermal losses of the building. The cost for these measurements have to be weighed against the cost for studying a large number of buildings.

The number of heating seasons available for measurements will be of importance when choosing between e.g. the before- after experiment and the test- reference experiment. If the retrofit can be reversed, the on- off experiment can be used instead of the before- after experiment. If there are no occupants in the building when the retrofit is introduced, it might be possible to use this occasion for simulation studies of the performance of the heating system, the thermal behaviour of the building, and for simulated occupancy studies.

The experimenter will also have to consider how to generalize the results from the measurements. If he only wants to study the effect of the retrofit on a very well defined class of buildings, using the statistical approach, he may choose a representative number of such buildings for the experiment. The answer he gets will then probably be true for all buildings of this class. But it may not be possible to generalize this result to other building classes. If the experimenter wants to know the effect of the retrofit for several building types, he will have to classify buildings according to some criteria relevant to the study of the retrofit. He will probably find out that the number of building classes grows very quickly with the number of criteria used for the classification of the buildings (and maybe also their surroundings).

Instead, the experimenter can use the analytical approach. The model can then be used to predict the retrofit effect for other types of buildings. The experimenter will have to assign a value to the parameters of the model to describe the properties of these buildings in order to generalize his results. However, the value of these parameters will probably not be known for other buildings. The effect of the occupancy on energy consumption will also be unknown to the experimenter, for he has probably not been able to record it even in the monitored buildings.

At this stage the experimenter finds himself in a complicated situation. He has a model where he can estimate the magnitude of some, but probably not all, energy flows. He has a number of experimental designs to choose between. He can use a statistical or an analytical approach or a combination of these. There are some practical limitations to what he can do. Finally he has to consider how to generalize the results.

The optimal choice for the experimenter in this situation is probably to start by exploiting as far as possible a suitable experimental design along with a statistical approach to free the model from as many unknown energy flows as possible. The energy flows to get rid of are probably those which have a strong dependence on the occupancy. The practical limitations and the want for generalization will of course determine how far the experimenter can go in this direction. It now remains for the experimenter to construct a model for the remaining energy flows. The numerical value of these will also have to be determined.

Every one of the remaining energy flows should be modelled in terms of measurable variables and in terms of parameters of the system and its components. To these variables and parameters numerical values must also be assigned, which can come from measurements or can be assumed to be known (see ch. III a). The guiding principle in the construction of the model should be simplicity. In the model as few variables and parameters as possible should be included. A simple and robust model is almost always preferrable to a very sophisticated one, where the values of the parameters can not often be determined accurately. The experimenter should always try to use only parameters that can be given a simple physical interpretation. However, in this case one often has to make compromises if one wants a simple model.

The construction of the model is, however, not yet complete. The experimenter must also decide the maximal error due to the measurements that he can accept for the estimate of the retrofit effect. This will determine by what resolution and precision the measurements have to be performed. The time-resolution of the measurements will also have to be decided upon. The demand for a small time- resolution will be greater for a dynamic model than for a static one. This decision will especially affect the choice of how to store data.

There may still be some energy flows where the effect of occupancy can not be measured directly. One can then collect more information about the behaviour of the occupants by observations and survey techniques. Even if this is done, it may be difficult to quantify this information in such a way that it can be used as input to model calculations. It is seldom exactly known how a certain behaviour affects the energy consumption. One can, of course, gather such information from a large sample of occupants living in a certain type of residential building and relate this to their energy consumption by means of refined statistical techniques. Such information is, however, difficult to generalize to occupants living in other types of buildings. Therefore such studies have only rarely been performed.

Nonetheless the experimenter should always be aware of the existence of these phenomena. Even if no broad study of these effects can be performed, there are simple observations, the results of which can be used as indicators if there is a difference in the behaviour of the occupants between the retrofitted and the non retrofitted building. A list of some simple measurements and observations is given below.

1) the indoor temperature should always be measured. If there is a great difference in indoor temperature between the retrofitted and the non retrofitted building, this may explain a substantial part of an observed difference in energy consumption.

2) the consumption of household electricity and gas can easily be measured. If the indoor temperature has been too low or there has been draught before the retrofit, the occupants may have used auxiliary electric or gas- fired heating appliances. If the building is equipped with a cooling or a mechanical ventilation system, this may have been used more frequently in the building having the higher indoor temperature.

3) airing is frequently used by occupants to control the indoor climate. Usually a rather small number of observations under similar conditions, before and after the retrofit, suffices to establish if the retrofit has changed these habits.

4) shielding of windows is frequently used to protect from solar radiation. If the retrofit has the effect that the contribution to the free heat from solar radiation changes substantially, the degree of window shielding will often be different. This will also be true if the amount of solar radiation is different during, e.g., the before and after periods, when the before- after method is used.

5) if the use of hot tap water changes because of the retrofit, this is a clear indication that the occupants have changed their habits.

6) the time spent at home by the occupants should be about the same in the retrofitted and the non retrofitted buildings. If there is a large difference, there will probably also be a difference in the amount of energy used for household appliances, hot tap water, airing etc. The contribution to the heating of the dwelling from the human metabolism will also be different. Information about the time spent at home by occupants will probably require a separate investigation (see ch. IV c). A simpler way of gathering this information indirectly (at least if the study includes a sufficient number of households) is to collect information on

7) the age and occupation of the occupants. This information is useful also for other reasons. Occupants of different age and occupation have different habits and this is likely to have a great impact on the consumption of energy.

8) a simple way of checking if the occupants experience a difference in the indoor climate between the retrofitted and the non retrofitted building is to ask a representative sample of them about their habits of dressing at home. If

TABLE II a-1

Summary of the steps of planning "description of the system" and "design of the experiment and choice of the model" treated in ch. IIa

description of the system	1)Define the system: building and components, weather, retrofit, environment, occupants, interactions 2)List all energy flows of importance for determining the retrofit effect 3)List all components of the system which take part in the production of a certain heat flow or can influence it 4)List energy flows and components affected by the retrofit 5)Construct a descriptive model of the system before and after the retrofit
design of the experiment and choice of the model	1)Estimate the magnitude of all energy flows if this is possible 2)Exclude small energy flows from the model 3)Choose a suitable experimental design considering: The possibility of excluding from the model energy flows that can not be measured or are influenced by uncontrollable variables (occupancy and weather) What buildings are available? What period is there for measurements? Is the retrofit reversible ? Are there occupants? What is the cost and the possibility to generalize the results to other buildings if a certain experimental design is used along with a combination of a statistical and an analytical approach? 4)Construct a model of the system with the remaining energy flows in terms of measurable variables and parameters describing the properties of components 5)What are the possibilities of checking if nonmeasurable energy flows remain unaltered? 6)Decide maximal error of measurements and the time resolution 7)Time planning of the experiment

the indoor climate is similar, the thermal insulation ensured by the clothes should also be about the same (see ch. I c).

The experiment design process and the choice of the model is now almost finished. What remains is, however, as important as the previous stages. The experimenter must now make a time plan for the experiment

- when does the construction of the measurement system have to be finished?
- when are the measurements to start?
- when is the retrofit to be implemented?
- for how long time shall the measurements go on?
- what time is there for the analysis of the data?
- when must the final report be written?

Finally it must be stressed that the procedure outlined in this section is almost <u>never a one- stage process</u>. The construction of the measurement system (see ch. III g) will often provide a <u>feed back</u> to the above procedure. It is not always possible to make measurements with the wanted accuracy,resolution and precision. The planned measurements may turn out to be too costly. Such events will often make a revision of the model necessary and, maybe, even a revision of the design of the experiment. In Table II a-1 a summary of the discussion on the design of the experiment in the previous two sections is given.

- <u>common experimental designs</u>

Some common experimental designs that can be applied to reduce the number of energy flows will be described below. To facilitate this description, it will be assumed that the study includes only one or a few buildings, and the only measurement performed is that of the total energy consumption.

To clarify the difference between some common experimental designs, a very formal approach will be used. Assume that the energy consumption, C, is an explicit function of the physical properties and the status of the building, B, the weather, W, the indoor climate, I, and the influence of the occupants, O. Assume, further, that O has an implicit dependence on B, W, I and other factors which will be denoted by A. The behaviour of the occupants depends on what building they live in and the prevailing outdoor and indoor climate (B, W and I), but also on other factors (A), e.g., various attitudes and factors of economic nature. This can be expressed by the formal relation

$$C = C(\ B,\ W,\ I,\ O(B,W,I,A)\ )$$

1) Now imagine that two buildings could be found which are identical and situated close to one another. If one of them is retrofitted (the test building) and the other is not (the reference building), their energy consumptions during the same period can be measured and compared to one another.

The above experimental design is referred to as the test- reference experiment. From the formal analysis below, it follows that the ideal case to use the test- reference design is when the following conditions are fulfilled:

a) the buildings are really identical before retrofit,not only nominally so
b) the occupants of the two buildings behave in the same way before the retrofit and if they change their behaviour after the retrofit this change is identical and only due to different weather conditions
c) the indoor climate of the two buildings is the same and that of the test building is the same after the retrofit as before

When the test reference design is used, these underlying assumptions or conditions must always be verified if the energy consumptions alone are measured and compared to one another. Otherwise unpredictable errors will always be present.

2) Now consider another possibility. Assume that the energy consumption, before and after the retrofit, is measured over two equally long periods. Assume also that the change in the occupants behaviour is not due to the retrofit, or that the weather conditions can be neglected.

The above experimental design is referred to as the before- after experiment. Evidently the ideal case to use this design is when the following conditions are fulfilled:

a) the behaviour of the occupants does not change because of the retrofit or for other reasons
b) the weather is the same before and after the retrofit
c) the indoor climate is the same before and after the retrofit

As for the previous method these assumptions must be checked if energy consumption alone is measured.

TABLE II a-2

Advantages and disadvantages of some common experimental designs

	Advantages	Disadvantages
Before-after	No reference building required Often less variation in behaviour of occupants than in other designs The outdoor environment is the same before and after The same model with the same parameter values can be used for most components before and after the retrofit	Often more than one heating season required for measurments Running-in and learning period often required to counteract initial change of behaviour The outdoor climate is not the same before and after Requires a model to correct for differences in the outdoor climate The measurement equipment must be removed when retrofitting
Test-reference	One heating season suffices for measurements No difference in environment and outdoor climate if test- and reference buildings close Difference in energy consumption directly associated with retrofit effect if buildigs identical The same model can be used for most building components	Reference building required Difficult to verify that occupancy behaviour is the same in test- and reference buildings Difficult to ascertain that test- and reference buildings technically identical in all respects Values of the parameters can be different even if model is the same Requires calibration phase if previous difference in energy consumption Behavior of occupants in reference building may change if known that they take part in an experiment

TABLE II a-2 (continued)

	Advantages	Disadvantages
On-off	No reference bldg required *Can often be performed in one* heating season	Requires reversible retrofit *Time constants of building must be* considered when length of on-off periods is chosen
	The environment is the same	Outdoor climate during on- and off periods may not be the same
	The same model with the same parameter values can be used for for most components in on- and off states	Requires a model to correct for differences in the outdoor climate
	Long term changes of occupancy less important than in other designs	Short term reactions of occupants occupants may occur when switching from one state to another with unknown effects on consumption Dynamic model often required
simul-ated occup-ancy	Easy to study effects of various behaviour of occupants or to perform parametric studies of its influence on the consumption	Loss of information on behaviour of real occupants
	Easy monitoring of the occupancy	Expensive and difficult to construct schemes for the simulated occupancy
	One building of a kind often suffices for the experiment Retrofit effect separable from weather and occupancy effects	Extra cost for purchase or rent of the building If only one building of a kind is used variation of outdoor climate may be limited
	Easy to study effects of "standard occupancy schedules"	No information on variation in energy consumption due to varying habits of occupants

3) A third design exists, similar to the before after design, called the on- off experiment. This one can be used when the retrofit is reversible. The energy consumption is then measured during a number of repeated on- off cycles, and the consumption during the on- periods is compared to that of the off- periods. When this method is applied, the same conditions must be fulfilled as when the before- after method is used.

4) There also exists another design that is sometimes used. There are no occupants in the building. Instead, the presence of occupants is simulated by artificial means. This design is referred to as a simulated occupancy experiment. By using this design in combination with the test- reference design, the errors will be greatly reduced. It might even be possible to perform the simulation so that there will be no errors at all.

The above conclusions for the different experimental designs can formally be obtained as follows: let C,B,W,I and A denote the values of the respective entities during a measurement campaign on a non retrofitted building and let $C+\Delta C$, $B+\Delta B$, $W+\Delta W$, $I+\Delta I$ and $A+\Delta A$ denote the corresponding values of a retrofitted building. One then has the formal relation for the difference in energy consumption between the original and the retrofitted building:

$$\Delta C = \partial C/\partial O*\partial O/\partial A*\Delta A+(\partial C/\partial B+\partial C/\partial O*\partial O/\partial B)*\Delta B + (\partial C/\partial W+\partial C/\partial O*\partial O/\partial W)*\Delta W+ (\partial C/\partial I+\partial C/\partial O*\partial O/\partial I)*\Delta I$$

In this relation the term $(\partial C/\partial B+ \partial C/\partial O* \partial O/\partial B)* \Delta B$ can be identified with the retrofit effect. The terms $\partial C/\partial W*\Delta W$ and $\partial C/\partial I*\Delta I$ obviously describe the change in energy consumption due to the different climate conditions. The remaining four terms all describe the influence exerted by the occupants. The terms $\partial C/\partial O*\partial O/\partial W*\Delta W$ and $\partial C/\partial O*\partial O/\partial I*\Delta I$ describe the change in energy consumption due to a variation of the occupants' behaviour, coupled to the difference between the climate conditions. The remaining term $\partial C/\partial O*\partial O/\partial A*\Delta A$ describes other factors than B, W and I which can influence the behaviour of the occupants.

In a test- reference experiment the difference between the energy consumptions can, as $\Delta W=0$, formally be expressed as

$$\Delta C=\partial C/\partial O*\partial O/\partial A*\Delta A+(\partial C/\partial B+\partial C/\partial O*\partial O/\partial B)*\Delta B+(\partial C/\partial I+\partial C/\partial O*\partial O/\partial I)*\Delta I$$

From the assumptions for the before- after design follows that $\Delta A=0$. One then has:

$$\Delta C=(\partial C/\partial B+\partial C/\partial O*\partial O/\partial B)*\Delta B+ (\partial C/\partial W+\partial C/\partial O*\partial O/\partial W)*\Delta W+ (\partial C/\partial I+\partial C/\partial O*\partial O/\partial I)*\Delta I$$

If the simulated occupancy experiment is used in combination with the test-reference design, and the presence of the occupants is simulated according to the same rules as in the test and the reference building, one will have $\Delta W=0$ and $A=0$. As in this case also $\Delta I=0$ and $\partial O/\partial B=0$, there are no other terms than the retrofit effect.

In Table II a-2 the advantages and disadvantages of the experimental designs discussed above are summarized. It should not be forgotten that often a combination of these designs is more efficient than the choice of a "pure" design. It is, for example, always valuable to have access to a reference building and to know the previous consumption of energy.

- use of models

It will in general be necessary to use a model for the treatment of the data derived from the measurements on a retrofitted building. The simplest models in use are the static ones. The most simple model approximates the energy consumption of a residential building, W, as a linear 2-parameter function of one variable, the indoor-outdoor air temperature difference ΔT, i.e. $W=a+b*\Delta T$, where a and b are parameters.

If the model is used for predictive purposes it is often referred to as the degree-day model. The variable b is then calculated from the building characteristics, and it gives an average value of the heat conductance of the exterior walls of the building. The parameter a is generally taken to be non-zero. This then gives the possibility of taking also into account solar radiation and free heat from internal appliances etc.

If the model is used for descriptive purposes it is often referred to as the energy signature of the building. The parameters a and b are then determined from a fit to actual data on the energy consumption of the building.

When this model is used, the temperature difference ΔT is generally taken as an average over a rather long period of time.

One should be aware of the shortcomings of this model. The parameter b describes an average transmittance of the building envelope. This might not be a good approximation if different parts of the building envelope have very different transmittances. The parameter a describes a "background" energy consumption by the occupants, contributions to the heating of the building from solar radiation, part of the energy losses due to infiltration etc. Any of these factors may not be constant at all. Some energy flows will neither be constant nor have a linear dependence on ΔT, or may be influenced by other variables. The infiltration may, e.g., have a strong dependence on the wind speed and direction, and the energy losses due to a thermally driven infiltration will have a stronger dependence than a linear one on ΔT.

More complex models, linear in the parameters, have the same structure as the one described above but they also take into account other exterior climate variables like wind speed, wind direction, global radiation, and radiative temperatures. Models of this kind are in general used for explanative or predictive purposes. An example of such a model is given in Sonderegger-Garnier (1982).

If one prefers to use a dynamic model it will be necessary to take into account the heat capacity of the building components too. The thermal properties of different components of the building exterior, like walls, roof and windows, are then often modelled separately. It is also usual to model the performance of the heating system of the building. Models of this kind are often very complex computer models. They often no longer have a simple structure, e.g. linear in the variables and/or parameters, but they consist of a set of coupled non- linear differential equations which have to be solved simultaneously. If they are to be used for a predictive purpose they often require as input a very detailed knowledge about the thermal properties of the building components. As this knowledge is often lacking, one has to perform calculations with varying physical properties of the building components, and the model is used as a simulation model. The indoor temperature is then often treated in one of two ways. It is either taken to be constant, which corresponds to a perfectly thermostated building, or it is free-floating. The indoor temperature is then completely determined by the heat-flow equations of the model.

The models discussed so far have only taken into account the physical properties of the residential building. But the actual energy consumption will also to a great extent be determined by the behaviour and habits of the occupants (see ch. IV c). For this there does in general not exist any simple model. If factors of this kind are to be included in the model one will have to rely on experience and common sense.

TABLE II a-3

Guidelines for the construction of a model

1) Make the model as simple as possible. This will facilitate the data collection and the analysis

2) Try to model each energy flow separately

3) Choose the parameters so that they have a simple and direct physical interpretation

4) Let the retrofit be described by just one energy flow. This will make it easier to estimate the retrofit effect.

5) Use as few parameters as possible that have to be assigned a value by a fit to experimental data. This will reduce the error of the parameter values determined in the fit.

6) Compare the parameter value obtained in a fit to some other independent estimate of this value if it is possible. This can give an indication of the goodness of the model.

7) If possible, construct a model that can be used also for other buildings. This will make it easier to compare with results from other experiments. However, this demand will sometimes conflict with the demand for model simplicity.

A general discussion on the use of models can be found in Saaty- Alexander (1981). In Table II a-3 we give some guidelines for the construction of a model. However, it should be remembered that, when dealing with the evaluation of retrofits, every experiment and every residential building is unique and therefore no model used in one experiment can be applied in another experiment without forethought. Below are given some very simple examples on the use of models.

- Example 1

Consider a before- after experiment where one measures the output of the heating system, W, and the indoor- outdoor temperature difference ΔT. The building is retrofitted by adding extra insulation to the exterior walls. The time- resolution of the experiment is one day. One can then, assuming that there is a linear relation between W and ΔT, determine the parameters a and b of the model $W=a+ b*\Delta T$.

Assume, that for the before period, we obtain $W=a_1+b_1*\Delta T$ and for the after period $W=a_2 +b_2 *\Delta T$. The parameter b should here describe the average transmittance of the building envelope. As the retrofit consists of a reduction of the value of b, the difference between b_1 and b_2 should describe an improvement due to insulation. The parameter a, among other things, describes the free heat from solar radiation and energy consumption due to occupancy. Therefore, one should expect that a_1 and a_2 take about the same value ,unless, e.g., the amount of solar radiation has been very different during the two measurement periods or the occupants have changed their habits.

If both measurement periods are of the length t, the total consumption of energy, E, will be

$$E= \int W\, dt= a*t+ b* \int \Delta T\, dt$$

The total consumption of the before period, E_1, and that of the after period, E_2, are then

$$E_1=a_1*t+b_1* \int \Delta T(1)\, dt \text{ and } E_2=a_2*t+b_2* \int \Delta T(2)\, dt$$

To evaluate the retrofit effect one now has to calculate what the energy consumption of the retrofitted building would have been if the outdoor and indoor climate and the behaviour of the occupants, except for changes of the behaviour that can be directly ascribed to the retrofit itself, had been that of the before- period. With this model it is only possible to make a correction for the different average outdoor- indoor temperature difference. One then not includes the effects of an eventual different indoor temperature in the retrofit effect. However, if e.g. the amount of solar radiation has been different, or the occupants have changed their habits, both factors described by the parameter a, the effect of changes in these factors is included in the retrofit effect. The retrofitted building would then, according to the model, have consumed the energy

$E_2'=a_2*t+b_2*\int\Delta T(1)\ dt$
during the before period. The temperature corrected difference in energy consumtion can then be calculated as $(a_1 \ -a_2)*t+(b_1-b_2)*\int\Delta T(1)\ dt$.

If one wants to estimate the <u>retrofit effect</u> one has to correct also for factors other than the indoor- outdoor temperature difference. In this case one has to calculate what the energy consumption of the retrofitted building during the before- period would have been if all factors had been identical except for the retrofit, described by the difference in the parameter b. This then means that the parameter a would take the same value during the before- and the after periods. This can be arranged if a simultaneous fit to data from both periods is performed, a fit using 3 parameters, a, b_1 and b_2. This is certainly not a satisfactory procedure if e.g. the amount of solar radiation has been very different, but it is the best that can be achieved with this model. Assuming then that the parameter a takes the same value during the before- and the after-periods, the retrofit effect is given by
$(b_1 - b_2)*\int\Delta T(1)\ dt$.

- <u>Example 2</u>

In this example we will treat a case where the model includes many energy flows but still is a static one. The retrofit in this example is a retrofit package consisting of adding extra insulation to the exterior walls and weatherstripping of doors and windows. A group of houses has already been selected for the retrofit. A number of them are to be equipped with sensors.

The number of such houses is determined from the expected retrofit effect (see App. II and III). As only one heating season is available for the measurements, the test- reference design is to be used. The houses are divided into two groups, a test group of 20 houses which are to be retrofitted and a reference group of another 20 houses which are not to be retrofitted until this experiment has been finished.

All houses are nominally identical before the retrofit and are situated close to one another, but are not oriented in the same direction. The houses are electrically heated. The hot tap water is also electrically heated. It is only possible to record the total consumption of electric energy (heating, hot tap water and appliances). All houses have a natural ventilation system. The site of the houses is highly exposed to the wind.

The aim of the experiment is to determine the retrofit effect on the energy consumption for the retrofit package and if possible to separate the effects of the increased insulation and the increased air- tightness of the houses. A measurement equipment is chosen that allows the measurement of variables every hour, but weekly averages are to be used in the final analysis of the experiment.

When estimating the magnitudes of the different energy flows in the houses, it is found that five energy flows have to be included in the model:

We= electric energy consumption (heating, hot tap water and appliances)
Wr= solar and sky radiation through the windows
Wc= conductive and radiative heat losses through the building envelope
Wv= heat losses due to ventilation and air infitration
Wo= other heat losses, including heat losses to the ground, heat losses by airing, sewage water heat losses etc.

It is believed that when averaged over a group of houses, Wo is approximately constant in time and takes the same value for the test- and the reference houses. The model can then be expressed as

$$We+Wr=Wc+Wv+Wo.$$

It is obvious that in this model the term Wo includes most of the variation of energy consumption related to the habits of the occupants, in fact all of it except the use of domestic electricity and hot tap water. It is also clear that with this model it will not be possible to separate the effects of the two retrofits strictly. The difference in the term Wc between the two groups will describe the retrofit effect due to the increased U-value of the insulation while the difference in the term Wv will describe the effect of the increased airtightness of the houses due to the weatherstripping and the increased airtightness due to the adding of extra insulation.

The energy flows of the model are now expressed in terms of variables and parameters as:

$Wc = Cc^{*} \Delta Ta^{*} Ac$ where
ΔTa = the indoor- outdoor air temperature difference
Cc = average heat transmittance of the building envelope
Ac = area of building envelope

$Wv = (Cv^{*} v^{2} + Ct^{*} \Delta Ta)^{1/2} {}^{*}Ca^{*} \Delta Ta^{*} Ac$ where
v = wind speed
Ca = volumetric heat capacity of air
Cv and Ct are two parameters

$Wr = Cr^{*} Ar^{*} Qr$ where
Qr = the amount of solar and sky radiation on a vertical plane facing south
Ar = the window area of a house projected on a vertical plane facing south
Cr = short- wave radiation transmittance of a window

The above relations are rather self- explanatory, but the expressions for the energy flows Wv and Wr need some further comments. For the energy flow Wr one has assumed that most of the solar and sky radiation comes from the south during the measurement campaign. The validity of this assumption must of course be checked against meteorological data. One then has to measure only the radiation impinging on a vertical plane facing south. It is also assumed that the parameter Cr is independent of the angle of incidence between the radiation and the window.

For the energy flow Wv one has chosen a non- linear combination of the wind speed v and the air temperature difference ΔTa. The rate of air change is assumed to be proportional to the factor $(Cv^{*}v^{2}+Ct^{*}\Delta Ta)^{1/2}$ It is clear that for small wind speeds Wv is proportional to $\Delta Ta^{3/2}$ while Wc is proportional to ΔTa. There will therefore be a high degree of correlation between Wc and Wv for periods when the wind speed is small. The use of this model therefore requires that the measurement campaign includes periods when the ventilation and air infiltration are driven more by the resulting wind pressure across the house than by stack effects. One has not assumed any dependence on the wind direction. This can be a good approximation if strong winds come predominantly from one direction or if for every house of the test group there is a house of the reference group that has about the same orientation.

One now has to measure the variables ΔTa, v and Qr and the heat flow We. The entities Ca, Ac and Ar are either known physical quantities or can be calculated from the geometrical properties of the houses. The parameters Cc, Cv, Ct and Cr have to be assigned a numerical value. Here different methods are used. The short- wave transmittance of the windows, Cr, is assigned a value determined in laboratory and field experiments with windows of the kind found in the experiment houses.

The value of the parameter Ct is determined from measurements of the rate of air exchange in the test- and reference- houses during the heating season on occasions when there is no wind and the indoor- outdoor air temperature difference is relatively large. In principle the value of the parameter Cv could have been determined in an analogous manner in the summer on occasions with a strong wind and no temperature difference between the indoor and the outdoor air. However, this was not done in this experiment as the orientations of the test houses are not exactly the same as those of the reference houses, and one was a little uncertain about the effects of the wind direction.

The values of Cc and Cv then have to be determined by a fit to experimental data. Due to the non-linearity of the model in the parameter Cv, it is not possible to use a least- squares fit in this case, but a non- linear fitting procedure has to be applied. With the approximations that have been made, the model is now less suited to describe the thermal performance of a single house, but should be used to describe the "average" thermal performance of the test and the reference group respectively.

Below we will denote values belonging to the reference group by unprimed symbols and values belonging to the test group by primed symbols. One now has to determine the retrofit effect. Clearly the difference in energy consumption between the test and the reference houses due to the retrofits is given by $Wc-Wc'+Wv-Wv'$ which is identical to $We-We'+Wr-Wr'$ if one makes the a priori assumption that Wo takes the same value for the test and the reference houses. However, one does not want to identify this difference in energy consumption with the retrofit effect as the former includes e.g. the effect of a different indoor temperature in the test and the reference houses. Instead one wants to determine the values of the parameters Cc,Cc˜,Cv and Cv˜ from a fit to data so that the retrofit effect can be calculated. However, there are still two possible approaches.

The simplest one is to assume that Wo takes the same value for the two groups of houses. By a simultaneous fit to data from the test and the reference houses, one can determine the values of the above four parameters and Wo=Wo˜. In this case one will not have any way of determining if there has been any change in the behaviour of the occupants. The other approach is to determine the values of Cc, Cv and Wo from a fit to data from the reference houses, and apply the analogous procedure for the test houses. In this case the difference between Wo and Wo˜ is an indication of a changed behaviour of the occupants. However,this does not effect the calculation of the retrofit effect, ΔW. In both cases above it will be given by

$$\Delta W = Ac(Cc - Cc^{\sim})\Delta Ta + Ca((Cv * v^2 + Ct * \Delta Ta)^{\frac{1}{2}} - (Cv^{\sim} * v^2 + Ct^{\sim} * \Delta Ta)^{\frac{1}{2}}) + Wo - Wo^{\sim}$$

If the second approach above is followed, the retrofit effect can be calculated if Wo-Wo˜ is small compared to the magnitude of Wo, because in this case it seems likely that also the behaviour of the occupants has been the same. Then the requirements for the calculation of the retrofit effect, that the test and the reference buildings are identical in all respects, are fulfilled. The retrofit effect will then be given by the expression

$$Ac(Cc - Cc^{\sim})\Delta Ta + Ca((Cv * v^2 + Ct * \Delta Ta)^{\frac{1}{2}} - (Cv^{\sim} * v^2 + Ct^{\sim} * \Delta Ta)^{\frac{1}{2}}).$$

To check the validity of this model, the fitted values of Cc and Cc˜ should be compared to theoretical values calculated from knowledge about the construction of the building. At least the difference between Cc and Cc˜ ought to be well determined as this is a result of the retrofit.

- Example 3

In this example we will describe the use of a dynamic model in the evaluation of a retrofit package when the on- off design is used. The retrofit package consists of the installation of a heat exchanger and the introduction of night set back. The experimental building is a large multi- family residential building. The building is equipped with a mechanical exhaust and supply ventilation system. The heating system includes an oil- fired burner, a circulation pump and hot- water radiators in the flats. The hot tap water is generated electrically. The building has two dominant facades, one of them facing south. When the night set back is in operation no heat is delivered to the apartments for eight hours, but the circulation pump is still working, thus the heat stored in the pipes is given off to the radiators. The water of the furnace is kept at a constant temperature during the night set back. The ventilation system is after the retrofit equipped with a recuperative heat exchanger.

As there does not exist any suitable reference building and only one heating season is available for the measurements, the on- off design is to be used in this experiment.

When estimating the magnitudes of the energy flows that could be included in the model, one concludes that the model should contain the heat flows

Wh = energy input from the heating system
Ws = heat storage in the building interior and envelope
We = electric energy consumption
Wr = solar and sky radiation through the windows
Wc = conductive and radiative heat losses through the building envelope
Wv = heat losses through the ventilation system
Wo = other heat losses including heat losses to the ground, heat losses by airing, solar radiation through the exterior walls, distribution losses in the heating system etc.

The model is then Wh+ We+ Wr= Wc+ Wv+ Ws+ Wo

The working conditions of the heating regulation system are such that the burner will start if the temperature of the water leaving the furnace falls below a certain preset temperature. The burner will remain on until the temperature of the water leaving the furnace reaches another preset temperature.

The water leaving the furnace is mixed with part of the return water before being fed into the pipes. The temperature and the flow rate of the supply water is affected by the operation of a mixing valve which controls the mixing of the return water and the water leaving the furnace. This valve will open or close depending on whether the temperature of the supply water falls below or exceeds certain temperature limits determined by the outdoor air temperature. The effect of the burner varies with the load.

In order to avoid a detailed modelling of this heating system, which by itself would not serve any purpose, as the heating system has not been subjected to any retrofit, one decides to include in the model only the net energy given off by the heating system. One then measures the temperature difference between the supply water and the return water and the flow rate. The energy flow Wh is then, when the night set back is not in operation, given by

$Wh = Cw * \Delta Th * Qh$ where

ΔTh = temperature difference between supply and return water

Qh = flow rate of the heating system

Cw = volumetric heat capacity of water

When the night set back is operating another model of the heating system is used. The total water volume of the piping system is known. The time constant of the heating system is also known. So when the night set back is operating and the circulating water gives off its heat to the radiators, it is assumed that the temperature of the water falls of exponentially. The energy flow Wh is then in this case given by

$Wh = Cw * Vw * \Delta Tw * \exp(-t/\tau)$ where

Vw = volume of water in the pipes

ΔTw = average temperature difference between the water and the indoor air when the night setback starts

τ = the time constant of the heating system.

During the first hour after the night set back some of the heat given off by the burner is used to raise the temperature of the piping system and the water contained in it. During this hour one assumes that the energy flow Wh is given by

$Wh = Cw * (\Delta Th * Qh - Vw * \Delta Tw)$

Electric energy is used for hot tap water and domestic electricity. It is assumed that only a certain fraction of the consumed electricity will contribute to the heating of the building because of sewage water losses, airing in connection with cooking etc. The energy flow We is then modelled as

We = Ce* Ee where
Ee = the total consumption of electric energy
Ce = the fraction contributing to the heating of the building

It is believed that the major contribution to the heating of the building from solar and sky radiation consists of radiation through the windows. As this radiation can be measured on the inside of a window, the energy flow Wr is modelled as

Wr = Ar* Qr where
Ar = window area of the southern facade of the building
Qr = impinging short- wave radiation measured on the inside of a window
The energy flow Wc is modelled as

Wc = Cc* Ac * ΔTa where
Cc = average heat transmittanc of building envelope
Ac = area of building envelope
ΔTa = indoor- outdoor air temperature difference

The parameter Cc is assumed to be constant in time. The thermal performance of the external walls is thus assumed to be static, and thermal gradients in the insulation are not taken into account in this model, although other energy flows of the model are dynamic.

In the ventilation system the flow rate of the supply air is smaller than that of the exhaust air. This will create a pressure inside the building that will enhance the effect of the pressure on the windward side of the building but instead reduce the flow of air through the leeward exterior wall. The overall effect will in general be an increase of the uncontrolled infiltration. A ventilation system of this kind will also enhance the uncontrolled infiltration due to stack effects. The heat loss caused by ventilation, Wv, is expressed as

Wv = Ca* ΔTv *Qs where
Ca = the volumetric heat capacity of air
ΔTv = the temperature difference between the exhaust air leaving and the supply

air entering the building (or the heat exchanger if this one is in use)
Qs = the flow rate of the supply air

The heat storage in the building will take place mainly in three building components, the heating system, the interior of the building and the building envelope. The heat storage in the heating system has been accounted for in the energy flow Wh. The energy flow Ws is modelled as

Ws = Cs* dTi where
Cs = a parameter describing the effective heat capacity of the building
dTi = the temperature difference of the indoor air between two measurements

The parameter Cs will in effect describe not only the heat storage of the building interior ,but also that of the building envelope, as the energy flow through the building envelope, Wc, was treated as a static one. As hourly data are to be used in the analysis, the temperature difference dTi will be the difference of the indoor temperature between two consecutive hours. The indoor temperature is measured in a number of flats determined by a procedure like the one described in App. III. Because the temperature to be used in a proper model should be that of the building fabric, and not that of the indoor air, which can fluctuate rapidly due to solar radiation through windows and heat sources in the apartments, it is important that such factors do not affect the measurement of the indoor air temperature.

The remaining heat source Wo is assumed to be constant in time and take the same value during the on- and the off- periods. This is probably a good approximation in this case, as much of the possible differences in the habits of the occupants has been taken into account in the energy flow We.

One then has to measure the temperature variables ΔTh, ΔTa, ΔTv and dTi, the flow rates Qh and Qs, the radiation Qr, and the electricity consumption Ee. The parameters Ca and Cw are known physical properties of air and water, the areas Ar and Ac can be calculated from the building geometry. It has already been described how the parameters of the heating system Vw, τ and ΔTw are assigned a value. It remains to assign a value to the parameters Ce, Cc, Cs and the energy flow Wo. From previous studies on similar buildings it is known that the value of Ce is about 0.5 . This value is taken as input to the model. The parameters Cc and Cs are the same during the on- and the off- periods. The values of Cc, Cs and Wo can now be determined in a simultaneous fit to data from the on- and the off- periods. A fit to the data from the off- period alone would probably result in a very poor determination of the parameter Cs unless the swings of the indoor temperature have been large. The values of Cc and Cs should be compared to theoretically calculated values of these parameters from knowledge about the construction of the building. If there are large discrepancies between the fitted and the theoretical values, the underlying assumptions of the model should be reviewed.

One should now turn to the evaluation of the retrofit effect. In this case one has a good model describing the thermal performance of the building in rather detail. It turns out that the calculation of the retrofit effect meets with some difficulties. Probably the average indoor temperature has been lower during the on- periods than during the off- periods due to the night setback. The resulting energy saving could also have been achieved by simply lowering the indoor temperature all the time. So one would like to know what the effect of the night set back had been if the average indoor temperature had been that of the off- period. There is no simple way of estimating this with the above model. No energy flow can be directly associated with the effect of the night setback. In a sense the model is too complex for the evaluation of the retrofit effect of the night setback, the effect of the night setback is distributed between too many other energy flows.

One can calculate the contribution to the heating from the heat exchanger, but only for the actual indoor temperature of the on- periods, not what this contribution would have been if the indoor temperature had been that of the off-periods. This is so, because the temperature of the exhaust air entering the heat exchanger is not the same as the indoor temperature because of heat losses in the ducts. A calculation using the temperature of the off- periods as input could have been performed if a more complex model of the heat exchanger had been used and also the temperatures of the supply air entering the heat exchanger and the exhaust air leaving it had been measured. One would also in this case require knowledge about the efficiency of the heat exchanger.

The model is too complex for the estimation of the effect of the night setback, but too simple for the evaluation of the effect of the heat exchanger. A way out of this dilemma is to use a more sophisticated variant of the on- off design. One can let off- periods alternate with periods when only one of the retrofits is on and with periods when both retrofits are on (see Cox 1958).

- Example 4

In this example we will decribe a case when a model, linear in the indoor-outdoor temperature difference ΔT, had to be modified by the inclusion of a non-linear term.

The experimental buildings are situated at a high latitude. A before-after experiment was carried out on a group of detached single- family dwellings during two heating seasons. The retrofit consisted of the installation of heat exchangers in the exhaust and supply ventilation system, and the replacement of double- glazed windows by triple- glazed.

One recorded the weekly averages of indoor temperature, outdoor temperature, consumption of electricity for hot tap water, household electricity, and the energy supplied by the heating system and the heat exchanger during the heating season (9 months). The flow- rate of the ventilation system was fixed during the experiment, and was measured at two occasions in both heating seasons. Tracer gas measurements were also performed. It was estimated that the air exchange due to infiltration never exceeded ten per cent of the air exchange forced by the ventilation system. One would then expect that the transmission and ventilation losses would be linear in ΔT.

It was found that the energy used for heating was not as linear in ΔT as expected, neither for the before period nor for the after period. The situation was even worse if the consumed electric energy was added to the energy for heating.

At first it was believed that the observed effect could be explained by the neglect of solar radiation in the energy balance of the building. However, a rough estimate showed that this could only account for part of the observed effect. Another argument, in favour of a more complicated explanation, was that a fit linear in ΔT was not acceptable even if data from periods with a strong solar radiation were excluded from the data set. One therefore performed a more detailed study of the energy balance of the building.

One wanted to estimate, among other things, the contribution to the energy balance of the building from heat losses to the ground, penetration of solar radiation through the windows, and infiltration losses due to wind. No measurements had been performed of these variables. The estimate therefore had

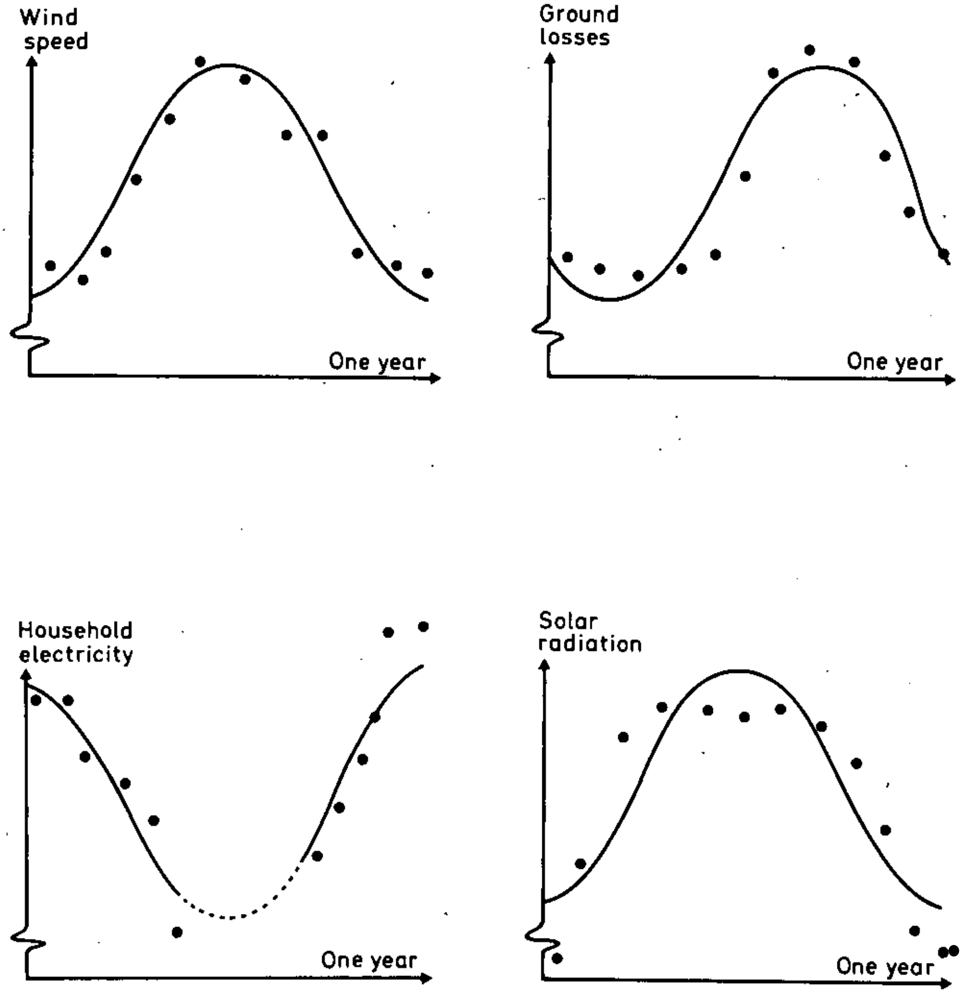

Fig. II a-2 The variation of some energy variables during the year.

to be based on data recorded at the meteorological station closest to the building site.

One plotted the estimated transmission losses to the ground, the estimated solar radiation through windows, the average wind speed, the actual consumption of electricity for hot tap water, and the actual consumption of household electricity versus the number of the week.

It was found that all the plotted variables, except for the consumption of hot tap water, which was constant during the measurement period, could be well described as functions of time by a constant plus a trigonometric function (see fig. II a-2). It was, thus, believed that many energy flows could be represented by an expression containing a term proportional to $\sin 2\pi/52(n-n_0)$ plus a constant, where n is the number of the week and n_0 is a phase. As a sum of expressions of this kind can be written in the same manner, the model was modified to

$$E = a + b*\Delta T + \Delta E*\sin 2\pi/52*(n-n_0)$$

where

E = energy used for heating

n = the number of the week

ΔT= the indoor- outdoor temperature difference

and a,b,ΔE, and n_0 are parameters of the model, whose values are to be determined by a fit to experimental data.

It was then found that, using this model, a satisfactory fit to experimental data could be obtained.

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Keywords

accuracy of experimental method
aim of experiments
behaviour of occupants
climate correction
data analysis
design of experiment
measurement cycle
parameters, environmental
reference building
time constant

II b On-off experiments

Description of the on-off experiment

The on-off experimental design can be used whenever the retrofit in a residential building consists of the introduction of a system, or a component of an already existing system, that can at will be either turned on or switched off. The retrofit can also consist of a new way of operating an already existing system. Examples of such systems, or components of systems, are heating systems, ventilation and air-conditioning systems, heat exchanger, heat pump, and solar energy systems.

The use of the on-off experiment offers several advantages. Regarding the enviroment of the building and the exposure to outdoor climate, the building will be its own reference. The length of the period when the system is in an on or off state can be chosen to satisfy the special regquirements of the experiment in question. If this period is short enough, it will be possible to go through several on-off cycles. If the number of such cycles is large, a statistical treatment of the results becomes possible. In many cases it may then be possible to reduce the extension and cost of the measurements compared to when, e.g., the before-after method is used.

The length of the period when the building is in an on or off state should, in an ideal case, be greater than characteristic time constants of the building and systems of the building, but shorter than the time required for a change in the average values of environmental parameters.

The value of such time constans can vary much between buildings. The time constant of the thermal capacity of a building may, depending of course also on the degree of insulation, be of the order of one day for a building of light construction, but be a week or more for a building of very heavy construction.

If the building studied has typical time-constans of the order of one day, the length of the period mentioned above should comprise at least a few days. If it is of the order of one week, or shorter, it will be possible to go through several cycles of measurements during one heating season. It may be possible to get an average climate for the on-periods which is close to that of the off-periods. One may also have measurements from different climate situations for the on as well as for the off periods. What has been discussed so far is valid independently whether the experiment is carried out in an inhabited or an uninhabited building.

Regarding the influence from occupancy, the on-off experiment is also an advantageous method. If the time of the on-off cycle is short enough, the occupants are given the possibility to experience the prevailing conditions, during the on as well as the off periods, several times during a comparatively short interval of time. In this way the occupants may eventually get used to the shifting conditions, and no longer notice whether the on or off state is prevalent for the moment. This will of course not be true if the indoor climate is very different during the on- and off-periods.

In cases when the behaviour of the occupants is quite different during the on and the off periods, e.g., if the indoor temperature is higher during the on periods and this leads to a more frequent airing, this behaviour during the on period would be the same if the on state were permanent. This behaviour of the occupants must in this case be considered to be part of the natural interaction between occupant, building and enviroment.

One should, however, be aware that the difference between the conditions during the on- and the off-state may be such that the occupants need a very long time to adapt themselves to the new situation after a change of state. If this is so, the behaviour of the occupants will clearly influence energy consumption. If this influence can be expected to be so large that it is of the same order of magnitude as the expected difference in the observerd energy consumption, it will not be possible to use the on-off experiment as described above. In this cse one will either have to advice a method to measure or estimate the influence of the occupants, perform the measurements in an uninhabited building, or choose an experimental design, where this influence is minimized. Whether this is possible can only be determined case by case.

It will in most cases be necessary to make a correction in relation to climatic differences. This correction is most easily performed if an appropriate model of the interaction between the building and the external climate is used.

It follows from what has been discussed above that the use of the on-off method offers no special problems with regard to the validity or the accuracy of the method, possibly with one exception. This exception is that the building has some properties unknown to the investigator, properties that are specific to the experimental building but not to other, similar, buildings. If this is the case, the lack of a reference building might be disastruous for the outcome of the experiment. It is therefore always of value to have access to one or more reference buildings even if this is not per se required for the use of the on-off method.

The use of the on-off method is illustrated below with 3 simple examples. The first of these illustrates the influence of the time constants of the building.

- Example 1

In this example the accuracy of the on-off experiment will be illustrated with a few simple cases. We have chosen to discuss the use of the on-off experiment in experiments to determine the efficiency of night set-back.

In this case we will calculate the ratio of the observed energy saving and the theoretical energy saving and this entity will be denoted by α. These calculations are intended to serve as examples of the kind of analysis that should preceed every experiment where the on- off method is used.

We will first dicuss the case of a residential building equipped with a thermostat reacting on the indoor temperature T_i. The heating system can supply a maximal heat output of P_{max}. The thermostat has two settings, T^+ amd T^-. During the day the heat output will be P_{max} if the indoor temperature falls below T^+. If the indoor temperature reaches the value T^+ the heat output will be such that T_i is kept at this level. At night no heat will be supplied if T_i is greater than T^-. If T_i falls below T^-, sufficient heat will be supplied to keep T_i at this level. It is further assumed that the heat losses of the building are proportional to the indoor-outdoor temperature difference with a proportionality constant k_i, and that the heat capacity of the building is C_i. The outdoor temperature will be denoted by T_0 and is assumed to be constant. The heat output during the day will then be $P=k_i*(T^+-T_0)$ if $T_i= T^+$.

We will assume that the thermostat setting is such that the day- and the night period are of equal length, τ_o (in this case $\tau_o = 12$ h). The length of the on- and off periods of the experiment is $2N\tau_o$ (i.e. N days).

To diminish the influence of the heat capacity of the building on the energy consumption of an on- or off-period, one can neglect the first N_o days of each period. When α is determined, one will then take into account only the energy consumption of the last $(N - N_o)$ days of each on- and off period. The on- and off-periods are assumed to start with a night.

If the indoor temperature reaches the value T^+ during the off-period, one can distinguish four cases.

a) The first night of the on- period T_i does not fall to T^-. During the next day the heat output P_{max} is sufficient to raise T_i to T^+. The development of T_i is then the same for all days of the on-period and T_i takes the value T^+ during the whole off-period.

b) The temperature T_i falls to T^- during the first night of the on-period and reaches the value T^+ during the following day. In this case the change in T_i in time is also the same for all days of the on-period and T_i is equal to T^+ during the off-period.

c) The temperature T_i falls to T^- during the first night of the on-period, but the heat output P_{max} is not sufficient to raise T_i to T^+ during the following day. The development of T_i will be the same for all days of the on-period but the first one. The indoor temperature will not be equal to T^+ for all of the off-period.

d) The indoor temperature does not fall to T^- during the first night and does not reach a value of T^+ during the first day. The development of T_i in time will be different for each day of the on-period, and T_i will not be equal to T^+ except for part of the off-period.

The development in time of the indoor temperature T_i in the four cases listed above is indicated in fig. II b-1. For a given residential building and fixed values of P_{max}, T^+, and T^-, more than one of these four cases can occur depending on the value of the outdoor temperature T_o.

In the cases a) and b) the observed energy saving will always be equal to the theoretical energy saving so α will be identically 1. In case c) α will in general be close to 1 if the energy consumption of the first day of the on- and off-periods is excluded when α is calculated.

The case d) requires a further treatment. The theoretical energy consumption if the on-state were permanent would be equal to $(N-N_o)*\tau_o*P_{max}$, and if the off-state were permanent the energy consumption would be $2(N-No)*\tau_o*k_i*(T^+-T_o)$. The theoretical energy saving would thus be equal to $(N-N_o)*\tau_o*(2k_iT^+ - 2k_iT_o - P_{max})$.
The observed energy consumption during the on-period is the same as the theoretical one, i.e. $(N-N_o)*\tau_o*P_{max}$

If it is assumed that T_i reaches the value T^+ at the time t_s, $t_s > 2N_o*\tau_o$, after the off-period starts, the observed energy consumption of the off- period will be equal to
$P_{max}*(t_s - 2N_o\tau_o) + (T^+ - T_o)*(2N\tau_o - t_s)$.
The observed energy saving is thus equal to
$k_i*(T^+ - T_o)\ (2\ N\tau_o - t_s) + Pmax*(t_s - N\tau_o - N_o\tau_o)$.
If the ratio $P_{max}/k_i(T^+- T_o)$ is denoted by r, the value of α is
$\alpha = 1 + (r - 1)\ (t_s/\tau_o - 2\ N_o)/(N - N_o)(2 - r)$
Clearly this case can only be realized when $1 < r < 1+\exp(-\tau_o/\tau)$ where $\tau = C_i/k_i$ is the time constant of the building.

For the two extremes $t_s = 0$ (i.e. also $N_o = 0$) and $t_s = 2\ N\tau_o$, the values of α equal to 1 and $r/(2-r)$ respectively are obtained. It is obvious that if one wants a value of α close to 1 one should either take $2N_o$ close to t_s/τ_o or take N large.

e) In this case we assume that the residental building is equipped with a water radiator system. The temperature of the feed water is varied during the day so that a night temperature set-back is obtained. It will also be assumed that the outdoor temperature, $T_o(t)$, varies in an arbitrary manner during the day and that there is a free heat gain, $Q_f(t)$, that also varies in an arbitrary manner during the day. The heat transfer to the building from the heating system is assumed to be proportional to the difference between the feed water temperature, $T_h(t)$, and the indoor temperature, $T_i(t)$, with a proportionality constant k_h. The heat losses of the building are assumed to be proportional to the difference between the indoor and outdoor temperature with a proportionaly constant k_i. The indoor temperature is then determined by the equation

$Q_f(t) + k_h (T_h(t) - T_i (t)) = C_i*dT_i/dt + k_i(T_i(t) - T_0(t))$

The length of the night set-back is assumed to be τ_0=12 h. For simplicity also assume that the variation of the feed water temperature $T_h(t)$ in time is antisymmetric with respect to the time of the onset of the night set-back. The feed water temperature can then be represented by the series.

$T_h(t) = \bar{T}_h + \Sigma_n \Delta T_h^{(n)} \sin wnt$

where $\bar{T}_h$ is the average temperature of the feed water, $w=\pi/\tau_0$ and $\Delta T_h^{(n)}$ are coefficients. The indoor temperature T_i will then vary during the experiment as shown in fig. IIb-1 if the feed water temperature has a square wave form. The feed water temperature during the off-period is assumed to be equal to the maximum feed water temperature of the on-period. It can thus be shown that the ratio of the observed energy saving and the theoretical energy saving, α, will be independent of the outdoor temperature $T_0(t)$ and the free heat $Q_f(t)$. One obtains

$\alpha = 1 + \beta(1 + \Sigma_n \Delta T_h^{(n)} wn\tau/(w^2 n^2 \tau^2))/(T_h(max) - \bar{T}_h)$

where $T_h(max)$ is the maximal feed water temperature during the day, and τ, the time constant of the building, is equal to $1/(k_i + k_h)$, and

$\beta = (\bar{T}_i - \bar{T}_0)/(\bar{T}_h - \bar{T}_i)*(\tau/\tau_0)*(\exp(-2N_0\tau_0/\tau) - \exp(-2N\tau_0/\tau))/(1+\exp(-2N\tau_0/\tau))/(N-N_0)$

T_i and T_0 are the average of the indoor and the outdoor temperature, respectively. If the feed water temperature is assumed to have a simple square-wave form such as

$T_h = \bar{T}_h - \Delta T_h$ for $0 < t < \tau_0$

$T_h = \bar{T}_h + \Delta T_h$ for $\tau_0 < t < 2\tau_0$

the above simplifies to

$\alpha = 1 + 2*\beta/(1 + \exp(\tau_0/\tau))$

if the on- period starts by a night, and

$\alpha = 1 + 2*\beta/(1 + \exp(\tau_0/\tau))$

if the on-period start with a day.

A few results should be stressed in this case

1) α is always greater than 1, so the energy-saving is overestimated. (This was true also in the cases a) - d) above).
2) It is favourable to start the on-period with a night.
3) α will be closer to 1 if N or N_0 are increased. However, if N is increased, α will approach 1 as 1/N, while if No is increased it will approach 1 as $\exp(-N\tau_0/\tau)$.

It will, in general, be more efficient to increase N_0 than N. In Table II b-1 below we give the value of α for some cases. It has then been assumed that the temperature difference ratio $(\bar{T}_i - \bar{T}_0)/(\bar{T}_h - \bar{T}_i)$ is equal to 1/2.

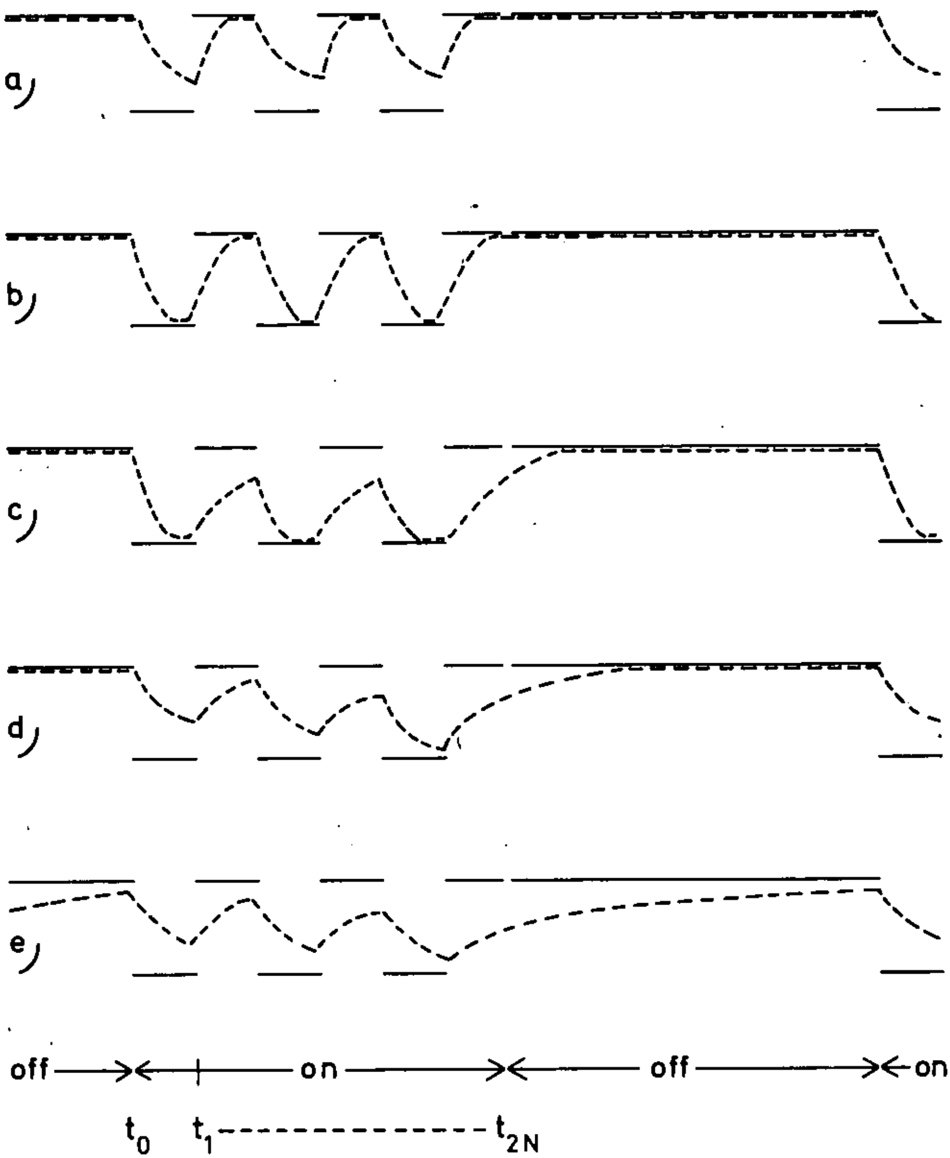

Fig. II b-1 The development of the indoor temperature T_i during an on-off experiment (hatched curves). Fig. a) to d) refer to different cases for a residential building equipped with a thermostat. The full-drawn lines are the settings of the thermostat. Fig. e) refers to a building with water radiators. The full-drawn lines represent the asymptotic temperature.

TABLE IIb-1

The ratio of the observed to the theoretical energy saving for a residential building with water radiators and night set back.

2N= 14 (7 DAYS)

	$2N_0$ =	0	1	2	3	4	5	6
τ =1 DAY	DAY	1.18	1.12	1.08	1.05	1.03	1.02	1.02
	NIGHT	1.11	1.07	1.05	1.03	1.02	1.01	1.01
τ =2 DAYS	DAY	1.30	1.25	1.21	1.18	1.15	1.12	1.11
	NIGHT	1.24	1.20	1.16	1.14	1.11	1.10	1.08
τ =3 DAYS	DAY	1.38	1.34	1.31	1.27	1.25	1.22	1.20
	NIGHT	1.32	1.29	1.26	1.23	1.21	1.19	1.17

2N= 28 (14 DAYS)

	$2N_0$ =	0	1	2	3	4	5	6
τ =1 DAY	DAY	1.09	1.06	1.04	1.02	1.01	1.01	1.01
	NIGHT	1.05	1.03	1.02	1.01	1.01	1.01	1.00
τ =2 DAYS	DAY	1.16	1.13	1.10	1.08	1.07	1.06	1.05
	NIGHT	1.12	1.10	1.08	1.07	1.05	1.04	1.04
τ =3 DAYS	DAY	1.23	1.20	1.18	1.15	1.14	1.12	1.10
	NIGHT	1.19	1.17	1.15	1.13	1.11	1.10	1.09

2N= 42 (21 DAYS)

	$2N_0$ =	0	1	2	3	4	5	6
τ =1 DAY	DAY	1.06	1.04	1.02	1.01	1.01	1.01	1.00
	NIGHT	1.04	1.02	1.01	1.01	1.01	1.00	1.00
τ =2 DAYS	DAY	1.11	1.09	1.07	1.05	1.04	1.03	1.03
	NIGHT	1.08	1.07	1.05	1.04	1.03	1.03	1.02
τ =3 DAYS	DAY	1.15	1.13	1.12	1.10	1.09	1.08	1.07
	NIGHT	1.13	1.11	1.10	1.09	1.07	1.06	1.06

N = number of days in an on-off or a static cycle

N_0= number of days in the beginning of a cycle not used in the analysis

τ = the time constant of the building

DAY and NIGHT indicate if the on-off cycle is started by a day or a night

- Example 2

- type of object: An eight-storey residential building with 48 flats. The building has been erected rather recently, it is of a light construction and well insulated. Windows are double-glazed. The heating system is waterbased. Radiator valves have been preset, and the heating system has been balanced. The ventilation system is of the exhaust air type with a fixed rate of air change. The building is situated in a suburban enviroment.

aim of experiment: To determine the energy consumption for heating the building, when a night setback of the heating system is used, compared to when the building is continuously heated.

design of experiment: a night setback of the heating system was used every second week during one heating season. The weekly energy consumption for heating, when a night setback was used, was planned to be compared to the consumption when the building was continuously heated.

One intended to compare the results of the measurements to the results obtained from measurements on a reference building. However, the final choice of rather extensive measurements on the test building turned out to be so expensive that one could not afford the use of a reference building.

The choice of one week as the period for a change from one state to the other was mainly dictated by the fact that the time constant of the thermal capacity of the building was estimated to be of the order of one day. For every week the first day, when the way of heating the building was changed, was excluded from the data analysis (see below measurements).

The weekly consumptions should be grouped according to the weekly average of the indoor-outdoor temperature differences. To determine the average indoor temperature, this was measured at one position in 8 flats. This number was based on the assumption that the variation in indoor temperature between different flats was 3 K and on the request that the average indoor temperature should be known with an accuracy of 1 K (see App. III).

measures taken: from information about the heat capacity and time constant of the building and the heating system, a suitable design of the night setback was worked out. The maximum indoor temperature during the day was estimated to

23°C and the lowest at night to 18°C. With continuous heating it was planned that the average indoor temperature should be 22°C.

measurements: the indoor and outdoor temperature, and the temperature and flow of the supply and return water were measured every hour. These data were stored on a magnetic tape recorder. The consumption of domestic electricity and hot tap water was read off manually at the beginning of the first day and once at the end of the last day of each period that was to be included in the final analysis of the data.

course of investigation: the measurements started as planned. After a month there were complaints by the occupants that the indoor temperature was too low at night. From the temperature measurements it was possible to see that, in some flats, this temperature had in some cases been as low as 16°C. The procedure for the night setback was adjusted to compensate for this, the minimum indoor temperature was calculated to be raised by 1-2 K. After this correction fewer complaints were received. There were also some complaints that the indoor temperature during tha day was too high. This did not depend on whether the heating was continuous or the night set back was used. These complaints had been received mainly on days with a strong solar radiation. It was also observed that on such days many residents opened their windows for rather long periods during the day. This was belived to influence the energy consumption, but it was not possible to estimate to what extent this was the case. Therefore no measures were taken to counteract this behaviouror or to modify the experimental design.

data treatment: it was found that the energy consumption for heating was lower when night setback was used than when the building was continuously heated. But there was a rather large scatter in the data. It could be demonstrated that the largest deviations had occurred for weeks when the solar radiation had been intense, according to meteorological observations. The data for the use of domestic electricity and hot tap water were not used in the final analysis of data. The reason for this is not known. A possible explanation is that these data were collected by the care- taker of the building, and those in charge of the project did not want to use these data, either because all data were judged not to be trusted, or maybe because these data were lacking for some weeks.

comments: in this case the research design was rather simple. If the daily energy consumption had been used instead of the weekly one in the analysis, a grouping of data could have been made also according to solar radiation. This would have been possible as the temperature was recorded every hour. On the other hand, it was possible to reach a definite conclusion also using a time resolution of one week. In this case an alternative would have been not to perform so extensive measurements, but to use only weekly averages. The cost would then have been so much lower that it would have been possible to perform measurements also on a reference building. This would probably have made it possible to reach a conclusion about whether the deviations for weeks when the solar radiation was intense was typical for buildings of this kind also when night set-back was not used. The scatter of data would probably also have been smaller if the energy used for domestic electricity and hot tap water had been added to the energy consumption for heating when the final analysis of data was performed. It would then also have been possible to use a simple model of the energy balance of the building. This would have facilitated the final analysis. The remaining scatter of data could mainly have been ascribed to the influence of the occupants.

- Example 3

type of object: twenty terraced two- storey single- family houses. The houses are situated in a suburban environment. The insulation of the houses is good and the windows are double-glazed. The houses are of light construction. The heating is electric and the houses are equipped with a supply and exhaust air ventilation system with pre-heating of the supply air. The hot tap water is electrically heated inside the buildings.

measures taken: the houses were equipped with temperative heat exchangers with water and glycol as circulating medium. The off- state could be reached using a simple by-pass circuit.

aim of experiment: to determine the energy consumption when the heat exchanger is in function and when it is not. A second aim was to determine the efficiency of the heat exchanger in situ.

experimental design: the twenty houses are grouped in two rows with ten houses in each. Every second week the heat exchangers were put into operation function in one of the rows while they were shut off in the other row and the situation was reversed the following week. This was done during one heating season. The daily consumption of energy was measured for every house. It was planned that these data should be grouped according to the difference between indoor and outdoor temperature, wind speed, and solar radiation. A comparison of the energy consumption when the heat exchangers were in function and when they were not should then be performed for every such group. For the determination of the efficiency of the heat exchanger, data should be grouped according to outdoor temperature.

measurements: in every house the indoor temperature was measured at one position in each of the two storeys. The average of these two values was taken as the average indoor temperature. The temperature of the exhaust air was measured just before arriving at the heat exchanger. The temperature of the supply air was measured after the pre-heating. The mechanically controlled constant air flows of the ventilation system were measured once every second month during the heating season. The amounts of electricity used for heating, for pre-heating of the supply air, and for the heating of hot tap water were measured separately.

The outdoor temperature and solar radiation were measured in the neighbourhood of the houses. The wind speed and direction was measured a few hundred meters away at a place where it was thought that the free wind was undisturbed by the enviroment. All data from these measurements were stored as one-hour averages from which the daily average was then calculated. The air infiltration was measured twice in all the houses during the heating season.

course of investigation: before the heating season the heat exchanger and the measuring equipment were installed in the house. Continuous measurements were carried out as had been planned. The infiltration measurements were performed one week in the middle of the heating season using a tracer-gas technique. During the measurement period there was a change of ownership for two of the houses. These two houses were thereafter excluded from the investigation.

This was done because it is well known that energy consumption differs much even between identical houses, due to differences in the habits of the residents. It is also well known that the new residents need a year or so to learn how to manage a house and the pattern of the energy consumption can change drastically during the first year.

data analysis: after grouping of the data, the data were analyzed. A strong correlation was found between energy consumption on one hand, and indoor-outdoor temperature difference and solar radiation on the other hand. No such clear correlation was found between energy consumption and wind speed. Here there was a large scatter in data. This was ascribed to the infiltration being different for winds of the same strength but of different direction. Although no final conclusion about this could be drawn from the data of the infiltration measurements, there was a strong indication that this was the case. When data from all wind directions, except the most prominent one, had been excluded from the analysis, a better correlation between energy consumption and wind speed was obtained.

After this the energy consumption, when the heat exchangers were used and when they were not, could be compared in an unambigious way. No problems were associated with the determination of the efficiency of the heat exchanger.

comments: in this investigation an unusually ambitious research programme was planned with a grouping of data according to three outdoor climate variables. For the aim of the experiment it would probably have sufficed to use only the indoor-outdoor temperature difference.

The data from the infiltration measurements were never used as an input into the data analysis, but they turned out to be useful when selecting the set of data to be used in the final analysis. Even if only the daily averages of the temperatures were used in the final analysis, the measurements were performed much more frequently. It would probably have been cheaper to use an experimental design where only the daily average temperature was stored.

As the air flows in the ventilation system could not easily be changed by the occupants in this investigation, there were no large problems associated with the behaviour of the occupants.

CHAPTER II c

Before-after experiments

Contents

II c Before-after experiments

- description of the before-after experiment

The before-after experimental design can in a sense be regarded as a special case of the on-off experiment where the measurements include only one (on-off) cycle. In practice, the advantages and disadvantages of these two experimental designs different that the above mentioned relation is not of much practical use. The before-after design has to be applied when the retrofit of residental building consists in a permanent change of the building itself, or when a system which cannot be turned on and switced off at will is introduced, or when this can not be done without affecting other systems. Examples of retrofits where the before-after experiment can be used are the sealing of windows, the increase of the insulation of the building, the replacement of the heating system, or the installation of a new type of ventilation or air-conditioning system.

When the before-after experiment is used one generally has to compare the energy balance of the building during two periods when external variables, like climate variables, have not taken the same values. Therefore one has often to use a model of the energy balance of the building to reach any conclusions. The measurements therefore have to be so extensive and accurate that it is possible to achieve the same time resolution as when, i.e., the on-off experiment is used.

Regarding the environment of the building and the exposure to outdoor climate, the before-after experiment offers the same advantage as the on-off experiment because the building is its own reference. However, regarding the prevailing climate during the before and after periods, the situation is different. When the before-after experiment is used, there is no guarantee that the average climatic situation is the same during the before- as during the after- period, even if the experimental period is made very long, i.e. several heating seasons. A correction has to be made if the average climate during the two periods has been different.

One has to calculate what the energy consumption during the after period would have been if the climate during this period had been that of the before period. The accuracy of this procedure will depend on the accuracy of the model that is used. Such a correction is not always necessary even if the measurements extend over only one or two heating seasons. There are often periods of time shorter than a week when the climatic conditions during the before periods were the same as those during part of the after period.

If the energy consumption for such shorter periods is known, it is sometimes possible to compare directly the consumption during two such short periods, one of them belonging to the before period and the other to the after period. A necessary provision is of course that the number of external parameters influencing the energy consumption is very small, or that the number of such periods is great. This procedure is sometimes a rather uncertain one, and special care should be taken when applying it.

When the before-after experiment is used the occupancy behaviour may be of greater importance than when the on-off experiment is used. This is associated with the very marked separation in time between the before and the after period. The introduction of the retrofit may easily raise unrealistically positive or negative expectations of the future performance of the building. Such expectations may lead to a change in the behavoiur and attitudes of the occupants which may affect the outcome of the experiment. It is therefore important that the occupants and the persons involved in the maintenance of the building are informed in advance about what the consequences of the retrofit and measurements will be.

If a result of the retrofit is a change in the indoor climate, this change should, if possible, be introduced gradually to give the occupants the possibility of adapting to the new indoor environment. Difficulties of the kind discussed above can to a certain extent be avoided if one introduces a "running-in and learning period". By this is meant that, when the retrofit has been performed, one can let a certain time pass before starting the measurements of the after-period. With this procedure one can avoid the influence of more temporary changes in the behavoiur of the occupants, changes not associated with the retrofit itself but only with the introduction of it. A study of the habits of the occupants and their attitude towards the retrofit and the experiment, before, during, and after the measurement period, should therefore be included in the research programme. Such a study must not necessarily be aiming at a complete survey of the behaviour and attitudes of the occupants, but may have the more limited purpose to ascertin that no great changes of these factors take place.

It follows from the discussion above that the validity of the before-after experimental design rests to a great extent upon the comparability of the outdoor climate and the constancy of the behavoiur and attituteds of the occupants during the before and the after period. The demand for the extension and accuracy of the measurements and for the analysis of data is generally greater than for other experiments like the test-reference and the on-off experiment. The use of the before-after experiment is illustrated with two simple examples below.

- Example 1

type of object: a 4-storey residential building with 100 flats. Electrical heating and ventilation system of the exhaust air type. The thermal insulation of the building is satisfactory and the building is situated in an environment shielded by other buildings. Hot tap water is electrically heated and stored inside the building. The indoor temperature of the flats varies between 20 and 25°C. Windows are double-glazed. There have been complaints about draughts from the windows in some flats.

aim of experiment: to determine the reduction in energy consumption after the pre-setting of the thermostats of electric radiators and the sealing of windows.

experimental design: as no similar building is available as a reference building, the measurement campaign is carried out during two heating seasons. During the first of these only measurements are to be performed. During the summer, measures to reduce the energy consumption will be taken, and measurements of the resulting energy consumption will be performed during the second heating season. The energy consumptions during the two heating seasons are to be compared after a correction using a simple model, which takes into account the average outdoor temperature and the average solar radiation.

measures taken: the thermostats were preset to allow a calculated maximal indoor temperature of 20°C. Due to the complaints about draughts all windows of the building were sealed. The occupants became interested in the investigation and expressed a wish to participate actively in the energy saving. Therefore an energy saving campaign was planned to be launched during the autumn of the second heating season. The occupants would be instructed on how to save energy by airing rooms less frequently and using less hot tap water.

measurements: the daily consumption of electric energy, indoor and outdoor temperature, wind speed, and solar radiation were measured and data stored as one-day averages. The estimated variation in indoor temperature between different flats is 2 K. As one wants to know the average indoor temperature with an accuracy of 0.5 K, the indoor temperature is measured in 15 flats (see App. III).

course of investigation: measurements were performed as planned during the first heating season. During the summer all windows of the building were sealed. The energy saving information campaign was started during the autumn. There was a delay in the presetting of the thermostats, and this work was not finished until several months of the heating season had passed. Among other things it was found that many thermostats had not been calibrated. This presetting resulted in many complaints by the occupants that the indoor temperature was too low, and the presetting of the thermostats was changed to 21°C instead of 20°C. When this work was finished only three months of the heating season remained to perform measurements. The energy saving campaign at first seemed to result in a substantially smaller consumption of domestic electricity and hot tap water, but the effect appeared to become less substantial during the winter.

data treatment: due to the delay in the measurement programme, the comparison of the energy consumption during the two heating seasons could not be carried out as planned. Insted, available data from the second heating season were divided into several groups according to the outdoor temperature, and compared to similarly grouped data from the first heating season. The scatter in data was large, but it was possible to conclude that a reduction in energy consumption had taken place.

The large scatter in data was ascribed to the fact that during the last three months of the heating season, when the measurements were performed, the contribution from solar radiation to the energy balance of the building could not be neglected.

comments: the noticed decrease in energy consumption can not with any degree of confidence be ascribed to the presetting of the electric thermostats solely, as was the aim of the investigation. It was caused by an unknown mixture of all three measures taken, presetting of thermostats, sealing of windows, and energy saving campaign. This campaign should not have been launched, above all because the effect of it was probably not constant during the heating season. The thermostats should have been preset to a higher value. The complaints now resulted in too short a measurement period. The data from the measurements of wind speed and solar radiation were never used. These measurements could have been omitted as there was no plan about how to use them in the experimental design.

If a simple model of the energy balance of the building, taking the contribution from solar radiation into account, and the available data on solar radiation had been used, it would probably have been possible to ascertain, with a higher degree of confidence, whether a reduction in energy consumption had taken place, despite the large scatter in data.

- Example 2

type of object: a 10-storey residental building with 40 flats. The heating system is waterbased and the ventilation system is of the supply and exhaust air type with preheating of the supply air. The thermal insulation of the building is considered to be satisfactory. Windows are double-glazed. The building is highly exposed to strong winds. On windy days the indoor temperature can become low in the upper part of the building. A temperature of 18°C has been measured at the top floor compared to a simulaneous temperature of 25°C at the bottom floor. The temperature of the supply air is also lower at the top floor. Because of this, the heating and the ventilation system are not regarded as working properly. Occupants in the lower part of the building have been observed to air rooms frequently due to high indoor temperatures.

aim of experiment: to determine the reduction in energy consumption after the balancing of the heating and ventilation system, the reduction of ventilation flows, and a lowering of the water and supply air temperatures, and the presetting of radiator valves. One was interested only in the combined effect of these measures on the energy consumption, not in the effect of a single measure.

experimental design: *the experiment was to be carried out during two* heating seasons. Between the two heating seasons the measures to reduce energy consumption were to be introduced. During the second heating season the same measurements as during the first one were to be performed.

measures to be taken: the balancing of the heating system consisted of

- presetting all values to calculated values
- establishing the flow in main distribution pipes by direct measurements
- checking the water distribution to terminals by measurement of pressure differences
- post adjustment in rooms where the obtained temperature deviates too much *from the desired value to be acceptable*
- instruction of the operator of the heating system.

Corresponding measures were taken for the balancing of the ventilation system. A calculation was made to determine how to preset radiator valves and flow circuits. Data from the measurements during the first heating season were used for this calculation and for a determination of optimal values of rate of ventilation and supply air temperature.

measurements: one hour average values of indoor and outdoor temperature, waterflows and temperatures differences for radiators, electric energy for the preheating of the supply air, consumption of domestic electricity and hot tap water were to be recorded. Arrangements were made to obtain metorological data from a nearby airport.

Due to the previously noticed large temperature differences between the upper and lower part of the building, it was considered useful to obtain a value of the average indoor temperature for these two parts of the building separately. The estimated variation of indoor temperature between flats belonging to one of the two building parts was estimated to 2 K. It was judged sufficient to determine these two average values with an error of 0.5 K. Therefore, the temperature was measured in 8 flats in each of the two building halves (see App. III).

course of investigation: during the first heating season the measurements were performed as planned. When the water distribution to the heaters was checked, it was found that the radiator valves had been preset to other values than planned due to a misunderstanding of the instructions. This was corrected and during the autumn the temperature of the supply water and the supply air was gradually reduced. Thereby the occupants were given the possibility to adjust to the new indoor climate. Not many complaints from the occupants were received during the first few months of the heating season. When checking data, it was observed that the indoor temperature of some flats was much lower than expected. It was found that the cause of this was that, in these flats, the temperature sensors had been positioned on the exterior wall.

After some unusally cold days an increase of the indoor temperature and of the temperature of the supply water was noticed. When investigating the cause of this, one found out that the manager of the heat plant had received many complaints about too low indoor temperatures during the cold period and therefore had raised the temperature of the supply water on his own initiative. This was accepted for the rest of the heating season.

data treatement: all data from the measurements were used as input to a computerized model of the energy balance of the building and the heating system of the building. This model needed as input, among other things, data on solar radiation. Data of this kind from the nearby meteorological station were used. It was possible to conclude that the measures which had been taken had resulted in a reduction in the energy consumption. The difference in temperature between different flats had decreased substantially.

comments: at several occasions there was a risk that the investigation could be jeopardized by unforeseen events. Due to a continous evaluation of obtained data these accidents could be observed in time and corrected for. The gradual lowering of the temperature probably minimized the number of complaints.

In this investigation the use of a computerized model was justified because of the complexity of the object and the measures taken, even if the cost turned out to be rather high.

CHAPTER II d

Test- reference experiments

Contents

II d Test- reference experiments

- description of the test refence experiment

Like the before- after experiment, the test- reference experiment can be applied to the study of most retrofits. When the test- reference experiment is performed, one must have access to at least two buildings. One of them (the test building) is retrofitted, the other one (the reference building) is not. The energy consumptions of these two buildings are to be compared. It is obvious that, apart from the retrofit, they ought to be as similar as possible in all respects. In practice this will seldom be the case. Therefore one will have to compare the energy consumption before the retrofit (the calibration phase) and after the retrofit (the comparison phase). It is of course also possible to use several test and reference buildings. Exactly how many will be required is determined by the expected magnitude of the retrofit effect (see App. II).

That the buildings should be as "identical" as possible means that they should have the same geometrical properties and be of the same constructional type. Their orientation and the behaviour of their occupants should be the same. Their surroundings and exposure to the outdoor climate should also be similar.

Minor differences between the buildings, like the internal distribution of rooms, can be accepted if a calibration phase is included in the experiment. A similar exposure to the outdoor climate can be achieved if the buildings are situated close to one another. The remaining climatic differences may then be due to, e.g., different shading or different shielding from the wind by the neighbourhood. These microclimatic differences will in general be easier to handle than the climatic differences if the buildings are not situated in the same climatic zone.

The calibration phase serves to determine the difference in energy consumption between the two buildings before the retrofit. This difference should be determined in such a way that the result is statistically significant. If only two buildings are used, their energy consumption must be known for a sufficient number of years to determine the average difference in energy consumption and its scatter. Alternatively one can use a sufficiently large sample of buildings to achieve this result. If one knows the reason for the observed difference of the energy consumption, and one can express this information in a quantitative form, a model describing the energy balance of the buildings can be used. The observed difference in energy consumption must of course be put in relation to the expected retrofit effect (see App. II).

What has been said above about the calibration phase applies also to the following comparison phase. If the test building was not retrofitted, its energy consumption would be that of the reference building minus the observed difference during the calibration phase. Hence, any observed deviation from this value can be attributed to the retrofit. To reduce the effect of a change in the behaviour of the occupants, assuming that such a change will be diminished in time, it is often convenient to include a "running- in and learning" period before the calibration phase, a period in which the occupants are given the possibility to get used to the retrofitted building.

If properly performed, the test reference experiment should have the following advantages:

- independence of the climatic conditions
- independence of the building characteristics
- the observed change in energy consumption depends only on the retrofit (including the reactions of the occupants)
- can sometimes be performed in a single heating season if the scatter of the observed difference in energy consumption of the test and reference buildings is small before the retrofit

- Example 1

type of object: two multi- family residential buildings of the same design, with the same orientation, built in the same year and situated close to one another.

aim of experiment: to determine the effect of the installation of thermostatic radiator valves on the energy consumption

<u>experimental design</u>: a direct comparison of the energy consumption of the two buildings is to be performed

<u>measures taken</u>: no other measures than the retrofitting of the test building were taken

<u>measurements</u>: data on the energy consumption of the two buildings for the five heating seasons preceeding the retrofit were collected. These five heating seasons then define the calibration phase. Data on the energy consumption of the heating season following the retrofit were also collected and this heating season then constitutes the comparison phase. The result of these measurements are given in Table II d-1. To facilitate a comparison the data have been normalized in such a way that the average energy consumption of the reference building during the calibration phase has been set equal to 100. No other measurements than those of the total energy consumption were performed.

<u>course of investigation</u>: all measurements were made a posteriori.

<u>data treatment</u>: from the data of Table II d-1 one noticed that the energy consumption of the reference building was 2 % lower during the comparison phase than during the calibration phase. The corresponding number for the test building was 1.5 %. One therefore concluded that the effect of the retrofit was negative.

<u>comments</u>: one first notes the relatively uniform energy consumption of the reference building during the calibration phase. The spread is very small. The energy consumption of the test building varies more; the spread is four or five times larger than for the nominally identical reference building. The reason for this ought to be investigated. Is it due to change of occupants, have adjustments been made to the heat plant of the test building, or is the heating system of this building not balanced? The average and the spread of the difference in energy consumption between the two buildings during the calibration phase are of the same size, 4.8 and 3.8 respectively. The observed difference during the comparison phase, 4.3, is therefore not statistically significant and no conclusions in either direction can be drawn. One would probably have to include several heating seasons in the comparison phase before any conclusions can be drawn.

TABLE II d-1

Energy consumption of the buildings

Heating season	Reference building	Test building	Difference
1	101.2	90.4	10.8
2	100.3	94.2	6.1
3	99.2	99.9	-0.8
4	99.8	94.7	5.1
5	99.5	96.8	2.7
Average of calibration phase	100.0+-0.7	95.2+-3.1	4.8+-3.8
6 (comparison phase)	98.0	93.7	4.3

- Example 2

type of object:two groups of single and double occupancy flats for old people. The total number of flats is 56. One of the groups consists of 24 flats of a "medium" or "low" insulation level. The other one consists of 32 flats of a "high" or "medium" insulation level. The distance between the two groups of flats is about ten km. All flats form part of two- storey blocks of a heavyweight construction. The installed heating system consists in electric radiant ceiling panels with a thermostatic as well as a time control which can be operated by the occupants. However, only a small fraction of the occupants used the installed heating system as the only means to heat their dwellings. Instead, most occupants used auxiliary electric devices for heating. Some used only devices of this kind. The occupants used only electricity for hot water generation and cooking. All flats are of a similar size and layout. Half of the two- person flats were occupied by only one person.

aim of the experiment: to determine the effect of the insulation level of the flats on the consumption of energy for space heating.

experimental design: to facilitate the analysis of the data the flats were divided into four classes:

1) one person flats from group one, insulation level high
2) " " " " " two " " medium
3) two " " " " one " " medium
4) " " " " " two " " low

By making the appropriate comparisons between the four classes of flats, the effect of the site, of the size of the flat, and of the insulation level on the energy consumption can be determined.

measures taken: as both groups of flats existed when the investigation started, the effect of the retrofit had to be evaluated by a direct comparison as described above, and no additional retrofitting was performed.

measurements: the total electricity consumption of each flat was measured weekly during one year. The indoor air temperature of the living room, bedroom, and kitchen of each flat was recorded every hour, and so was the external air temperature at the site of both groups of buildings. The global solar radiation was also recorded at both sites. In addition to these measurements, data on the external air temperature, sun hours, and wind speed were obtained from a meteorological station situated about fifteen kilometers from both sites.

A survey of the tenants was made. They were asked about how much time they spent at home and what use they made of hot water and electricity for cooking.

course of investigation: the occupants of six flats objected to the installation of sensors in their flats, thus leaving a sample of fifty flats. In some flats there were gaps in the occupancy, change of occupants, and measurement equipment brekdowns. This meant that only for part of the flats there was a continuous time- series of measurements.

data treatment: the time resolution used in the analysis of the data was one week. Even if the measurements went on for one year, only data from weeks belonging to the heating season were used in the analysis. The weekly average of the measured variables was calculated for each class of flats. Due to the incomplete dataset, it was necessary to apply some criteria for the inclusion of data from a certain flat in the calculation of a class average. To include a flat in the analysis it was judged necessary that temperature as well as energy consumption data were available for at least two thirds of the weeks. For the calculation of a weekly average for a class it was required that data from two thirds of the flats belonging to the class were available for the week in question. These demands reduced the number of flats considered in the final analysis to 42, with about ten in each of the four classes. From the above also follows that the number of flats for which a weekly class average was calculated could vary somewhat from one week to another.

If the external temperature or the solar radiation data were missing for a certain period at one of the building sites, an estimate of the missing data was made so that the period could be included in the final analysis. These estimates were based on a linear relation, determined by regression analysis, between, on one hand, the external air temperature at the building site and that at the meteorological station, and, on the other hand, between the observed global solar radiation at the building site and the number of sun hours recorded at the meteorological station. This procedure was judged to be reliable because of the relative vicinity to the meteorological station and the good correlation obtained in the regression analysis.

In the final analysis of the data a linear model was used, taking into account the combined fabric and heat losses (Hloss), the electric energy used for space heating (Hel), the electric energy used for domestic appliances contributing to the heating of the dwelling (Happl), the metabolic heat from the occupants (Hmet), and the contribution to the heating of the dwelling from the solar radiation (Hsol). It was assumed that the combined fabric and heat losses were proportional to the indoor- outdoor temperature difference ΔT, with a proportionality constant CT, or Hloss= CT*ΔT. It was also assumed that the contribution to the heating from solar radiation was proportional to the total global solar radiation Qsol, with a proportionality constant CQ, or Hsol= CQ*Qsol. The model can then be written as:

$$CT^{*}\ \Delta T = Hel + Happl + Hmet + CQ^{*}\ Qsol$$

The entities Hel, Happl and Hmet were calculated as described below. It was observed that, for all classes of flats, the total electric energy consumption decreased linearly with the outdoor air temperature up to a certain temperature. Above this temperature it remained constant, and there was a constant base load of electric consumption, Hbase. This base load was interpreted as the electric energy used by electric appliances.

It was then assumed that the difference between the total consumption of electric energy and this base load, Hbase, constituted the electric energy used for space heating, Hel. From the base load, Hbase, one also estimated the contribution to the heating of the dwelling from the energy used by appliances, Happl. From the survey of the occupants one could estimate that about one third of the energy used for appliances was used for hot water generation, one third for cooking, and one third for lighting and other uses. One also estimated that 30% of the energy used for hot water generation, 75% of the energy used for cooking and all the energy used for other purposes contributed to the heating of the dwelling. One could thus deduce that 68% of the electric energy used by appliances contributed to the heating of the dwelling, and this amount of energy was identified with the term Happl of the model, i.e. Happl= 0.68*Hbase.

From the survey of the occupants one also had information about how much time they spent at home. Assuming an average metabolic heat rate of 80 W the term Hmet of the model could be estimated.

As the entities ΔT and Qsol of the model were known from the measurements, the parameters CT and CQ of the model could be determined by a fit to data by use of regression analysis. This was done separately for each of the four building classes.

Comparing the differences between the values of the parameters CT obtained for the four classes, it was found that these differences agreed reasonably well with the differences between the theoretically estimated U-value*area of the flats. This would then mean that the theoretically higher insulation level had been achieved also in practice (provided of course that the infiltration rate of the four building classes was the same, which was never checked). This was not a trivial finding as the estimated effect of a better insulation would have been much lower if one had compared only the total energy consumption. The reason for this difference in interpretation could be ascribed to a higher average indoor temperature of the better insulated flats, and a possibly more efficient way of taking advantage of the incidental heat gains from solar radiation and energy used by domestic appliances.

It was the conclusion of the experimenters that the theoretically calculated effects of an increased insulation on the thermal losses could be verified. What the effect on the total energy consumption would be in other buildings could not be estimated. For this one needed more information about how the incidental heat gains were used.

comments: one should first note the reduction of the sample size for different reasons. In this case only 75% of the original flats could be used in the final analysis. This is something which often happens in experiments of this kind. The original intention of the experimenters was that each class of flats should be great enough so that the effects of occupancy could be neglected. Now each class finally consisted of only about ten flats, which may be too small a number to neglect the effects of occupancy.

Two parameters were estimated, CT and CQ, in the model, being constants of proportionality of the terms containing respectively the indoor-outdoor temperature difference ΔT, and the total solar radiation Qsol. There is often a strong correlation between the outdoor air temperature and the amount of solar radiation. Estimating the value of these two parameters may therefore be a dangerous procedure, because CT and CQ may not be independent. The model can reproduce the experimental data equally well if the values of CT and CQ are both increased or decreased.

The conclusions drawn by the experimenters rely to some extent on the assumption that the air infiltration was the same for all the four classes of flats. It would probably have been an advantage if this assumption had been checked.

Despite these shortcomings, the experimental design was in this case rather ambitious and reliable, and it is therefore highly probable that the results of the investigation are reliable too.

CHAPTER II e

Simulated occupancy experiments and Movers and stayers

Contents

II e Simulated occupancy experiments and Movers and stayers

- simulated occupancy experiments

The retrofit effect of energy conservation measures has been defined (see App. I) as the change in energy consumption which is imputable strictly to the retrofit. This change is due to the improvement of the building or heating system performance, but it will also, as a second order effect, be influenced by a possible change in the occupants habits in consequence of the retrofit.

As already seen in the previous chapters, the comparison of the energy consumptions in two buildings (test-reference experiments), or in two different heating seasons (before-after experiments), will in general produce a result which differs from the retrofit effect. This difference is in B-A experiments mainly due to variations of the weather from one heating season to another. It is mainly due to occupancy differences in T-R experiments. However, while a fairly accurate correction is possible in B-A experiments, when a relatively small number of meteorological quantities are measured, in T-R experiments such a correction would require the monitoring of a great number of activities performed by the occupants. This kind of approach therefore has to be rejected in many cases because of technical and economic difficulties. A better way of reducing the error in these experiments, (see ch. II d) is to perform a calibration before the measurement campaign, assessing the relevant differences between the occupants of the two buildings.

A good solution is to choose the two buildings in such a way that their energy bills have been the same in the past and there has not been a change in occupancy. A slight variation of occupancy can still occur between the calibration period and the measurement period, and possibly to a certain extent spoil an experiment which is likely to be expensive and time consuming.

To avoid this risk, simulated occupancy can be used in, e.g., T-R experiments. Actually, when the two investigated buildings are both equipped with an apparatus simulating the energy-related activities of the occupants, the "noise", produced by the presence of occupants, of the measurement will be suppressed.

There would also not be any "noise" if the presence of occupants were not simulated at all, but this procedure leads to results that cannot be generalized. Moreover, the utility of the experiment itself will then become disputable since the results could be more easily obtained by means of a good computer model of the building energy balance. On the contrary, simulated occupancy does not eliminate the influence of occupants on energy consumption, but will rather allow its control. The main drawback of this method is that it will not provide any information on human behaviour, but it will rather require such information as input. It will not enable the experimenter to investigate the second order retrofit effect (see ch. II a), unless the simulation can be influenced by some feed-back mechanisms based on physiological indexes, such as illumination, thermal comfort or noise indexes.

This kind of simulation requires that the physiological indexes can be objectively determined and measured, and that the relation between these stimuli and people's reactions can be assessed. This is the weak point of such a procedure, besides its technical feasibility and cost.

Summing up, the use of simulated occupancy in T-R experiments presents the following advantages:

- a reliable separation of the building effect on the consumption of energy from the weather and the occupancy effects
- the repeatability of the experiment
- the easy adjustment of the simulated occupancy if one wants to perform a parametric study of its effect on the consumption of energy
- the easy monitoring of the occupancy, since the equipment for simulation will be electrically driven (see ch. IV d)
- the establishment of "standard occupancy schedules" makes it possible to compare results from different experiments. It must be mentioned that this idea has already been used in cases when the relation between subjective physiological behaviour, and objective physical quantities had to be established, like the "standard eye" in illumination and the "standard ear" used in acoustics.

On the other hand, the disadvantages are the following:

- the loss of information on actual human behaviour, and its variation due to energy conservation measures
- the technical and economic difficulty of constructing simple schedules which do not consist of stereotyped preset trains of activities, but are

dynamic and include a feed-back mechanism simulating physiological stimuli (see ch. IV d)

- the extra cost for the rent or purchase of the dwellings, that cannot be occupied by actual residents
- the extra cost for the purchase of the simulation apparatus.

- movers and stayers

When a study of the energy consumption is performed on a number of single family dwellings, there will often be some houses that have changed ownership during the measurement period. Data from these houses are generally excluded from the collection of data before the final analysis of data is performed.

A method has been advocated how to retain these data so that they can be used to shed light on the influence of the occupants on the total energy consumption of the house (Sonderegger 1977). One then assumes that the variation of energy consumption between nominally identical houses can be ascribed to one of two factors:

1) variation is due to occupant behaviour
2) variation is due to differences between nominally identical buildings (e.g. differences due to building damage or to bad workmanship during the erection of the building).

The houses are divided into two categories, one consisting of houses where a change of ownership has occured and the other of houses where it has not. The latter category serves as a control group. The energy consumption of one heating season is then compared to the energy consumption of a second one.

If energy consumption is mainly determined by the properties of the building structure, the difference in energy consumption would be expected to be the same for the two categories of houses. If energy consumption is mainly due to the behaviour of the occupants, one would expect a smaller change in houses belonging to the first category than to the second one. In reality one has to make corrections for differences in the exterior climate between the two heating seasons.

If this method is to be applied, the only required data are the total energy consumption of two heating seasons, and data about where and when there has been a change of occupants. When this method was first applied (Sonderegger 1977) it was found that about two thirds of the variation in energy consumption between nominally identical houses could be ascribed to the behaviour of the occupants.

When this method was applied to 10 years of collected data from a set of nominally identical Swedish SFD (Lundström 1980), no correlation was found between the energy consumption of two consecutive years if there had been a change in ownership. There was, however, a very good correlation for houses having the same occupants.

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APPENDIX II

The probability of a retrofit effect

Contents

App. II The probability of a retrofit effect

- general introduction

The aim of the experiments we are dealing with is to establish the average effects of energy conservation measures (retrofits) in a population of buildings. The first source of error is the design of the experiment itself. Whenever information, due to only a small number of variables being measured (for example, the inside-outside temperature difference and the related energy consumption over a period), does not allow the experimenter to relate deterministically the effect of the retrofit to the building energy budget, the results should be examined with the help of statistical techniques (Everett, 1981, SCBR, 1981, Sonderegger, 1978). This approach is particularly suitable in a test- reference (T-R) experiment, if a large sample of buildings can be used, but could also be used in before- after (B-A) experiments whenever the measurement campaign extends over several heating seasons. In these cases it would be advantageous if the relation between the number of experimental units and the precision of the estimated retrofit effect was known. This kind of analysis may lead to the conclusion that the estimate will be affected by such large errors that no conclusions can be drawn. In other cases it may lead to the conclusion that an adequate precision can be reached with a smaller size of the sample.

When applying the statistical techniques that will be described below, the underlying assumptions are

1) all systematic errors can be identified and removed when choosing the the experimental units
2) the systematic error may be eliminated when calculating the effects of retrofits. In this case one can make use of the statistical theory dealing with random sampling and evaluate the problem by means of the "t-test" (see e.g. Cox 1958, or Kendall and Stuart 1963)

For the estimate of the difference in energy consumption between two groups of retrofitted buildings (GR8) and non retrofitted buildings (GNRB), define:
$\bar{x}_1$ = average energy consumption in GNRB
$\bar{x}_2$ = average energy consumption in GRB

n_1 = number of buildings in GNRB
n_2 = number of buildings in GRB

We also need a measure of the variation which affects the error of the average retrofit effect R in the population of buildings studied. This is the so called residual standard deviation s.

From previous experience the residual standard deviation for occupancy, s_o, (T-R experiments) is known to range from 20% to 30% of the total building energy consumption (Everett 1981, Sonderegger 1978), while the residual standard deviation for the weather, based on the seasonal degree-days variation, s_w, (B-A experiments) ranges from 6% to 10%.

However, when the two groups of buildings are chosen in such a way that they have almost identical energy consumptions before the retrofit, the residual standard deviation, due only to variations in occupancy in time and unrelated to the retrofit itself, will generally be around 10% (Sonderegger 1978).
The estimated retrofit effect $\hat{R}$ is defined as:

$$\hat{R} = \bar{x}_1 - \bar{x}_2 \qquad \text{(App II - 1)}$$

and the estimated relative retrofit effect $\hat{r}$ is defined as:

$$\hat{r} = 2(\bar{x}_1 - \bar{x}_2)/(\bar{x}_1 + \bar{x}_2) \qquad \text{(App II - 2)}$$

Assuming that s_1 and s_2 (standard deviations of x_1 and x_2 respectively) are both close to s, the standard error s_R in the estimate of R is given by:

$$s_R = s\sqrt{1/n_1 + 1/n_2} \qquad \text{(App II - 3)}$$

and the standard error s in the estimate of r is given by:

$$s_r = s/(\bar{x}_1 + \bar{x}_2) * 2 * \sqrt{1/n_1 + 1/n_2} \qquad \text{(App II - 4)}$$

For the case when the two sets contain an equal number of units n, the eq. App II -3 and App II -4 become:

$$s_r = 2s(2/n)^{1/2} \sqrt{(x_1 + x_2)} \qquad \text{(App II - 5)}$$

$$s_R = s(2/n)^{1/2} \qquad \text{(App II - 6)}$$

Here, then, two different evaluations can be made:

1) determine from the measurements the confidence interval which for a selected level of probability (confidence) covers or contains the average retrofit effect.

2) determine, before the experiments are performed, for different probability levels, the required sample size for some definite length of the confidence interval.

- determination of the limits of the retrofit effect

For qualitative evaluations, it can for large samples, be said that;

a) when the estimated retrofit effect is smaller than 1.65 times the standard error, s_r, there is no evidence that there is any true difference at all.
b) when the estimated retrofit effect is about twice its standard error, s_r, there is good evidence (probability level above 95 %) that the difference is not zero.
c) when the estimated retrofit effect, s_r is more than 2.6 times its standard error, there is a strong evidence (probability level above 99 %) that the true difference is not zero.

For a more significant quantitative evaluation, it can be said that the relative retrofit effect, r, is situated, at a probability level p, in the interval (so called confidence interval)

$$(\hat{r} - t(p,n)* s_r, \hat{r} + t(p,n)* s_r) \quad \text{(App II - 7)}$$

where

t(p,n) is a function of p and n given in Table App II -1

The width of the confidence interval w will be given by:

$$w = 2* t(p,n)* s_r \quad \text{(App II - 8)}$$

Example 1. Let us consider two groups of 10 buildings in a T-R experiment. The GNRB gives $\bar{x}_1$=80 GJ/yr, while the GRB gives $\bar{x}_2$=65 GJ/yr. Then, assuming s_o=20%, we have: $s_r = 0.2\sqrt{2/10}$ =0.089 =8.9% and $\hat{r}$ = 2*(80-65)/(80+65) = 0.207 = 20.7% which gives $\hat{r}/s_r$= 0.207/0.089= 2.32.

As a qualitative evaluation, we are able to say that there is good evidence that there is a difference between the two groups. If we wish a quantitative evaluation with a 95% probability level, we will find that t(0.95,10)= 2.26. Then r lies between 0.207- 0.089*2.26 and 0.207+ 0.089*2.26, i.e., between 0.6% and 40.8%. Similarly, with a probability of 2/3 (67%), the true r lies between 0.207- 0.089x1.03 and 0.207+ 0.089x1.03, i.e., between 11.5% and 29.9%.

- determination of the sample size

In this case the problem is that of determining an appropriate sample size for the experiment, leading to a preset length of the confidence interval. From the eq. App II-6 and App II-8, we derive the following implicit relation:

$n = 2*(2*s*t(p,n)/w)^2$

the solution of which, for p = 67, 75, 90, 95%, is given in graphic form as a function of 2s/w in fig. App. II -1.

Example 2. Suppose we are planning a T-R experiment assuming, as before, that s_o= 20%. We want to achieve a result which deviates at most 5% from the estimated r with a probability of 2/3.

We find 2s/w = 4, and from fig. App II - 1 we get n = 31. If this number is considered too high and, because the expected retrofit effect is fairly large, we can accept a larger confidence interval (for example, w = 20%), we will find that 2s/w=2 and therefore n lies between 8 and 9.

Similarly, if the two groups had been checked in advance and their energy consumption were very much the same, a lower standard deviation can be expected, for instance 10%. Accepting, as above, w=20% at a probability of 2/3, we would in this case find 2s/w=1 and n=3.

Example 3. For a 8-A experiment, assuming s_w = 7.5%, we would need about 5 to 6 6 heating seasons in each group in order to get a +-5% confidence interval with a probability of 2/3, and just 2 if a +-10% interval could be accepted.

As a final comment we want to point out that there are no "recommended" values of w and p. However, it appears that the confidence level p should not be chosen below 2/3, while the length of the confidence interval w should be fixed, taking into consideration the expected result of the measurement, e.g., the smaller the expected retrofit effect, the smaller w should be taken.

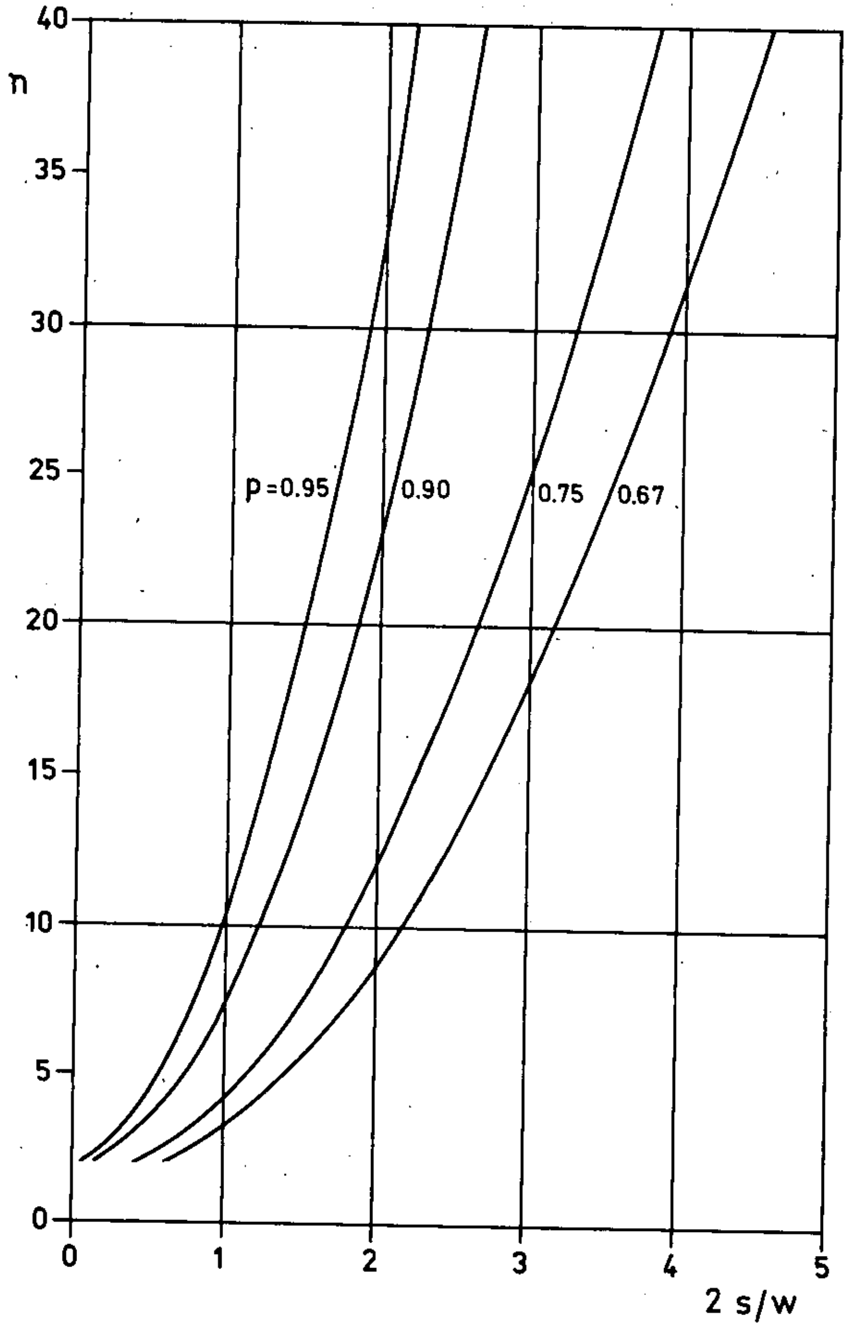

Fig. App II-1. Relation between sample size n and 2s/w, where s is the standard deviation and w is the width of the confidence interval, with the confidence level, p, as a parameter.

TABLE App II - 1

Values of t for different probability levels p and sample size n.

n=	2	3	4	5	6	7	8	9	10	15	20	30	40	oo
p=														
95	12.71	4.30	3.18	2.78	2.57	2.45	2.37	2.31	2.26	2.15	2.09	2.05	2.02	1.96
90	6.31	2.92	2.35	2.13	2.01	1.94	1.90	1.86	1.83	1.76	1.73	1.70	1.69	1.65
75	2.52	1.64	1.44	1.36	1.32	1.29	1.27	1.25	1.24	1.21	1.20	1.18	1.18	1.16
67	1.77	1.28	1.16	1.11	1.08	1.06	1.04	1.04	1.03	1.01	1.00	0.99	0.98	0.97
50	1.00	0.82	0.77	0.74	0.73	0.72	0.71	0.71	0.70	0.69	0.69	0.68	0.68	0.67

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PART III

MEASUREMENTS ON BUILDINGS AND ENVIRONMENT

Contents

Keywords

accuracy
archives
audit
data handling
diary
direct measurements
group comparison
interview
maintenance of measurement system
malfunction of equipment
measurement system
model
monitoring
observation
parameter
precision
quality of craftmanship
reliability
survey techniques
time resolution
variable

CHAPTER III a

General introduction and methods of measurement

Contents

IIIa General introduction and methods of measurement

-general introduction

Part III will deal with instruments, methods, and principles of measurement that can be used when evaluating the effect of retrofitting a residential building. A great number of different methods and techniques of measurement traditionally used in different scientific disciplines can then be applied. If the investigation includes the monitoring of a residential building, most of the necessary measurements will consist in a direct measurement of physical quantities.

Measurements of this kind will here be referred to as direct measurements.This topic is dealt with in ch. III b through III f,including the measurement of

- outdoor climate
- indoor climate
- thermal performance of buildings
- infiltration
- energy conversion and flow in heating systems

The measurement of household energy and hot tap water, how to complement direct measurements by information on the behaviour of the occupants when, monitoring a residential building, and performing simulation studies is dealt with in Part IV. Part III ends with ch. III g dealing with data acquisition systems and installation rules.

If an investigation involves a large number of buildings it will not be practical- or possible- to monitor all of them. Instead, the direct measurements will consist only of the measurement of the total energy consumption. The evaluation will then be performed using group comparison. To generalize the results of the energy measurements, one will in general want to classify the studied residential buildings according to some simple building characteristics.Background data for this classification must then be collected.

Several methods can be used for the collection of data on the behaviour of occupants and data on statistically meaningful building characteristics. These methods include observations, survey techniques and use of archive records. Under other circumstances it may be advantageous to use experimental methods. This may be the case, e.g., if one wants to study the behaviour of a building, simulating the influence by the occupants, instead of performing experiments with occupants in the building (see ch. II e and IV d).

If one wants to use existing data on behaviour and attitudes of occupants in residential buildings, and place any reliance on information of this kind, one should be able to judge the adequacy of the research behind it by evaluating the reliability of the research design, and by judging its applicability to the issues being confronted. In principle there are no differences between the demands on the methodology used when collecting data of this kind and the demands when performing, e.g., physical measurements. The terminology used to describe the procedures is the same. It is the data gathering techniques that are different. The usual demand for objectivity, reproducibility and validity in a scientific investigation must always be fulfilled. Of these demands it is often the one for validity that is most difficult to fulfil. Introductory articles on how to obtain and use behavioural information can be found in Lang-Burnette- Moleski- Vachon (1974). The use of observational techniques and data gathering from archives and records is described in Webb- Campbell- Schwartz-Sechrest (1971).

- relation between measurements and model

When the aim and design of the experiment have been decided and a model describing the energy flows of the building has been chosen, one has to determine what measurements are to be performed.

If the model describes the energy balance of the whole building or a component of the building, it will contain terms, each representing a particular energy flow, the sum of which is zero. Examples of such energy flows are given in ch. II a.

Some terms will represent a directly measured energy variable like the heat output from the heating system or the electric household appliances. Other terms will contain one or more building parameters (physical properties of the building) along with variables. An example of this is a term representing the *conductive heat flow through a building component*, *being the product of the* transmittance (the "U- value") of the component (a parameter), and the temperature difference across the component (a variable).

It is then clear that the determination of the energy flows will involve the measurement of directly measurable energy flows, other variables and parameters.

Assuming that the values of all parameters are known, a straightforward measurement of an energy flow can be performed in two ways:

1) a measurement of one energy variable only
2) a simultaneous measurement of several variables

1) In many cases it is possible to use a sensor which can directly measure the energy variable. An example is a Watt hour meter recording the electric consumption by electric domestic appliances.

2) Sometimes the determination of an energy flow has to be performed by a simultaneous measurement of more than one variable and a calculation of the energy flow from the value of these variables. An example is the determination of the net energy output by a water heating system. The water flow and the temperature difference between the feed and the return water can be measured separately. From this the energy flow can be calculated.

If an energy flow term contains parameters of the model as well as variables, the variables will in most cases have to be measured directly. These variables can be, e.g., the outdoor air temperature, the amount of solar radiation, the wind speed, the air pressure difference across the building envelope, indoor air and surface temperatures, the temperature of the hot tap water, the rate of air exchange, the amount of cold tap water consumed, the degree of shielding of windows etc.

A numerical value will also have to be assigned to the parameters of the model. *This can be done in various ways:*

1) the parameter is already known
2) the parameter can be directly measured
3) the parameter is determined by a fit to data

1) The value of the parameter can be assumed to be known from previous experience, from laboratory measurements, from construction data of the building etc. Some examples are: the constant term of a degree- day model, representing the "free heat", can be assumed to be known from previous measurements on similar buildings. The U- value of windows can be assumed to be known from laboratory experiments. The rate of air exchange produced by a mechanical ventilation system or the window area can be inferred from construction data.

2) The parameter can be determined with a single or a few measurements. Some examples are: the U- value of the exterior walls can be determined using a heat flow meter. The exterior wall area can be determined with a single measurement. The average heat capacity of the building can be determined by letting the internal temperature drop when the heating system is shut off.

3) The parameter can be determined by a fit to experimental data once all measurements have been performed. Some examples are: the slope of the internal- external temperature difference term in a degree- day model, representing the average U- value of the building envelope. When the infiltration rate has been assumed to be proportional to the wind speed, the proportionality constant can be determined by a fit to experimental data if the U-value of the external wall is known. The case when the amount of solar radiation through the windows has been assumed proportional to the solar radiation, incident on the exterior wall, can be treated in an analogous way.

What has been said above about parameters can in some cases apply also to variables. Sometimes the temperature of the ground or the internal air temperature can be assumed to be constants and treated as parameters.

The choice of the model will also have implications for the measurements other than those mentioned above like:

1) the time resolution of the measurements
2) the resolution and precision of the measurements
3) the accuracy of measured entities
4) the possibility of comparison with other experiments
5) the storage of data

1) The model will determine the time- resolution of the measurements. This may vary from one hour or less for dynamic models up to one month or one heating season for a degree- day model. All variables should, if possible, be recorded

with the same time- resolution. It is, however, necessary to perform the measurements for rapidly fluctuating quantities more frequently than indicated by the time- resolution of the model. But it should also in this case suffice to store data averaged over a time given by the time resolution of the model.

2) The measurement precision and resolution should be consistent with the model and the model should of course include only factors that can be estimated. An example: the model contains the heat flow across the external walls and also that through the ceiling. If both the U- value of the exterior walls and that of the ceiling are to be determined from the data, it will be necessary to measure the temperature difference across the exterior wall as well as across the ceiling. If these two temperature differences are strongly correlated, it will not be possible to estimate the difference between the two U- values. This will then necessitate a revision of the model.

If one of the energy flow terms of the model is associated with a large error, this will have implications for the demand of resolution and precision of the measurement of variables and parameters contained in other terms. It will not make any sense to require a too good accuracy or precision of these measurements if the error of model calculations is anyway determined by the term with the largest error. This error must in any case not exceed the required maximal error of the model.

3) The accuracy of the measurements of the variables has to be determined. Many models contain the "indoor- outdoor temperature difference". But the indoor temperature may vary from place to place inside the building. The air temperature in a room may differ by several degrees between two points in the room. The temperature of the building masonry is different from that of the indoor air and does not have the same time constant. It is therefore important how, and where, in the building the "indoor temperature" is measured if the wanted maximal error of the model is not to be exceeded.

4) If the results of the measurements or the results of the experiment are to be compared to results from experiments in other buildings, it is important that the variables have been measured in the same manner. This demand can never be completely fulfilled in practice, as no two buildings are identical. However, one should always try to perform the measurements in an identical way, at least if the same model is going to be used

5) The design of the experiment and the model will determine how the data are to be analyzed. It is then an advantage if the results from the measurements are stored in such a way that this task is facilitated. It is also an advantage if already before the measurements start one knows how the results of the experiment are going to be presented. Data can then be stored in such a way that the amount of work is reduced.

What has been said above about measurements should not be regarded as a one- stage process. There should be a feed- back to the previous stage of design of the experiment and choice of the model. Some measurements which have been planned may turn out to be too expensive. If it is not possible to perform measurements with an accuracy and a precision demanded by the model, this will have to be changed.

- measurement methods

i) direct measurements

If applicable, direct measurement is generally the method to be preferred. It is often more objective than the other techniques discussed below. Even if error sources are inherent also in this method, the resulting errors are often small compared to errors when another data gathering technique is used.

Using direct measurements it will be possible to achieve a break-down of the end use of energy in a residential building. Measurements of this kind can also be performed with a very small resolution in time, e.g., one-hour averages can be recorded.

The maximal error that can be allowed in the measurement of variables and parameters will in general be given by the demands on the model, which in its turn are determined by the aim of the investigation. What is interesting is then not the accuracy or resolution of a single sensor, but the resulting error of the sensor, data acquisition system, data storage, and data handling procedure. Before being implemented every data acquisition system should be evaluated to ascertain that it fulfils the following requirements (see also ch. III g):

1) the system accuracy is sufficient to meet the aim of the investigation and

more specifically the demands of the model

2) the reliability of the system does not lead to unacceptable loss of data
3) there are no unnecessary processing of inordinately large amounts of data
4) the system is maintainable by the available staff
5) the complexity of the system is compatible with the training and experience of the staff
6) the time schedule for the installation, debugging,calibration and processing of the data is realistic
7) the important variables being monitored are easily verifiable in the field
8) the redundancy of the system is sufficient for the purpose of the experiment

Other important questions than technical ones also have to be considered. These have to do with the interaction between the occupants and the measurement system. Some examples are: what are the relations with the landlord, occupants and the caretaker of the residential building? Will the sensors be disturbed by the occupants? Can the caretaker be asked to survey the measurement system and report malfunctions? Can the caretaker or the occupants be instructed not to change the function of any component of the building that is being studied?

The answer to these and other questions have to be found before the experiment starts. It will give the monitoring crew the necessary information for the choice of the monitoring equipment and the set up of the measurements.

ii) observations

Observational methods have traditionally been used to observe the behaviour of the occupant in social studies. Of more interest here are observations related to the energy consumption. An example is an energy audit performed in order to qualitatively assess the energy status of a building using, e.g., thermographic methods to observe surface temperature differences on a wall. Another example is the observation of the quality of craftmanship when a retrofit is implemented. This information may be useful to explain disagreement between the calculated and the actual energy saving. Another example is counting the number of open windows of a residential building in order to relate it to the exterior or the interior air temperature. Only little effort has so far been spent in this direction.

From these examples it is clear that observations are not always of a qualitative nature. They can sometimes be quantified. Observation is therefore an alternative to direct measurements especially if a continuous monitoring is not necessary.

A drawback of observation is that it is often an expensive and time-consuming method. If the observation involves observing an occupant, the interaction between the observer and the occupant observed is often uncontrollable. It is difficult to know to what extent the presence of the observer influences the behaviour of the occupant.

Observations are more reliable than survey techniques in gathering information about the occupant's actual behaviour. Observations give the possibility of recording and measuring the occupant's behaviour in his usual environment.

iii) survey techniques

Survey techniques include the use of interviews, diaries and questionnaires. Any of these can be used as an instrument to obtain information about the attitudes, behaviour and habits of the occupant related to the energy consumption. Data on, e.g., the occupant's use of household equipment, frequency of taking baths, or window opening habits are often not very reliable due to unreliable estimates by the occupant of his own habits and behaviour. Using these methods it might be possible to obtain more reliable information from the occupant about his habits of dressing at home (see chapter I c).

The interview is a quick way of gathering information. It is flexible and can be carried out at the occupant's home or by telephone. Interviews by telephone have the advantage that the respondent can tell about his actual behaviour just before the interview. He does not have to remember. Compared to many other techniques it is possible in an interview to maintain a better control of the sample and less effort on the part of the respondent is required.

Questions can be closed or open. In closed questions the occupant has to choose between a number of categories. In open questions the occupant is allowed to elaborate upon his response. In this case the interviewer can give additional questions to clarify the response of the occupant. The skilled interviewer can estimate the validity of the answer and observe how the information is given.

The interviewer's task is not only to present and record questions, but also to elicit accurate and unbiased information. To do this he has to establish contact with the occupant, be personable and demonstate an appropriate level of interest. He must lead the interview and not let it digress into irrelevant discussions.

An alternative to interviews is to let the occupant keep a diary. He is then instructed to write down when and where he performs some specified activities. This method can give accurate answers to questions about the behaviour and habits of the occupant. The drawback of this method is that keeping a diary can get rather boring after a while. The occupant should not be asked to perform this task over a prolonged period of time. This method has often been used in time-budget studies (see e.g. Szalai 1972). A discussion of the advantages and drawbacks of the use of diaries in energy-related studies can be found in Walker-Stafford-Hildon (1982).

Using questionnaires is an inexpensive method which enables the researcher to obtain information from a large number of people. Is is less time-consuming to administer a questionnarire than to conduct an interview. When a questionnaire is used, the situation is more uniform. The information can be coded and permits comparisons between individuals. The respondent can be given the possibility of remaining anonymous.

Questionnaires must contain specific instructions on how the form is to be used and how the questions are to be answered. The layout should be clear and legible. The questions have to be as unambiguous as possible, stated in simple terms. Each question should be clear and readily understood by all respondents. All available alternatives of answer should be presented. Wordings which are emotionally loaded or leading should be avoided. Questions should not be grouped so that a tendency to respond in a particular way is developed. The question should be used to communicate, not educate.

There exist ready-made sets of questions intended to cover a large set of possible purposes of investigations of this kind. An example of questions asked in a national survey on household activities including also questions relevant to the energy consumption in domestic dwellings can be found in Newman and Day (1975).

In any case, survey techniques should not be used without consulting experts.

iv) use of archives

Data collection from archives include, e.g., the collection of information on the energy consumption of a residential building from the sales records of an oil distribution firm. It can also include the collection of data on the age, size, and other building characteristics from an official estate office or from the records of a real estate agent.

Compared to survey techniques this method has the advantage of nonreactivity. Even if there may be substantial errors in the material, it is unusual to find masking (e.g. introduction of false records) of data because the producer of the data knows that his records will be studied.

There are two major sources of bias in archival records - selective deposit and selective survival. Selective deposit here refers to e.g. the fact that the record- keeper may choose between different ways of recording or presenting the data. Data on a residential building taken from a municipal tax record may also be erroneous simply because the owner of the building has given false information to the tax office.

Selective survival is usually a problem associated with old records. Sometimes official records are cleansed from "unnecessary" information. Some data will be kept, some will be thrown away. This may lead to the effect that the remaining data are no longer representative of the original population.

v) laboratory comfort measurements

An example of experimental methods is the use of psycho- physical laboratory techniques to study the comfort of an occupant for different indoor temperatures.

Experimental methods have for many years been used in psycho- physics to determine the human level of comfort when exposed to different combinations of air temperature and heat radiation and sometimes also humidity and air velocity, given the clothing and the activity. The optimal level of comfort when varying indoor climate variables mentioned above is well-known under certain circumstances (see chapter I c).

This can be used to predict the energy used when the occupant is performing certain activities. Assume that the occupant is resting in an indoor environment of optimal thermal comfort. If the indoor air temperature starts rising, he will try to lower it when it has reached the upper limit of the temperature interval where he feels comfortable. He will try to restore the temperature to its previous level. Whether this is to be done by shielding from solar radiation, opening a window or some other activity will depend upon the circumstances and will in general not be known. However, a lower limit for the change of the energy balance caused by this activity is given by the difference in heat content of the air and this can be calculated. It will only be a lower limit because if the activity involves airing out over a prolonged period the amount of energy consumed will be larger.

The operation of shutters and blinds can also to some extent be predicted using a similar method. Suppose windows are covered to shield from solar radiation. If the indoor illuminance falls below an acceptable level blinds or curtains will be operated upon by the occupant to allow an increased penetration of light from the outside. However, in this case the occupant may choose to switch on the lighting instead of operating the blinds.

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CHAPTER III b

Outdoor climate measurements

Contents

III b Outdoor climate measurements

- general introduction

Knowledge of the outdoor climate is of primary importance to establish the energy budget of buildings. A description of how meteorological factors affect energy consumptions of buildings is given in ch. I b.

The measurement of outdoor climate is an important task in many different fields of science and applied science. However, all factors are not equally important in each of these fields. Since the major meteorological stations are used as a support to air navigation, measurements performed at these stations will mainly yield data useful to air navigation. As a consequence, it will not always be possible to find, among the data recorded at meteorological stations, the data which can be used to assess the energy balance of buildings, and vice-versa.

Furthermore, the weather at the meteorological stations will generally be different from that at the building site. These data are not always available in such a form that they can be used for experiments on buildings. For these reasons it is sometimes advisable to place a station for meteorological measurements close to the building.

Recommendations for the correct measurement of weather parameters have been given by the WMO (World Meteorological Organization) 1971. It will not always be possible to meet these recommendations at the building site. When, on the other hand, data from a nearby meteorological station are used, an important question is how to relate them to the climate at the building site. Usually the building forms part of an urban environment; the microclimate can then be strongly affected by the environment. In this case the data have to be corrected by means of appropriate algorithms when extrapolating from the meteorological station to the building site. Since this procedure is quite complex, an expert should always be consulted.

Teletransmitting devices are particularly recommended for outdoor climate measurements. The measurements of the following meteorological factors will be discussed in this chapter:

- solar and atmospheric radiation
- wind
- air temperature
- air humidity
- precipitation

- measurement of solar and atmospheric radiation

Almost neglected for a long time, solar and terrestrial radiation is now taken into greater account in energy conscious building design. The request for more wide-spread, accurate, and detailed measurements has simultaneously increased. Many texts (e.g., Duffie and Beckman 1974, Kreider and Kreith 1977, 8alcomb 1980) have recently been published on solar energy, most of them related to its technological use. They usually contain some information about the physics of solar radiation and the angular relations which provide the sun position on the sky vault.

Detailed information about solar radiation measurements can be found in other more specific texts (e.g. Coulson 1975, Kondratijev 1969 and IEA 1978). We refer to these texts, and to the instruments instructions for further and more detailed information.

According to the form it assumes when reaching the Earth, solar radiation can be divided into:

i) direct solar radiation
ii) global radiation
iii) diffuse solar radiation
iv) reflected solar radiation

When no instruments are available for solar radiation measurements, some rough information can be obtained by using records of

v) sunshine duration

In this case supplementary information will be given by recording

vi) cloudiness

We further have to consider that part of the Earth radiative balance for which the Earth itself is directly responsible, called

vii) atmospheric radiation

Finally, a description will be given of instruments measuring the radiation

balance of the Earth over the whole spectrum, also called
viii) total radiation

In experiments on buildings the measurement of global horizontal solar radiation is often sufficient, but sometimes the global solar radiation on facades turns out to be more conventient. Detailed experiments will sometimes need more than one vertical instrument, placed in front of and behind the window panes. Sunshine duration and cloudiness records should be avoided. For special scientific purposes the measurement of atmospheric or total radiation can provide new and interesting data.

Many of the instruments for measurement of solar and atmospheric radiation are very fragile. To avoid any measurement errors, the instructions of the manafacturer regarding calibration, positioning, shielding, mounting, and maintenance must be rigorously followed. In some cases calibration and maintenance must be performed very frequently.

Care must be taken in the treatment of solar and atmospheric radiation data. Since solar radiation (especially its direct component) is a repidly varying physical quantity, an integrator, sampling data at least every 5 minutes, will have to be used whatever the time resolution of the experimental apparatus. Usually such integrators are provided directly by the manufacturers of radiation instruments. Sunshine duration and cloudiness records require theoretical elaboration in order to provide estimates of global solar radiation. Atmospheric radiation is a rather slowly varying quantity. Hourly sampling can be sufficient.

i) Direct solar radiation

Direct solar radiation is the energy flux coming directly from the solar disk falling on a unit surface per unit time. For the measurement of direct normal solar radiation Pyrheliometers are used, generally based on the thermoelectric Seebeck effect. The WMO has classified pyrheliometers (PYRH) according to sensitivity, stability, temperature dependence, spectral selectivity and time constant.

The sensitive element of the Eppley Normal Incidence Pyrheliometer, NIP (Eppley lab., 1975) is a wire wound plated (copper- constantan) multijunction thermopile, provided with a temperature compensating circuit. The thermopile is mounted at the base of a brass tube, the aperture of which subtends an angle of

5.7^o. The signal of the NIP is suitable for remote recording and the case is weatherproofed for continuous operation at exposed locations. In this case the instrument has to be attached to an electrically driven tracking device.

The Linke-Feussner Pyrheliometer (Kipp and zonen Actinometer) uses a Moll thermopile consisting of 40 manganin- constantan thermocouples arranged in a circle of 1 cm diameter. The thermocouples are arranged in two opposite arrays, one exposed to the sun and the other shaded, in order to compensate for temperature fluctuations. The angle aperture of its collimator is 10.2^o, and the maximal response time is 8-10 seconds.

Pyrheliometers which are normally used as operational instruments are not designed to be absolute instruments, and they require calibration against standard instruments in the case absolute values are to be determined through their indications. The primary standard is the Ångström PYRH. Once a secondary instrument has been calibrated against it (this operation is usually accomplished by the manafacturer), it can be used to calibrate an operational instrument. The comparison should be made under clear and stable sky conditions and the two instruments should be very close to each other. For every calibration many (at least 10) comparisons should be made. For an instrument working continuously this calibration should be repeated several times a year.

The first step in setting a tracker is the choice of the location. A site, free from shadows, should be chosen to insure that the tracker will be free to rotate 360^o. There are four settings which have to be considered to insure proper tracking of the sun:

- North to South
- Latitude
- Declination
- Time of the day

ii) Global solar radiation

Short-wave solar radiation is composed of the direct component of sunlight and the diffuse component of skylight. When measured together, the value is referred to as the global radiation. The other short-wave component of the radiation budget is that reflected from natural surfaces. The wave-length of these components is usually identified with the interval 0.3-3 micrometers.

The instrument for the measurement of global solar radiation is called pyranometer (PYR); the sensor itself is usually a thermoelectric generator; less precise sensors, based on photovoltaic cells, are also available at lower prices. All these instruments are meant to be used on a horizontal plane. All attempts to use them at different inclinations (e.g. vertically), without a previous specific calibration, will lead to large errors.

The WMO (1971) has given a classification of PYR according to sensitivity, stability, temperature dependence, spectral selectivity, time constant, cosine response and azimuth response.

The Kipp and zonen (called solarimeter by its manufacturer) PYR is widely used in Europe. It uses, as a transducer a Moll thermopile; for protection against atmospheric influences this thermopile is mounted under two glass domes with an effective transmission range of 0.3 to 2.5 µm. In order to achieve perfect stability regardless of temperature changes of the outer dome, a second glass hemisphere which blocks the radiation exchange between the thermopile and the outer dome is incorporated within the outer dome. A white screen prevents the mounting from being heated by radiation.

The Eppley PSP PYR comprises a circular multi-function Eppley thermopile of the wire- wound type. The instrument is supplied with a pair of removable precision ground and polished hemispheres of Schott optical WG7 glass, which can be removed or substituted by other Schott glasses and with a spirit level and a desiccator. The WG6 clear glass is transparent from a 0.285 to 2.800 µm. For solar UV measurements, quartz hemispheres are available.

The detector in the Eppley BW PYR is a differential thermopile with the hot- junction receivers blackened and the cold- junction receivers whitened. The element is of radial wirewound - plated construction. Temperature compensation is provided by a built in thermistor circuit. A precision ground optical glass hemisphere of Schott glass WG295 uniformly transmits energy from 0.285 to 2.800 µm. This hemispherical envelope seals the PYR from the weather, but is readily removable for instrument repair. Models designed now can be used with any tilt and orientation angle without any effect on sensitivity.

Pyranometers based on Photovoltaic cells make use of silicon photovoltaic cells. They have some advantages against the previously described pyranometers: the low cost, simplicity, the almost instantaneous response, the high current output, the direct proportionality between current and radiation and the stability with respect to time and weather.

The principal disadvantage of these instruments is, however, the low accuracy, due to the selective response of the cells to incident solar radiation. Their sensitivity is restricted to wavelengths from 0.4 to 1.1 micrometers. Therefore, due to the variability of the solar radiation spectrum, the calibration is not very reliable, and it can lead to an error of perhaps 2%. Another source of inaccuracy is the deviation from the cosine law, (Coulson, op. at., p. 121-124) which, at an angle of incidence of 60^{o} is already 20%, and reaches 50% at 80^{o}; this source of error is however strongly reduced by mounting the cell below a plastic diffuser.

PYR are generally calibrated by exposure in an integrating hemisphere (artificial sky) with a diffuse radiation of approximately 700 W/m^2. In routine operation in the field, there are two ways PYR's can be checked for constancy of sensitivity. The first is to preserve a similar (calibrated) pyranometer for this purpose and occasionally (once a year) compare it with the field instruments, ideally on clear days. The second way requires that a well calibrated pyrheliometer is available: direct solar radiation I_b is measured by the pyrheliometer and simultaneously the decrease ΔV of the signal from the pyranometer, when shaded from direct radiation, is measured. Hence, the calibration constant k is given by the relation $k = \Delta V / I_b * \cos(z)$, where z is the zenith angle of the sun.

The site for a PYR should be free from any significant obstructions above the plane of the sensing element, free from shadows, and not be close to any object reflecting sunlight onto it. A flat roof is generally the best location.

There are two main requirements for the operation of a PYR

- periodic verification of PYR calibration
- application of corrections, when horizon obstruction has to be considered

The procedure to make these corrections consists in isolating the diffuse radiation (by measurement or estimation), correcting it and then adjusting the total short-wave global radiation accordingly. In general, radiation coming from angles less then 50. above the horizon will give a negligible contribution to the total.

iii) diffuse solar radiation

Diffuse solar radiation is caused by aerosol and molecular scattering in the atmosphere, and it reaches the ground from all directions of the sky vault. By preventing direct solar radiation from reaching a pyranometer, one can measure the diffuse component. The shading can be done in a very simple way, by means of a band stand, intercepting the sun beam. Of course, the measurement must be corrected for the portion of sky screened by the band. The problem of correcting the pyranometer data should be approached both theoretically and experimentally. The fraction of diffuse radiation shaded by the shadow band can be calculated theoretically (see IEA, op. cit.).

iv) reflected solar radiation

The value of the reflected solar radiation (see ch. Ib) depends on the view factor between the ground and the surface, and on the shortwave reflectivity of the ground surface (often referred to as albedo).

In order to measure the shortwave solar radiation balance over a surface, an instrument called albedometer (ALB) is used. The Kipp and zonen ALB consists of two identical pyranometers mounted in opposite directions: one measures the incident solar radiation, the other the radiation reflected by the surface. The technical features of an ALB do not differ from those of common pyranometers.

v) sunshine duration

Sunshine duration is the amount of time of the day during which direct normal solar radiation is higher than 200 W/m^2. The most common instrument for this purpose is the Campbell- Stokes sunshine recorder (sometimes caled heliograph), which has an average threshold of about 210 W/m^2. It consists of a cut glass sphere which concentrates direct solar radiation on the spot on a graduated paper strip corresponding to the time of the day. The rays leave a burnt trace on the paper. The Campbell- Stokes sunshine recorder must be accurately oriented in a north-south direction and the latitude be adjusted. The paper strips must be substituted every day. Manual interpretation of the records is the drawback of this kind of sunshine recorders.

There are only a few electrical sunshine recorders commercially available. They are generally based on photosensitive elements which are alternatively illuminated and shaded by a rotating aperature.

A model of sunshine monitor for automatic registration of sunshine duration has been introduced (Thornblad 1975) and is now commercially available. It has no moving parts, since sunshine is monitored by 18 photodiodes placed around a central axis. These are connected to a common output which is driven by the element receiving the strongest radiation. The monitor is to be mounted vertically and the cylinder inclination must be equal to the local latitude. The inaccuracy of this instrument, due to the selective behaviour of the photodiodes, can be considered to be 25% or 5 minutes at threshold intensity (200 W/m^2).

vi) cloudiness

Knowledge of cloudiness (see ch. Ib), of the prevailing cloud type and their height can lead to a first estimate of solar radiation by using, for instance, the method developed by Kimura and Stephenson (1969).

The measurement of cloudiness is performed by visual observations. The clouds base height can be determined by means of aircraft reports, radar and by using a ceilometer (based on light reflection)

vii) atmospheric radiation

For the definition of longwave atmospheric radiation, see ch. Ib. The instrument for the measurement of longwave atmospheric (also called terrestrial) radiation is called Infrared Radiometer, or, sometimes, Pyrgeometer. It measures the exchange of radiation between a horizontal blackened surface (the detector) and the target viewed (sky or ground). In the case of a net radiometer, the instrument can be designed to eliminate the radiation emitted by the detector.

A common type of Pyrgeometer (PYRG) is the Eppley Precision Infrared Radiometer. This radiometer is a development from the Eppley PSP, intended for unidirectional operation in the measurement of incoming or outgoing terrestrial radiation. Temperature compensation of the detector is also incorporated: radiation emitted by the detector is automatically compensated.

For the measurement of longwave radiation and for separating its flux from the solar shortwave radiation in daytime, the glass hemisphere system has been replaced by a hemisphere of KRS5. On its inner surface there is a vacuum-deposited interference filter; the outer surface has a weather protective coating. The composite envelope transmission shows a sharp transition between 3 and 4 micrometers, from complete opaqueness to maximum transparency, and a transmittance of about 0.50, decreasing to 0.3- 0.4 around 50 micrometers. A thermistor- battery- resistance circuit is incorporated for detector temperature compensation.

The fundamental calibration of detectors is based on their exposure to an ideal blackbody radiator. However, the alternative method of comparison against a calibrated standard PYRG can also be employed. In this instance, a good source of steady long-wave radiance is a cloudless night sky. There are three main requirements for PYRG maintenance: periodic verification of calibration, periodic testing of battery stability, and verification that there is no obstruction to a free horizon.

viii) Total radiation

Total radiation comprises solar and atmospheric radiation. The instruments for measurement of total radiation are called pyrradiometers. Net pyrradiometers measure the difference of total radiation in the upward and downward directions.

Among net pyrradiometers which can be used for continuous monitoring, hence provided with shielded sensors, the following can be mentioned (Coulson, op. cit., Ch. 11) the CSIRO Net Pyrradiometer, the Schulze Net Pyrradiometer, the Eppley Pyrradiometer and the Net Pyrradiometer of the Physico- Meteorological Observatory of Davos.

All these instruments make use of thermojunctions and differ mainly for the number of junctions and the choice of the thermocouple elements. The shielding of the sensors is obtained by means of domes which are completely transparent to radiation of any wavelength. Calibration of pyrradiometers and net pyrradiometers is usually performed following the same procedures as for the other radiation instruments.

- measurement of wind

The influence of wind on the building energy budget has already been pointed out in chapter Ib. A sufficiently complete description of weather conditions during an experiment, requires the measurement of
- wind speed
- wind direction
- wind pressure on facades may be measured in some cases.

Most instruments for wind measurements cannot measure the three components of the wind velocity simultaneously. Instead the horizontal component is determined by measurements of the wind speed and direction. In meteorology, wind speed is measured at a height of 10 meters above open terrain, and is reported in m/s. There are many ways to measure the flow of a fluid, but for wind measurements weather- proof and rigid built instruments are necessary. Among them we find:

1) deflecting vane anemometer
2) revolving wheel anemometer
3) cup anemometer
4) hot wire anemometer
5) propeller anemometer

1) The deflecting vane anemometer consists of a pivoted vane enclosed in a case. Air exerts a pressure on the vane passing through the instrument upstream to downstream. The instrument gives instantanteous readings on an indicating scale. Three vanes can be combined to measure all components of the wind velocity. Its range is from 1 to 120 m/s and its accuracy is 5%. Needs periodic check of calibration.

2) The revolving wheel anemometer consists of a light revolving wheel connected to a set of recording dials which read linear meters of air passing in a measured time. This instrument has a very low sensitivity, and is usually employed in the range of 1-20 m/s. Its accuracy varies between 5% and 20%.

3) The cup anemometer is the most common instrument for measuring wind speed. It consists of three or four hemispherical cups mounted on a vertical shaft. For electrical transmission an AC or DC generator is used, which converts the number of revolutions (which are proportional to the wind velocity)

into analogous voltage values. This transmitter can be used in the range from 0 to 60 m/s and within a temperature range from -35. to +80.C, but the effective range depends on the mechanical features of the sensor. A drawback of the heavier types of cup anemometer is its high starting speed and low response time.

4) For temporary use and when there is no precipitation, hot wire anemometers can be employed. This instrument is based on the principle that if a suitable sensing element is heated electrically at a fixed rate, and exposed to an air stream, the temperature difference between the air stream and the sensing element is a function of its velocity. In the hot wire anemometer a resistance thermometer is used as the sensing element. Its main advantages are high frequency response and high sensitivity, which makes the hot wire anemometer best fit for low velocities. The disadvantages are that it is an expensive and sensitive instrument and requires frequent calibration. A correct calibration of this instrument requires consideration of air humidity and pressure and of all factors that can affect the convective heat transfer between the air and the sensor.

5) The propeller anemometer consists of a light plastic propeller mounted on an axle. The number of revolutions per unit of time is proportional to the wind velocity component parallel to the axle. Three propellers can be mounted on axles perpendicular to one another to measure all three components of the wind velocity. The advantages of this instrument are: the short response time making it possible to measure velocity and large- scale turbulence in three dimensions (Hicks 1972), e.g., close to external walls, and the relatively small error. This instrument has therefore become popular in monitoring of buildings. The disadvantages are the need for calibration and frequent maintenance. This instrument should not be used in strong winds (above about 20 m/s).

Wind direction is defined as the direction from which the wind is blowing. The wind direction sensor is usually a wind vane or a "wind flag". The conversion of wind direction into a loggable value presents some difficulties. Sometimes an endless coiled and 3 times tapped ring potentiometer is supplied for the transmission according to the principle of the electrical axle. The indication of direction is often noncontinuous, since it is given by a maximum number of 8 indicators in parallel connection requiring auxiliary D.C. voltage.

Sometimes special ring potentiometers with built-in relays are available for the 540° recording of wind direction; the output is a direct current of 0 to 4 mA. For continuous direction recording, two self-synchronous motors, one at the transmitter vane and the other at the receiver, can be used.

Wind velocity and direction are particularly influenced by the environment. The correct procedure, suggested by WMO, would require that the instruments are placed in an open site, where the air stream is undisturbed by buildings, trees, etc., and mounted on a mast 10 m high. However, it will generally be useful to know the wind conditions close to the building, where the site is frequently far from being free from obstacles. As a general rule the instruments should be mounted higher than the top of the building, and, if possible, at a certain distance up-stream from it, so that there is little uncertainty about the indicated direction.

It is generally preferrable that all meteorological data are collected on the same time basis. Nonetheless, a shorter sampling interval (ranging from a few seconds to a few minutes) should be used for rapidly varying quantities such as wind velocity and direction. For most models describing the energy balance of the building, the average values over a period ranging from a quarter of an hour to four hours (Day 1983), should be sufficient. For more detailed models of ventilation, root mean squared values or statistics describing the frequency of occurrence of various wind speeds should be used. Combinations of wind direction and velocity are sometimes presented in typical polar graphs called "wind roses".

Wherever wind velocity is monitored far from the building site, a pre-elaboration of data to extrapolate them to the building site is necessary. The following formula is sometimes used for calculating the wind speed, v at a height z at the building site:

$$v = v_s * (d_s / z_s)^{\beta_s} * (z / d_b)^{\beta_b}$$

where

index s stands for "meteorological station" and b for "building"

d is the boundary layer thickness

β is the characteristic exponent of the local boundary layer

Typical values of d and β can be found in Jackman, 1978.

As has already been pointed out in ch. Ib, the action of the wind is especially important from the point of view of natural air infiltration through the building enclosure, due to the pressure difference established across it. The relation between wind pressure, wind velocity, and wind direction is often difficult to predict, as shown in the experimental works by de Gids, Ton and Schijndel.

It may therefore be useful to directly monitor the wind pressure over the building external walls. This can be accomplished by measuring the deformation of a thin pane of glass by means of an estensimetric transducer (Meert and van Ackere). Another technique makes use of electronic differential low pressure transducers, which can go down to 0.1 Pa in the range from 0 to 100 Pa, and which are fixed on the two sides of the building walls. Instruments for the measurement of pressure differences are in general quite expensive.

- measurement of air enthalpy

Enthalpy can be defined as the "total heat", that is, both the so called sensible and latent heat, possessed by a thermodynamic system. In the evaluation of atmospheric air enthalpy its content of water vapour, almost negligible from the point of view of its percentage weight, turns out to be quite important because of the high amount of latent heat possessed by it.

When measuring air enthalpy it is necessary to measure separately

i) air temperature and
ii) air humidity

the humidity being often negligible in the heating season, when water vapour content of the outdoor air is low.

i) measurement of temperature

The measurement of temperature is made by using sensors which are based on the same physical principles. A very wide literature is available on this topic (e.g., Herzfeld and Brickwedde 1962, Omega Engineering, 1980). We refer to it for further explanations.

Any device for measuring temperature is a thermometer. The quantity which detects temperature variations in a sensor is called thermometric quantity. In Table III b-1 an overview of the main temperature transducers and some of their features is given. The sensors more widely used in building experiments are shown in fig. III b-1. Their main advantages and disadvantages are listed in Table III b-2.

A correct siting of temperature instruments is very important, due to large temperature gradients occuring close to surfaces exposed to radiation. These gradients are influenced by the amount of solar radiation, by re- emitted infrared radiation in the night- time, by the radiative properties of the surrounding surfaces, and by local air movements. WMO (1971) recommends that the instrument is placed 1.25 m above a surface covered by grass with free exposure to the wind. Calibration of thermometers should always be performed before the instrument is used for the first time and then at regular intervals. The instruments should be calibrated against some more accurate (secondary standard) calibrated temperature sensor.

For almost all purposes hourly sampling of outdoor air temperature should be sufficient, since air temperature is not rapidly varying. For more accurate measurements the sampling could be done every 5 minutes and an average value be recorded hourly. In other cases even daily or weekly averages could be used, but sampling should always be performed at least every third hour.

In building experiments the most suitable thermometers, considering the possibility to perform remote measurements, precision, and cost are

1) thermocouples
2) resistance thermometers (e.g. Pt 100)
3) thermistors
4) integrated circuit (IC) transducers

1) In thermocouples the thermometric quantity is the e.m.f. generated by the temperature difference between the junctions of two dissimilar electrical leads, (Seebeck effect). If one of the junctions is kept at a constant known temperature it will possible to determine the temperature at the other junction. To measure the voltage generated by the thermocouple, a high precision voltmeter with high impedance, to avoid current flow, has to be used.

TABLE III b-1

General features of some temperature sensors (source: ASHRAE, 1977)

Measurement means		Application	Range, °C	Precision, K
1) Glass-stem thermometers				
Mercury-glass		Temp. of gases and	-39/300	< 0.05 to 5
Alcohol-glass		liquids by contact	-73/78	< 0.05 to 5
Jena or quartz mercury nitrogen			-39/500	< 0.05 to 5
2) Thermocouples				
Chromel-alumel	(K)	High temp., rem. read.	< 1200	0.05 to 10
Iron-constantan	(T)	High temp., rem. read.	< 800	0.05 to 10
Copper-constantan	(T)	Low temp., rem. read.	< 400	0.05 to 10
Chromel-constantan	(E)	Low temp., rem. read.	< 400	0.05 to 10
3) Resistance thermometers				
Platinum-resistance		High precision, rem, read. by contact	-200/1800	< 0.01 to 3
Nickel-resistance		Rem. read. by contact	-100/ 150	0.2
4) Thermistors		Rem. read. by contact	< 300	0.05
5) Integrated-circuit thermometers		Remote reading	< 200	
6) Bimetallic thermometers		For approx. temp.	0/500	> 0.5
7) Pressure-bulb therm.				
Gas-filled bulb		Remote testing	-70/ 500	1
Vapour-filled bulb		Remote testing	-10/ 250	1
Liquid-filled bulb		Remote testing	-50/1200	1
8) Radiation pyrometers		For intensity of tot. high temp. rad. (remote)	any range	

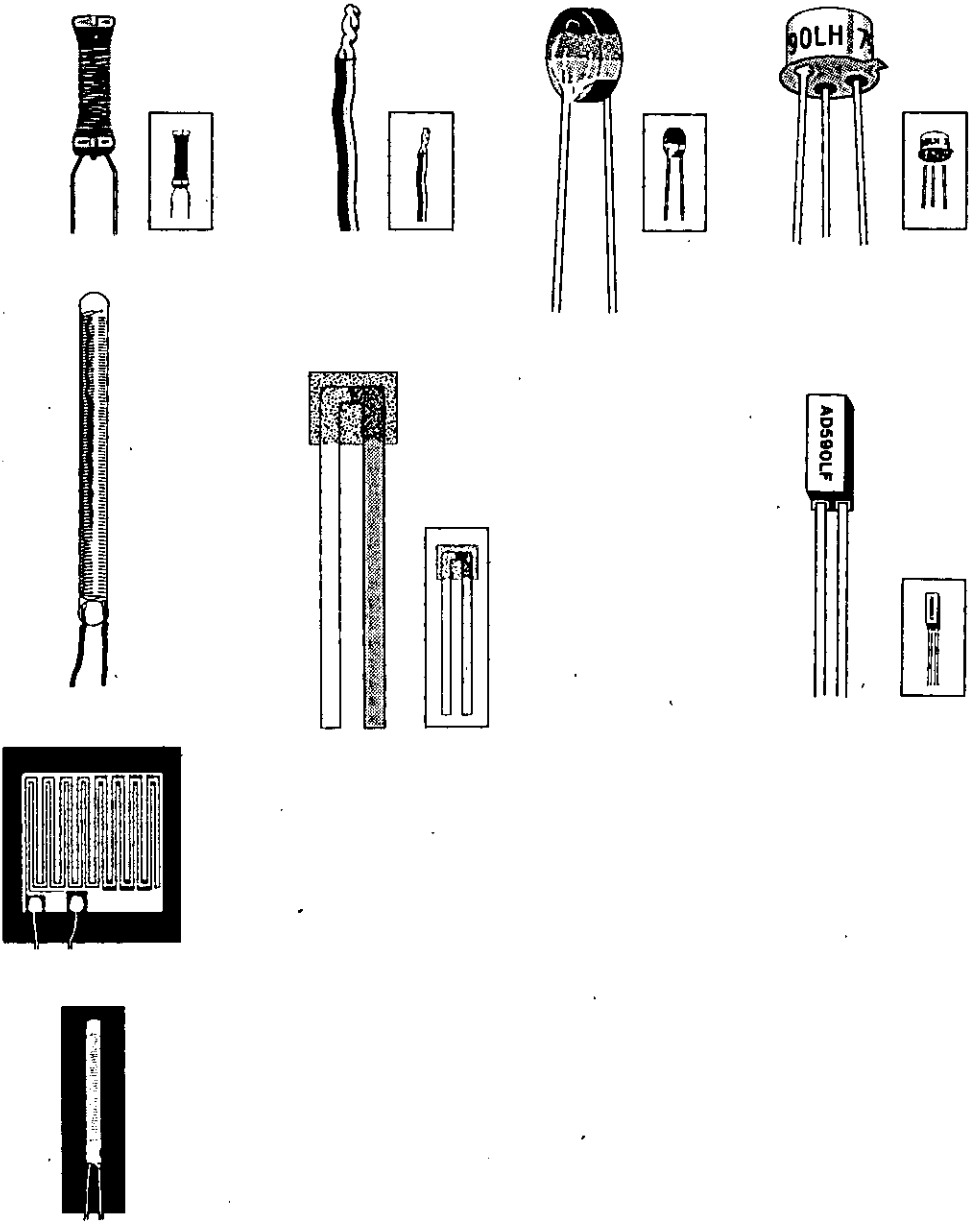


Fig. III b-1 Some representatives of temperature sensors. The sensors depicted here (if in enlarged scale the actual size is indicated inside a frame) are from left to right: resistance thermometers, thermocouples, a thermistor and IC temperature transducers.

Instruments of this type generally contain an automatically compensating cold junction relieving the user from the need to furnish a reference temperature. Such a compensation will work only within a limited temperature interval. Therefore the instrument must be calibrated. This should be done by comparison to a reference having a constant temperature.

Thermocouples are available in different sizes. Small thermocouples have a faster response than large ones. Some practical precautions should be taken when using thermocouples, to avoid measurement errors. Most of them may be traced back to one of these sources:

- poor junction connection
- decalibration of thermocouple wire
- shunt impedance and galvanic action
- thermal shunting

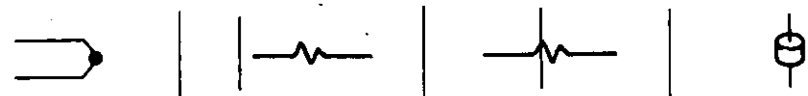
Two thermocouple wires can be connected in many ways: soldering, silver-soldering, welding etc. When the thermocouple wires are soldered together a third metal is introduced into their circuit, but if the temperatures on both sides of the thermocouple are the same, the solder does not introduce any error. Since the solder limits the maximal temperature to which the junction can be subjected, at high temperatures it is convenient to weld the joints. A poor welding or soldering can result in an open connection, which can be detected by performing an "open thermocouple check", a common test function available with data loggers.

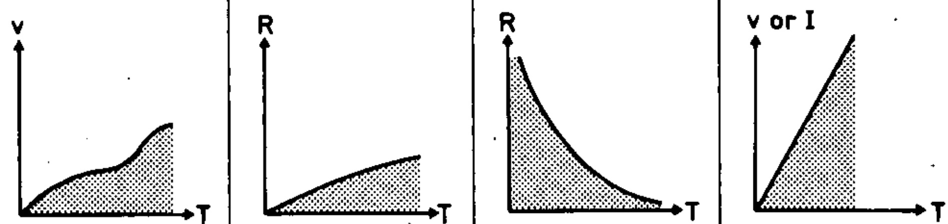
Decalibration is the altering of the physical make- up of the thermocouple wire caused by temperature extremes.

Atmospheric and thermal effects can make the insulation resistance decrease to the point that it creates a "virtual junction". If the leakage resistance is so low that an alternative circuit is closed, an improper voltage reading will result. Atmospheric effects can be minimized by choosing the proper protective metallic or ceramic sheet. The dyes used in some thermocouple insulation can form an electrolyte in the presence of water; this creates a galvanic action, with a resultant output hundreds of times greater than the Seebeck effect. Precautions should be taken to shield the thermocouple wires from harsh atmospheres and liquids.

TABLE III b-2

Advantages and disadvantages of some thermometers (after Hewlett & Packard 1980, and other sources)





	THERMOCOUPLE	RTD	THERMISTOR	I.C. SENSOR
ADVANTAGES	• Self-powered • Simple • Rugged • Inexpensive • Wide variety of physical forms • Wide temperature range • Fast	• Most stable • Most accurate • More linear than thermocouple	• High output • Fast • Two-wire dims measurement • Large resistance change at low temperatures • Inexpensive • Accurate	• Most linear • Highest output • Inexpensive
DISADVANTAGES	• Non linear • Low output • Reference junction required • Least stable • Amplification required	• Expensive • Slow • Current source required • Small resistance change • Low absolute resistance • Self-heating	• Non linear • Limited temperature range • Fragile • Current source required • Self-heating	• $T < 200^{o}C$ • Power supply required • Slow • Self-heating • Limited configurations • Poor stability

Thermal shunting is the alteration of measuremed temperature due to the insertion of a transducer. To avoid this, small thermocouples are used, but small wires are susceptible to contamination, annealing, strain and shunt impedance. To reduce these effects, an "extension wire" can be used, which is intended to cover long distances between the measuring thermocouple and the voltmeter. It is generally larger in size, stronger and cheaper than a small thermocouple wire.

Thermocouples can be arranged in series forming a thermopile. Every second junction is kept at a common temperature. An instrument of this type is useful for observing small temperature differences. Thermocouples are well suited for the measurement of surface temperatures. An advantage is that thermocouples are cheap, a draw-back is their low sensitivity. A typical output is around 0.04 mV/K.

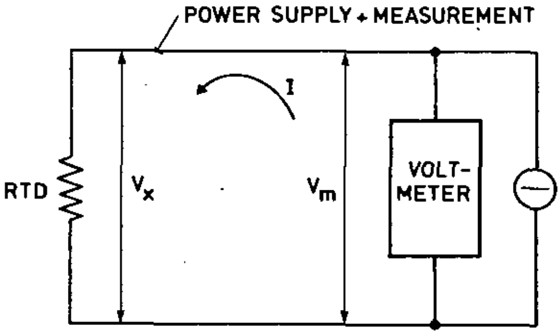
2) In RTD´s the thermometric quantity is the electric resistance of metal wire, usually made of platinum, nickel or "Balco" (a nickel alloy), varying with temperature. The RTD does not require any reference temperature during the measurement; it relies, however, on a constant current source. This fact is a source of errors for two main reasons:

- power is dissipated by Joule effect and hence self- heating occurs.
- if the sensor is connected to the measurement system by means of two cables, used also for power supply, the measured resistance is that of the sensor plus that of the connection cables.

To minimize these problems, it is necessary:

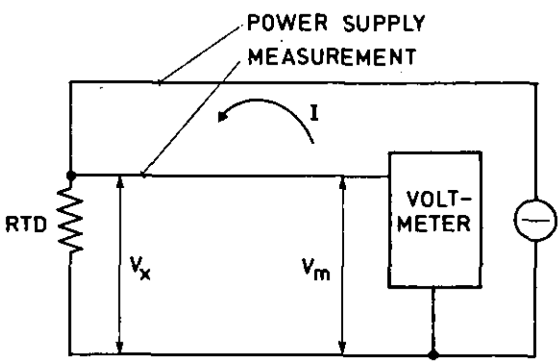
- to operate with low currents through the sensor (around 1 mA for continuous excitation, or 25 mA for pulse measurements).
- to know the resistance of the connecting cables if these are used for power supply and measurement together (fig. III b-2a). A similar solution (3-wires arrangement) is shown in fig. III b-2b. A better solution is to use the 4-wires arrangement shown in fig. III b-2c, where the use of a high impedance voltmeter avoids the current flow in measurement cables. In this way, the exact e.m.f. difference across the sensor is known, and hence its resistance.

With a current flow of 1 mA the typical output of a Platinum RTD will be 0.385 mV/K, about ten times greater than that of thermocouples. The great fragility of the RTD should be taken into account, together with its high thermal shunting. Platinum RTD´s can be used to very high temperatures, while



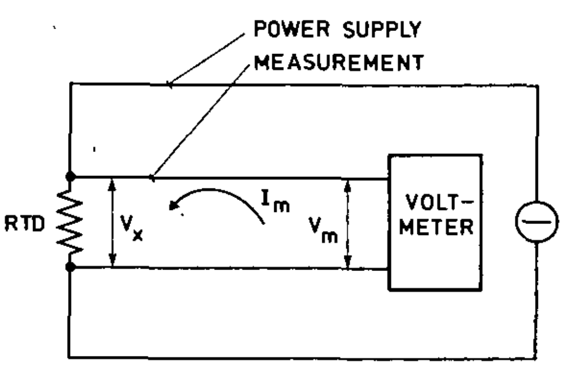
III b-2a

V_x = true voltage difference
V_m = measured voltage difference
R_c = cable resistance
I = current intensity
$V_x = V_m - R_c I$



III b-2b

$V_x = V_m - R_c I/2$



III b-2c

I_m = current intensity in measurement circuit
$I_m \cong 0$
$V_x \cong V_m$

Fig. III b-2 Possible arrangements for measurements with resistance thermometers (RTD's). From top to bottom: 2-wire, 3-wire and 4-wire RTD measurement.

platinum film thermometers are generally used in the range from -50°C to 150°C. They are very linear in this range.

3) A resistance thermometer where the sensing element consists of a semi conductor compound is called a thermistor. Compared to thermocouples and RTD´s, thermistors have some advantages:

- the temperature coefficient is about ten to one hundred times greater then that of RTD´s; this fact is a warranty for high sensitivity.
- a much higher resistance than that of metals reduces errors due to wires and contact resistance.
- since thermistors produce a high output for a low current drive, they can be used with battery equipment.
- low cost of the sensor
- small dimensions of sensor, and therefore low thermal shunting.

Disadvantages and/or limitations are:

- high non- linearity which requires a linearisation apparatus or an individual calibration.
- high dispersion between individual sensors (20%), which requires individual calibration if high accuracy is to be achieved. A consequence of this is non-interchangeability
- the stability of calibration is good in a narrow range of temperature. In the literature the best stability is considered to be found below 110°C.
- to reduce self- heating of the sensor, the excitation current has to be less than 1 mA.
- thermistors must be carefully mounted due to their fragility, which is even higher than for RTD´s. In some cases they need to be encapsulated in glass or otherwise protected, thus increasing their thermal inertia.

4) The IC temperature transducer uses a fundamental property of silicon transistors to produce a voltage which is proportional to the absolute temperature. This voltage can be converted into a current by means of a low-temperature- coefficient resistor. Typical IC transducers are the Analogue Devices AD590 and the LM134Z. Unlike the other thermometers discussed above, the output is thus either a current or a voltage, both linearly proportional to absolute temperature. Typical values are 1 A/K and 10 mV/K. IC temperature transducers do not need any reference temperature or device for measuring resistance. They can be constructed to have high accuracy and to be almost linear over a limited temperature range (Timko and Suttler 1978, O´Neill and

Derrington 1979). However, they have the following disadvantages:
- self- heating
- fragility
- need for external power source.

Air temperature measurement requires particular care, due to solar and infrared radiation impinging on the sensor from the surroundings.To reduce this source of error two techniques can be used:
- shielding of the sensor
- ventilating the sensor

The shielding can be performed by surrounding the sensor with from one up to three polished screens. Aluminium, steel or wooden screens of cylindrical or spherical shape are commercially available.

Natural airing should in any case be provided. But, as previously stated, this type of protection is often not sufficient, especially when strong radiation occurs, even if the whole apparatus is accurately screened. In this case the thermometer should be inserted in a protective casing with electrical ventilator. The ventilation speed at the measuring bulb should be at least 3.5 m/s. If such an apparatus is set up, the measurement error can be reduced to 0.1 K at $0^{\circ}C$ when platinum resistance thermometers, according to the DIN 43760 Standard, are used.

ii) measurement of air humidity

Air humidity should be measured only when information is requried about its effect on building heat losses, or on atmospheric radiation, or when one is especially interested in air conditioning and ventilation. Atmospheric radiation can be estimated from the empirical equations (see, e.g., Kondratijev 1969 and ch. I b), relating it to air temperature, humidity and cloudiness. There are many methods for measuring the air relative humidity; only some of them are suitable for remote reading.

The Psychrometer, or Wet and Dry bulb thermometer, consists of two temperature sensors, one with a cotton sock wetted with distilled water. The sensor with the sock will register a temperature close to the thermodynamic wet bulb temperature. Knowing the dry bulb and wet bulb temperatures and the barometric pressure, the relative humidity can be determined.

Some of the requirements for psychrometers, as taken from WMO (1971) are:

- the wet and dry bulbs should be ventilated and protected from radiation by a minimum of two polished metal shields.
- at sea- level air should be drawn across the bulbs at a rate between 2.5 and 10 m/s.
- measurements should be performed at a height between 1.25 and 2 meters above ground level.

Psychrometers cannot be used when the air temperature is below $0^{o}C$. They need frequent cleaning and replacement of the cotton sock.

Dew point hygrometers measure absolute humidity by means of the temperature of a cooled polished metal mirror exposed to external air. When the surface begins to be covered with condensated water vapour, the temperature reached is the so called "dew- point temperature". Moisture is detected using a light source and a photo- electric cell. The measuring apparatus is rather complicated and expensive, due also to the necessity of cooling the surface by means of a thermoelectric device or by the adiabatic expansion of a compressed gas. Dew point hygrometers are not suitable for measurements at low temperatures if one does not know whether dew is composed of supercooled water or ice crystals.

Mechanical hygrometers (Lambrecht, 1975) make use of organic fibrous materials (Pernix element, or human hair), which change their dimensions according to the quantity of water in the air. The dimesional variation is converted into the analogue variation of an electrical signal or the oscillation of a mechanical indicator. This measuring apparatus is widely used, due to its easy mounting and low cost; its precision is, however, not high and it needs periodical (sometimes even daily) calibration. Furthermore, the instrument is, extremely unreliable at low temperatures (below $-10^{o}C$).

The Lithium-Chloride cell hygrometers exploit the property of the salt lithium- chloride (LiCl) to become electrically conductive when absorbing moisture from the air. The sensor, a cell containing a lithium- chloride solution, is heated by passing an AC between the electrodes. This reduces the moisture content and increases the resistance of the solution. An equilibrium temperature which is measured by a separate sensor, is reached. This temperature can be converted into a dew-point temperature. The LiCl hygrometer is a simple and comparatively cheap instrument.

- precipitation

There is still little knowledge about the influence of rainfall on the building energy- related performances, especially in the long run.

An instrument for measuring precipitation is called a pluviometer, or rain gauge. The height of precipitation is the height of liquid precipitation, that would cover the ground surface. A widely used instrument for the measurement of precipitation is the Hellman rain gauge, which consists of a receiving vessel with known surface, of a collecting can and of a measuring cylinder. The collected precipitation - which may have to be melted - will be recorded by an observer at regular intervals.

Rainfall recorders can also be used; they consist of a cylindrical case to which a receiving vessel is soldered. The rain-water entering the receiving vessel is led through a metal pipe into a cylindrical vessel. Inside the vessel there is a float with a vertical hollow axle soldered to it. The pen arm bearing the recording pen is fastened to the axis. When the level reaches 10 mm, the water is automatically discharged by means of a glass siphon into the collecting can located at the base of the instrument. This type of rainfall recorders can be used for temperatures down to -25°C, provided they are equipped with heating and with a thermally insulated double walled casing. Electrical transmission of rainfall is feasible by means of resistance teletransmitters, or impulse transmitters using a "tipping bucket" device.

Combined wind and rain produce the so called driving rain that is the horizontal component of rain. It can lead to moistening of walls and, consequently, to the decrease of their insulation performance. Driving rain on facades can be measured with an instrument described by Lyberg (1979) which consists of a collar of aluminium (diameter = 200 mm) as collector, and a tipping bucket system, and which is mounted on the building facade.

In the absence of measuring devices driving rain can be calculated through the wind speed v, the terminal velocity of water drops v_t (linked to their radius) and the vertical intensity of rain I_v: $I_h = C * v * I_v / v_t$, where I_h is the driving rain component and C is a constant

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CHAPTER III c

Indoor climate measurements

Contents

Keywords

air temperature, indoor
air velocity
anemometer
comfort, thermal - occupants satisfaction with temperature of surroundings
comfort, human - occupants satisfaction with environment
contaminants, indoor
daylight
globe thermometer
humidity, indoor
laboratory experiments with human beings
lighting
metabolic rate - heat production by human body
nuclear radiation, indoor
radiant temperature, indoor - average temperature of surrounding surfaces
sensor positioning
simulation with dummies
temperature gradient - change of temperature with distance

III c Indoor climate measurements

- general information

When defining indoor climate it can be advantageous to make a distinction between indoor climate as a factor in physical energy calculations, the physical indoor climate, and as a factor in human environment, the physiological indoor climate. The physical indoor climate can almost be reduced to indoor air temperature. The energy losses due to heat conduction through external walls is in first approximation proportional to the temperature difference between indoor and outdoor air. The energy losses due to infiltration and ventilation are proportional to this temperature difference times the flow rate.

Indoor climate as a factor in human environment is much more complex. Here indoor air temperature, interior surface temperatures, air velocity and humidity interact in a complicated way to determine the thermal comfort of the resident. However, temperature gradients, temperatures changing with time, and temperature differences between e.g. indoor air and floor are also important for the thermal comfort. Still, thermal comfort alone does not constitute the indoor climate of the occupant. Noise and lightning are important components of the indoor climate. Another factor that must be taken into account is the presence of air contaminants, odour and dust, which can be counteracted by e.g. ventilation. The air exchange rate is therefore also important for the indoor climate. Many of these factors can be directly experienced by the occupant through his senses. Others, like many air contaminants, can not, but may still affect the health and well-being of the occupant.

It is the combined effect of all these factors that will determine the physiological comfort of the occupant.

In the sections of this chapter the measurement of indoor climate is discussed. With a few exceptions only instruments that permit remote measurements will be described. These sections describe measurement of indoor air, surface and resulting radiant temperature, measurement of air velocity, measurement of humidity, measurement of air contaminants, measurement of lighting and measurement of thermal comfort. The greatest attention is given to the measurement of temperature. This section is the only one where the questions of sensor positioning is discussed in some detail. For a discussion on error evaluation see App. III. For a fuller treatment of the topics concerning indoor climte we refer to Givoni (1976) and van Straaten (1967), who however mainly discuss indoor climate in hot and mediterranean climates, McIntyre (1980) and Fanger - Valbjørn (1978). For topics concerning instruments for the measurement of indoor climate we refer to ASHRAE Fundamentals (1981), Doebelin (1966), Neubert (1977) and McIntyre (1980) and the proposed ISO standard (1980).

- measurement of indoor air and surface temperature

i) temperature distribution in a dwelling

The thermal environment in a room is asymmetric with respect to thermal radiation and air temperature. A typical room has one or two exterior walls through which most of the heat loss occurs in the winter time. This may be nearly all if the room is at an intermediate floor of a multi- storey building. The effect of this heat loss is to produce large cold surface areas, which radiate less to the occupant than do the interior partitions, and a major movement of cold air towards the floor along the full length of the exterior walls. This down draught at the exterior wall surfaces produces a vertical air temperature gradient from floor to ceiling and a horizontal air temperature gradient from the cold wall to the warm partition unless the heating system effectivily counteracts this effect. In fact, the major performance requirement of the heat terminals is to compensate for this asymmetrical air and radiant temperature pattern in a room in a residential building (Eberhard 1969) .

In fig. III c-1 some qualitative examples are given of what the vertical temperature stratification might look like for different heating systems. In fig. III c-2 some examples of the temperature distribution on interior surfaces are given.

The asymmetry of the thermal environment is even greater under summer conditions where air conditioning is contemplated. This unbalanced environment is caused by ne or more exterior walls exposed to outdoor conditions, to instantaneous solar gains through windows, and to warm ceiling surfaces at a top floor level.

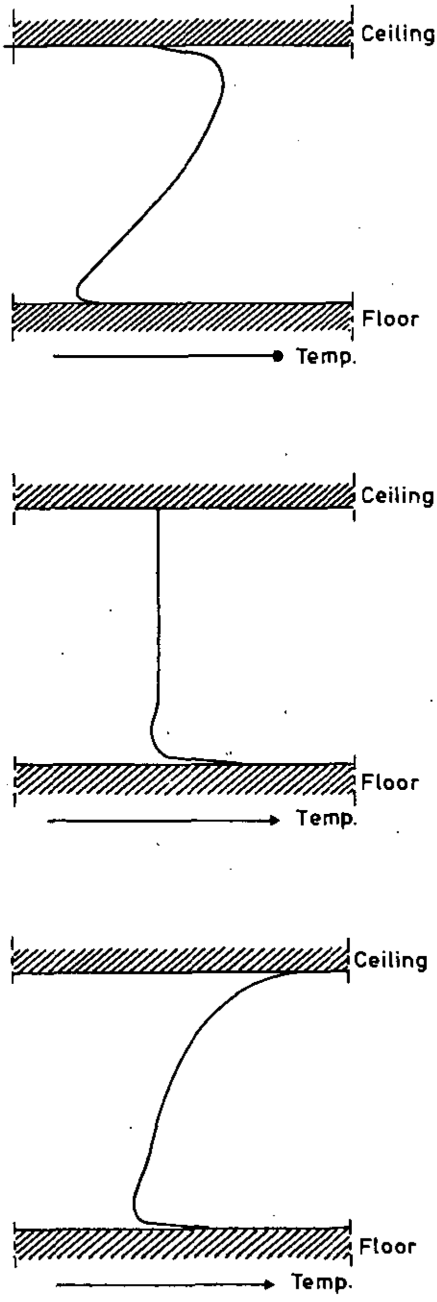

Fig. III c-1 Examples of the vertical temperature stratification in the middle of a room for different heating systems. From top to bottom: radiators, floor heating, ceiling heating.

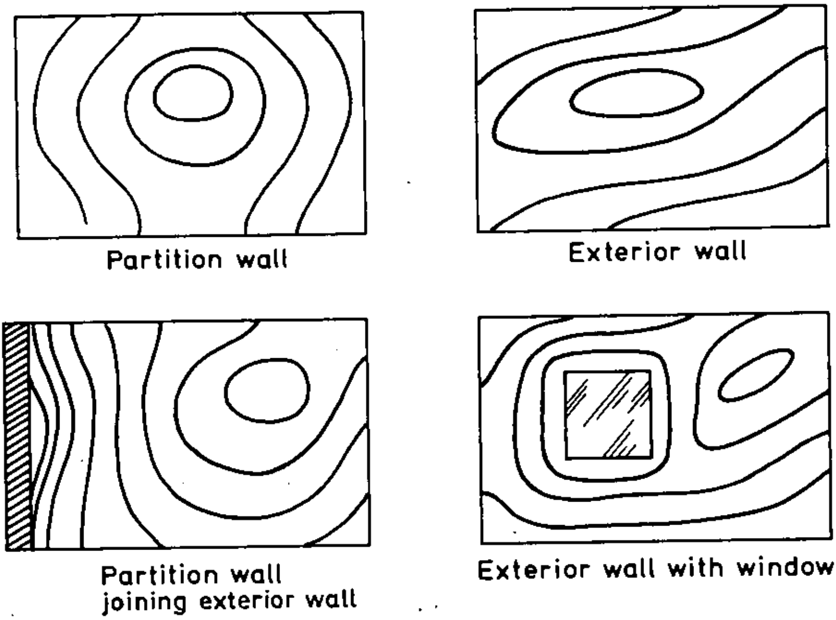

Fig. III c-2 Examples of isotherms on partition walls and exterior walls in a room.

The temperature is often not the same in different parts of the living area of a flat or a house. Closets and bathrooms may not be equipped with heating facilities. Rooms where the occupants spend much time can have a higher temperature than other rooms, due to the presence of the occupants, and the use of electric appliances. The temperature of the cellar and the attic in a house is often different from that of the living area. In a residential building with many flats there will often be a temperature difference between the bottom floor and the top floor if the heating system is not very efficient. Flats at the gable often have a lower temperature than other flats. The temperature can rise in rooms having windows on a facade exposed to solar radiation.

The local air or surface temperature will also fluctuate with time even in a room where the temperature is controlled by a thermostat. It is therefore clear that "the" indoor air or surface temperature does not exist even for a single room.

For calculations inside the framework of a model it is in general necessary to define a space-averaged temperature (and also time-averaged if the model is a static one). This can be done if it is possible to place temperature sensors at several locations inside the dwelling. But due to the existence of temperature gradients, and to the fact that the number of sensors is always limited, the calculated average temperature will always differ from the "true" space-averaged temperature.

For practical reasons it is often possible to place only one sensor in each room. The reading from this one sensor must then represent the average temperature of the room. It is then obvious that the placing of this sensor must be carefully considered.

The variation of the indoor air temperature and the variation of the surface temperature of a partition wall or exterior wall in a room both are typically at least 2-4 K. If the measurement of one of these entities is performed at only one point, and this point is badly chosen, the measured temperature will differ from the average temperature by 1-2 K.

Taking a time-average of the temperature will often introduce a smaller error than the space-averaging procedure because it is generally possible to read the temperature frequently. These questions will be discussed in more detail below.

ii) temperature measurements in uninhabited rooms

When measurements are performed in an uninhabited room, sensors for the measurement of air temperature can be placed openly. A ventilated sensor is required for an accurate determination of the air temperature. If it is not possible to use a ventilated sensor, the sensor should at least be shielded from heat radiation, which should be done in such a way that air movement is not hindered.

The vertical temperature stratification of the air is often stronger in uninhabited rooms than in inhabited ones. It is therefore customary to place several sensors above each other to get a good estimate of the average temperature. How many sensors are needed will depend on how the temperature gradient changes in the vertical direction. This should therefore be investigated before deciding the required number of sensors. Often one uses three sensors placed, e.g., 0.1 - 0.2 m above the floor, at medium height of the room, and 0.1 - 0.2 m below the ceiling, or four sensors placed, e.g., 0.1, 0.8, 1.5, and 1.8 m above the floor. To get a good estimate of the average room temperature the lateral temperature gradient also must be taken into account. The magnitude of this gradient will be determined by the presence of windows, radiators annd cold or hot walls. In fig. III c-3 we give a few examples of the required minimum number of measuring points to get a good estimate of the average temperature. At all these laterally distributed points, the temperature should be measured at more than one height. This arrangement of the sensors will in most cases give a good estimate of the average temperature, provided the rate of air change is not too high (i.e. not substantially larger than 1 air change per hour).

When measuring surface temperatures, there should be good contact between the sensor and the surface in question. The sensor should have the same radiative properties as the surface of the wall. One way to do this is to cover the sensor by a sheet of thin metal foil which is then painted in the same colour as the surface.

The temperature distribution on the surface should be investigated before it is decided how many sensors should be used and where these should be positioned. This can be done by using e.g. thermographic methods. However, it must be kept in mind that this temperature distribution is not a static one. There are, e.g., often strong diurnal variations of the surface temperatures, specially if there is a strong solar radiation during the day and cold cloudless

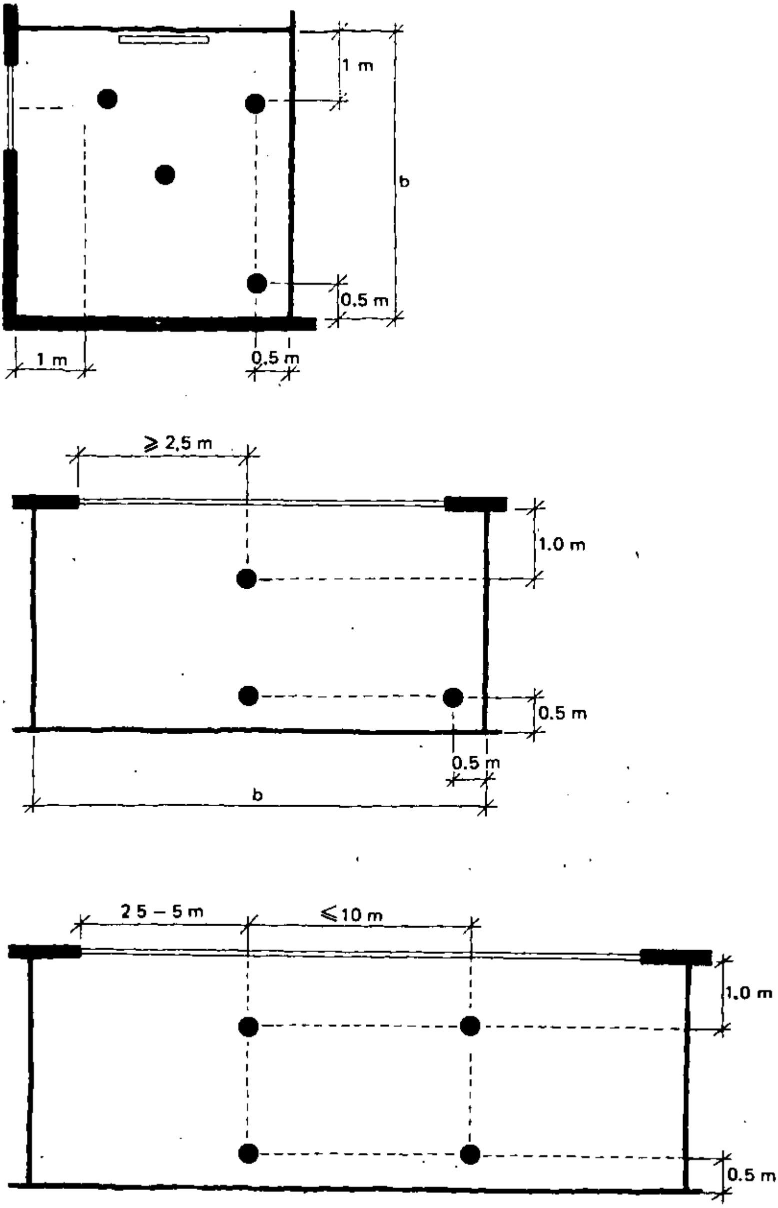

Fig. III c-3a Examples of positioning of sensors for the measurement of room air temperature in different kind of rooms. At every position the measurement should be performed at more than one height.

nights.

The measurement of surface temperatures of windows is difficult. If the sensor is placed in contact with a window pane, it is in general not possible to shield the sensor from radiation which in most cases will cause a deviation of the measured temperature from the actual surface temperature of at least a few degrees K.

If the window surface temperature is measured using radiative methods, the reading will be affected by the radiation penetrating the window and this will cause a deviation from the actual value. In this case a simultaneous measurement of the incoming radiation and knowledge of the transmittance properties of the window would make it possible to calculate the surface temperature of the window. In practice, however, this method gives rather uncertain results (see ch. III f).

iii) temperature measurements in inhabited rooms

The measurement of the temperature in an inhabited room poses more problems in addition to those encountered in measurements in an uninhabited room. The occupant will not be likely to accept more than a few sensors in his living area. This creates problems especially for the measurement of indoor air temperature as it will not be practical to have a sensor positioned anywhere but attached to a partition wall. In this case contact between the sensor and the wall must be prevented by placing an insulating material between the partition wall and the sensor. The sensor should also be shielded against heat radiation from surfaces, but this poses a more difficult problem as the air movement in the vicinity of the sensor must not be prevented. The sensor should be placed on a partition wall far from radiators or any other surfaces with a temperature that is noticeably different from the air temperature. Nor should the sensor be positioned in such a way that it faces a window or a radiator directly.

Because of the vertical temperature stratification, the sensor should not be positioned close to the floor or the ceiling, but preferably at medium height. Because of the insulation between the sensor and the surface, instruments where self- heating may be a problem are not well suited for this kind of measurements. For the measurement of surface temperatures there are no special problems connected with measurements in inhabited rooms compared to uninhabited ones.

The local mean radiant temperature at a point in a room can be calculated if the surface temperatures are known. An easier way is a direct measurement of the mean radiant temperature using, e.g., a globe thermometer. A measurement of this kind is of interest when considering human comfort criteria. It can also be used for energy balance calculations (Lebrun - Marret 1975). In this case it will not be necessary to measure the air temperature and the surfasce temperature. For human comfort applications measurements must be performed at least at two points, e.g., near the centre of the room and in front of the window.

iv) temperature measurements in buildings

In this case the possibility that all the rooms of the living area do not have the same average temperature must be taken into account. If the temperature is not measured in every room, the sensors should be placed so that a representative average temperature of the flat can be obtained. In a multi-storey building the temperature should be measured at least at one position on each storey.

In model calculations of a house, it is often necessary to treat the living area, the cellar, and the attic as separate components of the house. Therefore the temperature of the cellar and the attic should be measured separately (see ch. Ib).

For a large residential building with many flats, it will in general be practical to measure the indoor temperature only at one position in a limited number of flats. The positioning of this single sensor in a flat must of course be considered with the same care as discussed above. The choice of the flats where a sensor is to be installed should be determined by statistical means if one wants to obtain a representative indoor air temperature.

Suppose one is interested in determining the average temperature of a residential building with many flats. If one suspects that some flats, e.g., those at the top floor, or at the gable, of a long parallel epiped shaped building have an air or interior surface temperature different from the rest of the flats, the flats can be divided inte two or more groups, (see App. III).

v) sensors for indoor temperature measurements

Thermometers of different construction can be used to measure the indoor air and surface temperatures. However, their properties depend upon construction and some are more suited than others for a given measurement. An instrument of a certain kind is often available in many different designs. It is therefore often possible to obtain an instrument that is well suited for exactly the kind of measurements one wants to perform.

The sensors used for indoor temperature measurements are most often thermocouples, resistance thermometers, or integrated circuit transducers (IC-transducers). For a description of these sensors see ch. III b and III g.

In physiological applications it is often of interest to determine the heat balance of the human body at a point in a dwelling. It is then common to use instruments which measure a combination of air temperature and the <u>mean radiant temperature</u> at one point. One such instrument is the <u>globe thermometer</u>. It usually consists of a thin-walled sphere painted black with a temperature sensor at the centre of the sphere. The globe thermometer is suspended at the test point and allowed to come to thermal equilibrium with its surrounding. Over a limited temperature interval, the globe thermometer can be considered to measure a linear combination of the local air and mean radiant temperature.

The influence of the local air temperature on the reading will depend on air flow past the sphere. If the air temperature is measured separately, it is then possible to calculate the local mean radiant temperature. The globe thermometer is a simple instrument, but the calibration is difficult especially if it is necessary to correct for air flow. The time necessary to reach thermal equilibrium with the surroundings can vary from 5 to 20 minutes for different globe thermometers. The performance of several globe thermometers has been investigated by Graves (1974). The performance of a globe thermometer can be improved by enclosing the globe in a polyethylene envelope. Such an instrument has been described (McIntyre 1976).

- measurement of air velocity

The measurement of air flow in a dwelling is in general difficult because the flow pattern is seldom stable and the air velocity is relatively small. The velocity fluctuations are often of the same magnitude as the speed of the air. This makes it very difficult to perform measurements with visual reading of the instrument.

The thermal comfort of an occupant exposed to "draught" will depend not only on the average speed of the air, but also on the magnitude and frequency of the fluctuations in air velocity. It is therefore in general not sufficient to measure only the average air speed if the aim of the measurement is to determine the thermal comfort (Olesen- Thorshauge 1978 and Lebrun- Marret 1978). To obtain a stable average value of the air speed, it is in general necessary to extend the measurement over a time of at least several minutes and then perform the averaging over this time interval.

The magnitude of the air speed for which complaints about draught are likely to be made by the occupants depends on the indoor air and surface temperatures (see ch. Ic). However, for air speeds smaller than 0.1 - 0.2 m/s there are seldom any complaints at a normal room temperature. Some typical situations when the air speed can exceed 0.15 m/s are illustrated in fig. IIIc-4 (Eriksson- Löfstedt- Valbjørn 1979).

Before measurements of the air velocity in a dwelling are performed, it is important to get a picture of where in the dwelling large air velocities are frequent. This can be done rather quickly using a smokepuffer or a smoke-stick (see also ch. III e).

For measurements of air speed in a dwelling it may seem advantageous to use a non-directional anemometer (an anemometer that can measure only the speed of the air stream, not the direction), since the air flow in a room is usually neither visible nor constant. The instruments that can be used in practice are however either completely directional (the response of the sensor depends on the direction of the air flow), like the hot wire anemometer, or difficult to make non-directional. An instrument with only a small directional dependence has been discribed by Jørgensen (1979). One therefore has to determine the main direction of the air stream before the instrument is used. This can be done e.g. using a simple hand-held smoke- puffer.

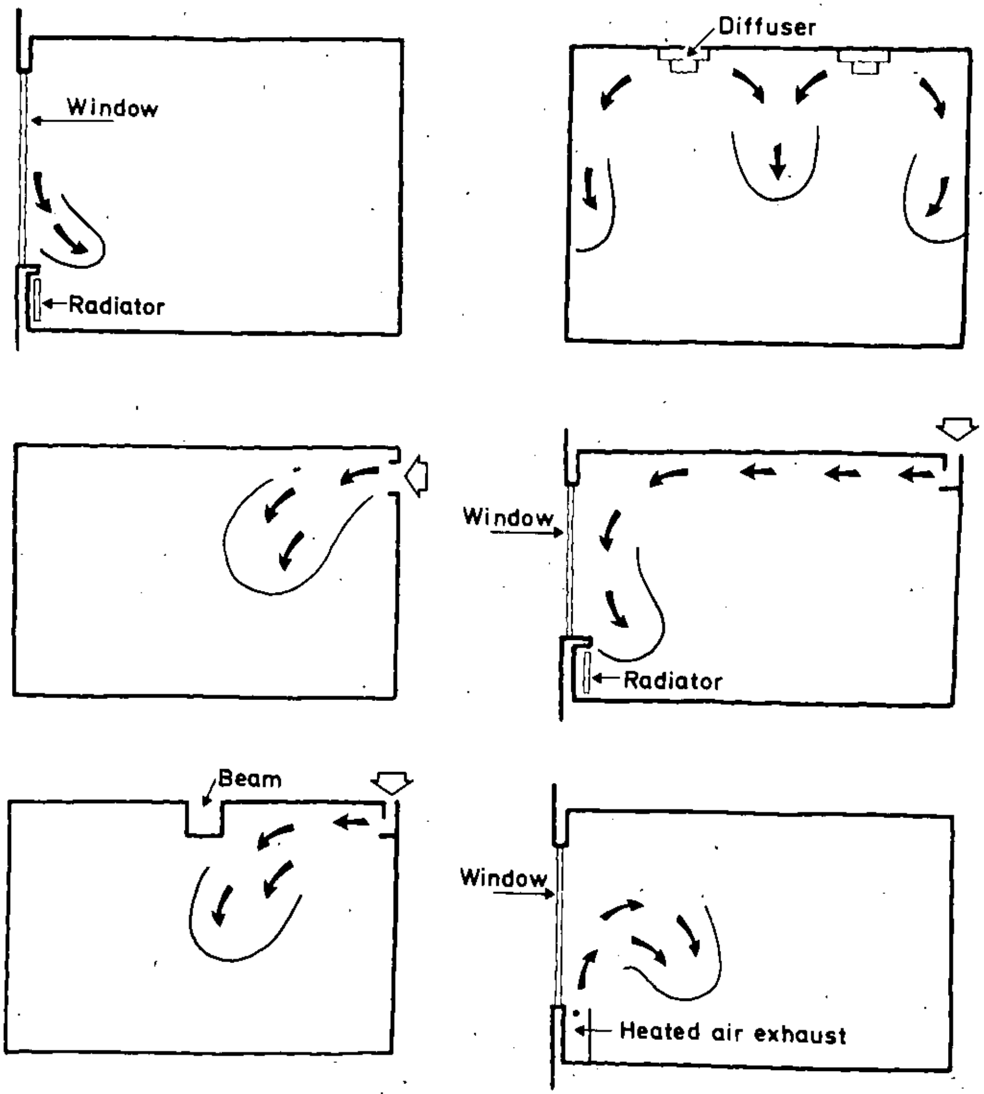

Fig. III c-4 Examples of a situation when the air velocity may exceed 0.15 m/s. (After Erikson- Löfstedt- Valbjørn 1979)

The sensor of a <u>hot wire anemometer</u> consists of a thin metal wire having a length of 1-2 mm. The wire is either kept at a constant temperature, or else the electric current through the wire is kept constant. In either case the voltage drop across the wire will be a function of the air velocity over the wire and the angle between the wire and the air stream. The hot wire anemometer has a very high accuracy and can measure very rapid velocity fluctuations. It is the basic research tool used in wind-tunnel studies. It is, however, a costly instrument.

Other anemometers use the rate of cooling of a heated body as the sensing head. If the heated body is spherical in shape such an anemometer would in principle be non-directional. However, in practice most instruments of this type are more or less directional. Often the heated body is of a shape other than spherical. The response to a change of air speed is often slow.

The <u>heated thermocouple anemometer</u> is calibrated to give velocity in terms of the difference in electromotive force between the two thermojunctions of a thermocouple exposed to an air stream. This anemometer has a rather slow response to rapid velocity fluctuations, and is rather insensitive for small air velocities. Therefore, this type of instrument should only be used for steady-state measurements and for air velocities greater than 5 cm/s. The heated thermocouple anemometer is a comparatively cheap instrument.

In a <u>thermistor anemometer</u> a thermistor is coupled in series with a fixed resistance. The supply voltage is kept constant. When an air stream passes the heated thermistor, its temperature and thus its resistance will change. The voltage across the thermistor is a measure of the velocity. The thermistor used as sensor is often given an ellipsoidal shape. If there is no temperature compensation, the air temperature must be measured separately. Thermistor anemometers can be designed to be rather insensitive to heat radiation and to have a small time constant (Hårdeman 1974). Several thermistor anemometers have been critically reviewed by Finkelstein et al. (1973).

A simultaneous determination of air speed and direction can be performed if directional sensors, e.g. hot wire anemometers, are used. But this will require the use of six sensors and the data must be numerically processed. Determination of the air flow in this way is therefore seldom performed in practice.

When the instruments discussed above are calibrated, one must take into account the temperature, humidity, and atmospheric pressure. They require accurate calibrations at regular intervals. These calibrations should always be carried out in a miniature wind tunnel, or some other suitable device, at the relevant temperature.

Measurements of air flow velocities are likely to be rather rare, and the indoor airflow is of interest for the comfort, but only indirectly through the influence on the behaviour of occupants, for the energy consumption. General information about the measurement of air velocities can be found in Ower - Pankhurst (1977).

- indoor humidity measurements

The humidity inside a dwelling is not evenly distributed. Often the humidity is substantially higher in the bathroom and somewhat higher in the kitchen than in other rooms. Often instruments that are used for the measurement of outdoor humidity can be used also for the measurement of indoor humidity. This includes the psychrometer, the lithium-chloride cell, the mechanical and the dewpoint hygrometer. For a detailed description of these instruments see ch. III b.

Humidity values in a dwelling are not very important from the energy consumption point of view, except possibly when certain heat-exchangers are used. Humidity is important mostly with respect to human comfort, and only if some upper or lower concentration limits are exceeded.

Indoor humidity can lead to condensation on parts of the building structure which in turn can damage the building material. There is a risk that the occurence of such damages will increase when a building becomes better insulated after a retrofit. It is therefore important that a retrofit is performed in such a way that the risk of condensation is minimized.

- measurement of air contaminants

As measurements of air contaminant concentrations are of interest only to determine if some absolute limit of concentration, unacceptable for human wellbeing and health, has been exceeded, this subject will only be discussed here briefly.

The identity and concentration of gaseous contaminants can be determined through analytical methods. The analytical data are often obtained by accumulation in collectors containing organic polymer absorbents. The sample collected in situ can then be analyzed in a laboratory using gas-chromatography or mass spectroscopy (see e.g. Dravnieks, Whitfield and Shah 1979). For field meaurements simple instruments are available which use the property of gases to absorb infrared light. But these instruments can only be calibrated to measure the concentration of one gas at a time.

The first method described above for the determination of gaseous contaminants can also be applied for the identification of odourous contanimants. However, even if the identity and concentration of the odour is known, this does not adequately characterize the resulting odour and the human response to the particular odour. Instead one has to rely on a sensory evaluation in order to quantify the odour effects in indoor air.

A subjective determination can be obtained by using a scentometer. The use of the nose is required. The method consists of making an odour comparison with clean air as reference. The clean air is obtained by filtering. The observer makes the comparison by sniffing alternately and estimating an odour level. If an experienced panel is used, the method gives good results for the determination of odour threshold.

For the determination of odour supra threshold intensities, there exist standardized methods (ASTM 1978) using a reference odour instead of fresh air as a reference. For a discussion of the above topics see Dravnieks (1978).

Nuclear radiation can be instantaneously detected using ionization type counters or scintillation counters. The ionization type Geiger-Müller counter (G-M-counter) meaures radiation from beta or gamma sources. The G.M. counter is sensitive and inexpensive. The electrical output is high.

When ionizing particles pass through certain crystals, e.g., a gamma-photon through a NaJ crystal doped by tallium, a scintillation detector can sense flashes of light produced in the crystal. If a photomultiplicator is optically coupled to the crystal, the light is amplified and converted to an electric signal, which can give information about the number of photons and their energy. Scintillation instruments are more effective than G.M. counters for gamma counting. They are expensive and require frequent maintenance. Other detectors use photographic emulsions to detect alfa particles. These detectors provide a permanent record but require exposure over a prolonged period.

The number of particles of the indoor air can be determined after a collection of such particles. The particles are generally collected by letting an air stream pass through a filter. The amount of particles can then be determined by optical methods, counting particles by the use of a microscope, or by weighing the filter before and after the collection of particles.

- lighting measurements

Lighting measurement traditionally means measuring the illuminance in lux. There are simple and more sophisticated lux-meters available with a photocell designed to have the same spectral sensitivity as the eye and also arranged to have the expected variation in sensitivity with the angle of incidence, the so called cosine-correction.

For more elaborate measurements of the visual environment one should also measure the luminance of the room surfaces. There are fairly few luminancemeters on the market.

Measurement of the daylight factor is more complex as it involves a simultaneous measurement of daylight illuminance indoors and outdoors from an unobstructed overcast sky. It is important that the measurements are made at the same time as the daylight varies rapidly even when it appears to be constant. In many countries there are standards or recommendations for daylight in dwellings. In some cases a certain availability of sunshine is also requested. The standards are expressed in different ways in different countries. Various points of reference in the rooms are used (fig. IIIc-5).

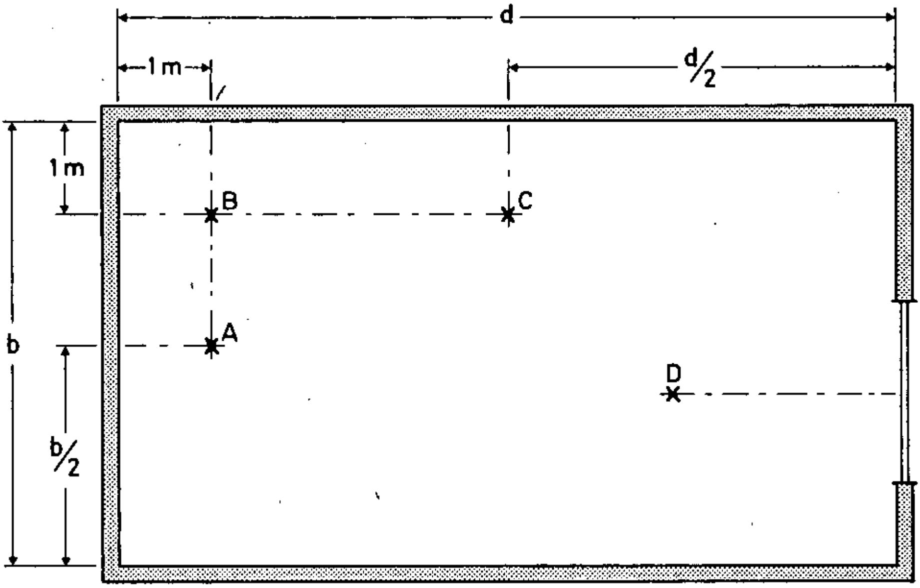

Fig. III c-5 Examples of reference points for definition of the daylight factor. B is the darkest point. C gives gives more of a mean value with some guarantee that the daylight is not too uneven. D is right in in front of the window and there is a risk of very dark parts of the room.

A theoretical daylight factor is generally calculated based on the design of the building. The windows are assumed clean and no shadings like curtains, blinds or potted plants are supposed to reduce the daylight penetration. When measuring the daylight in an occupied dwelling, it is often difficult to remove all shadings. A control is therefore best done by calculation of the daylight factor after the retrofit. What daylight level the occupants have in reality then depends on individual habits, interior decorations etc.

The factors influencing the change in the theoretical daylight factor are mainly the transmission factor of the glass, fixed shading devices outside the windows, and the glass area.

Which method of calculation to use is generally stated in the standard. If no method is given, the "BRS Daylight Protractors" (Longmore 1968) are suggested. For vertical double glazed windows a corresponding method has been presented (Fritzell-Löfberg 1970).

- <u>measurement of thermal comfort</u>

Observations of behaviour and of energy consumption in the home gain immensely in value if they form part of a field experiment rather than a passive survey of existing conditions. In the latter case, secondary and often quite unexpected linkages between factors can negate the value of the observations or even give rise to incorrect interpretation. A properly designed field experiment, in which one or more factors are varied without regard to other, possibly more influential factors, their linkage broken by proper randomization techniques, yields clear- cut comparisons and an unequivocal interpretation. There need be no dichotomy between the field and the laboratory, merely a gradation of realism for the participants. The home can be more or less converted into a laboratory, or participants can be made to feel more or less at home in a laboratory. The choice is usually governed by the practical difficulties encountered in gaining the required degree of control over the factors to be studied, or in achieving the required degree of realism. The aim should always be to provide the maximum amount of realism for the participants while achieving the necessary degree of control and measurement. The best features of laboratory experiments can often be incorporated into field experiments.

Field measurements of human comfort. Thermal comfort can be defined in a variety of ways. It is usually defined as the absence of discomfort. This negative definition defines a no- complaints zone that permits a certain latitude for variations in the thermal climate even for an individual. However, thermal comfort is sometimes defined as the state where a subject cannot decide *whether he would like the temperature raised or lowered even if pressed.* This point can be found fairly exactly by experiment. Unfortunately it differs greatly between individuals even if they are all under the same conditions. The comfort zone is then defined as the region where a certain, quite arbitrary proportion of people are in exact thermal comfort. This provides very little information about the consequences, for an individual rather than a large group of people, of deviations from the ideal.

Complaints of thermal discomfort are caused in the first place by an unsuitable combination of the six factors determining the heat balance of the human body: temperature, thermal radiation, air velocity, humidity, clothing and metabolic rate. They are also caused by a mismatch between what the occupant is trying to do, and what he would have to do to be thermally comfortable- undress, stop work or sweat if it is hot, dress up, work harder or shiver if it is cold. Any study of thermal comfort must take account of what the subject is doing and would like to be doing. Thermal comfort cannot be measured as if it was some inevitable product of environmental factors alone. Occupants must be given an idea of the activity for which the environment is supposed to be comfortable .

Thermal comfort responses can be obtained by means of questionnaires with labelled categories of response. The 7-point scale below is used almost universally

7 Much too hot
6 Too hot
5 Comfortably warm
4 Ideally comfortable
3 Comfortably cool
2 Too cold
1 Much too cold

If possible, the replies should be obtained by a verbal sequence of questions, starting by asking whether the temperature is comfortable. This places the response unequivocally in the 345 "comfort zone" or outside it. If the analysis later calls for an assessment of the proportion "too hot" or "too cold", there is then no doubt about where to draw the line: the subjects themselves have done so.

Mean skin temperature is closely related to thermal comfort in the cold, but hardly at all in the heat, where skin-wettedness is the best predictor. This is very difficult to measure. In most energy conservation work it is a good idea merely to obtain a measure of hand or finger surface temperature. This provides good information about the thermal state of the body in the region where vasodilatation and vasoconstriction are sufficient to regulate the heat balance of the body. Finger temperature is itself of interest because of its influence on finger- tip sensitivity and manual dexterity, usually important in dwellings as well as workplaces, whereas hand temperature is probably a better predictor of grip strength.

Studies using skin temperature as a criterion can involve repeated measures with no limitation. Useful data can in this case be obtained from a mere 5-10 subjects. If thermal comfort responses are to be studied, it is unwise to ask for too frequent assessments, and often better to use an independent measures design to avoid routine answers or boredom. In this case, 10-20 subjects will be required to distinguish reliably between conditions differing by a few degrees K, i.e. 10-20 subjects to experience each condition once only. This number is also appropriate for independent comparisons of skin temperature measurements. If behavioural measures, for example of work performance, are to be obtained, it is not advisable to use repeated measures because of the learning that takes place between repeated exposures. Independent measures designs involving work performance usually require 20-30 subjects under each condition if significant differences are to be shown, even between conditions that clearly differ subjectively.

It is usually also worth supplementing the information obtained by a thermal questionnaire by asking for a simple 3-category (too low /OK/ too high) assessment of thermal radiation, air velocity, humidity and floor temperature, if appropriate, for diagnostic purposes and remedial action.

An assessment of air quality (stuffy /normal /fresh) is also informative and easy to obtain at the same time.

Human beings in controlled laboratory experiments. The usual justification for this approach is that extraneous factors will be absent or under control, but it is often so that the measurement techniques or procedures to which the participants are to be subjected are so intrusive that the experiments might as well, for convenience, be performed in the laboratory, i.e. realism for the participant would be low even in the field. One way of dealing with this problem is to deliberately mislead the participants as to the purpose of the experiment, perhaps presenting a second factor, such as noise, as the independent variable of interest while in fact studying responses to temperature or humidity. In this way the subjects' reactions to the concealed, true factors may be more naive and therefore approximate better to the reactions occurring in real life outside the laboratory. Ethical committees requiring full and informed consent can make it very difficult to employ this method except by using subtly different emphasis on the true and "decoy" factors of the experiment.

The measures taken in laboratory experiments on human requirements of the environment fall under three headings: physiolological, subjective and behavioural. These refer to the three levels of the system hierarchy comprising body systems, man as a unit, and the context in which he acts as a component. The criterion measures should be so defined that they are relevant to the system objective at each level, and are if possible measures of the degree to which the objective has been attained. Thus as the lowest level, body systems, the goal is continued, undamaged efficient functioning. Environmental factors are assessed at this level in terms of the impairment of function they introduce to body systems - the damage done to ears by noise, to eyes by light, to central nervous functions by chemicals or by heat. At the next level, man himself, the goal may be comfort and well-being or it may be performance despite discomfort. This must be determined or set by the conditions of the experiment. The subjective assessments obtained verbally or otherwise from the subject can be designed to provide information relevant to the achievement of these aims. Whereas physiological measures can be made on an interval or ratio scale, subjective assessments should usually be treated as ordinal, or even as nominal if category scaling is used. Subjective assessments are usually as stress-specific as physiological measures - it is difficult for subjects to make cross-modal comparisons, for example to compare heat discomfort with noise discomfort.

Behavioural measures refer to the functioning of man as a unit in context, interacting with his environment, with equipment, with other people. Such experimental measures demand a higher degree of realism of the experiment. Physiological measures can and often are made on prone, naked subjects instructed not to move or talk, subjective assessments can and often are obtained from bewildered subjects sitting in a bare room and waiting for something, anything, to happen. Behavioural measures involve observing what a subject does in a defined context. This may often include measuring his performance of a given task. The task should be chosen from or modelled on a task really performed in the environment in question. This is obviously the case in workplace studies, where the task provides the "raison d'etre" for the workplace. However, numerous well-defined activities are performed in the home - housework, study, reading, watching television, conversation, resting, sleeping. Measures of how well these activities can be performed are relevant criteria for energy consumption. They have the advantage over physiological and subjective measures that they are not stress-specific but are affected by all manner of environmental variables. They are also in many cases considerably more sensitive to sub-optimal environmental conditions.

Simulation with dummies. Physiological, subjective and behavioural measures must obviously be obtained from real people. Not so physical measures. Dummies simulating people have a place in energy conservation research. They can simulate the thermal and acoustic impact of people on the environment of a room. Care should be taken in simulating the thermal contribution of a human to a room. All too often a heat source of the required wattage is used without regard to its size, shape and surface temperature. Small, hot sources lead to quite different convective and radiation exchange conditions in a room even though their total heat contribution may be correct.

Physical measurements of the heat loss from heated mannequins have been extensively used to measure the total insulation value of clothing. Such mannequins must fit the clothing and should also have realistic skin temperature distributions. More detailed measurement of heat loss from different parts of the body in response to clothing, draughts, asymmetric radiation, etc. will require more sophisticated mannequins with physiologically correct skin temperature distributions even under sub-optimal thermal conditions. The influence of posture on heat balance can suitably be assessed using a thermal mannequin. In the near future thermal mannequins with the ability to sweat and to move realistically will be developed for more sophisticated assessment of clothing assemblies and their importance for energy conservation.

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CHAPTER III d

Thermal performance of buildings

Contents

Keywords

absorptance, absorptivity
conduction
conductivity, thermal conductivity
convection
diffusivity, thermal diffusivity
Envelope Thermal Test Unit (ETTU)
guarded hot box method
guarded hot plate method
heated wire method
heat flow, heat flux
heat flow meter
infrared scanner
radiation
reflectance, reflectivity
response factors method
steady-state regime
surface heat transfer coefficients
temperature
thermography, infrared thermography
transient-state (or unsteady-state) regime
transmittance, transmissivity
U-value, thermal transmittance

III d Thermal performance of buildings

- general information

The thermal performance of a building appears as a set of properties defining the ability to maintain a pleasant indoor climate throughout the year. It is, therefore, the technical answer to the user's requirements.

From a physical point of view, as there exists a temperature difference between the outside and the inside, energy flows will cross the envelope of the building. These energy flows will depend on:

- the composition of components (window, wall, roof, basement) of the envelope
- the order in which the constitutive layers of the wall are arranged
- the material used for each layer.

A short review of conductive heat transfer problems is given in ch. I b. The measurement of thermal properties of materials is first described.

In the steady-state regime the material considered is characterized by its thermal conductivity λ . A description will be given of the different measurements allowing the determination of this quantity, either in the laboratory, or in situ.

In the transient-state regime a material is characterized by its thermal diffusivity α (see ch. I b). The measurement of this physical quantity can be performed directly or indirectly (i.e., following the methodology adopted for the determination of conductivity).

In the field, the problem is generally not to find the relevant thermal properties of a given material, but rather to handle a multilayer wall, all layers being different. Here again one has to distinguish between steady- state and transient- state conditions.

In steady-state conditions the thermal performance of a multilayer wall can be described by means of a single parameter: the thermal transmittance (U-value) of the wall. The equipment to measure this quantity in the field will be described. Some information will also be given about the measurement of surface heat transfer coefficients and of the U-value of windows.

For transient-state conditions, it is generally impossible to measure directly the parameters introduced by the different mathematical methods such as finite difference and response factors. An indirect validation can be obtained measuring the surface temperatures, introducing them in the algorithm to be tested and finally comparing the calculated heat fluxes with the measured values.

When the Fourier transform method is used (see ch. Ib), which solves the heat transfer problem in the simpler case of periodic heat fluxes, the so-called "Fourier coefficients" can be measured in the laboratory. Regarding the building as a whole, its behaviour in transient- state conditions can be synthetically, even though unprecisely, described by its equivalent thermal parameters (ETP´s) (see ch. I b).

The last section of this chapter analyzes the methods for measuring emittance, reflectance and transmittance of building materials. An application of growing importance in the field of building science, namely thermography, is described.

- thermal properties of material

It is impossible, except in the case of gases at low temperatures, to predict the value of thermal conductivity, λ, (see ch. I b) theoretically. Therefore, all available information about the thermal conductivity is based on measurements.

In general, λ varies with temperature, but, at least for building materials the change is so small that, in most situations, thermal conductivity can be assumed constant. In a similar manner, the pressure dependence of thermal conductivity may be ignored.

Nevertheless, a factor which strongly affects thermal conductivity is the moisture content of the material. This is especially so for porous materials, i.e. materials consisting of solid matter with small voids. This category includes most of the insulating materials. Therefore, one should always be conscious of this fact when applying values from standard tables of thermal conductivity of building materials. These values generally take into account a certain moisture content of the material and therefore give higher values than those measured in the laboratory on dry samples.

The two standard methods used in the laboratory for the measurement of thermal conductivity in the steady-state and for an oven-dry sample, will here be described to stress the difficulties involved.

The guarded hot plate method (described by ASTM C177), is used for the determination of the existing thermal conductivity of dry homogeneous specimens of building materials. In its simplest form, the apparatus used in this method consists of an electrically heated plate and two liquid-cooled plates, as indicated in fig. III d-1.

Two similar slabs are mounted on each side of the hot plate. A cold plate is then pressed against the outside of each specimen by a clamp screw. The heated plate is divided into two portions: the central or measuring section, and the outer or guard section. During testing, the two sections are maintained at the same temperature, the guard section minimizing errors due to edge effects. The electric energy required to heat the measuring section is carefully monitored. The thermal conductivity of the material can be calculated knowing the energy required, the area of the section, the temperature gradient, and the specimen thickness.

The guarded hot box method (described in ASTM C236), is designed for measurements of non-homogeneous panels, e.g., components such as walls, roofs and floors of buildings. The hot box apparatus, as shown in fig. IIId-2, is a device by which a constant temperature difference can be established across a test panel for the time necessary to ensure constant heat flux, and temperature distribution, across the panel. The apparatus consists of three five-sided boxes: a cold box cooled by a refrigerating machine; a hot box, electrically heated; and a metering box, enclosed in the hot box, electrically heated as well.

The hot box is kept at the same temperature as the metering box to minimize heat exchanges to or from it. Therefore, the heat supplied to the metering box is equal to the heat flux across the panel. Knowledge of the electrical energy supply, the temperature difference, and the specimen area affords the calculation of the thermal conductivity or conductance of the test panel.

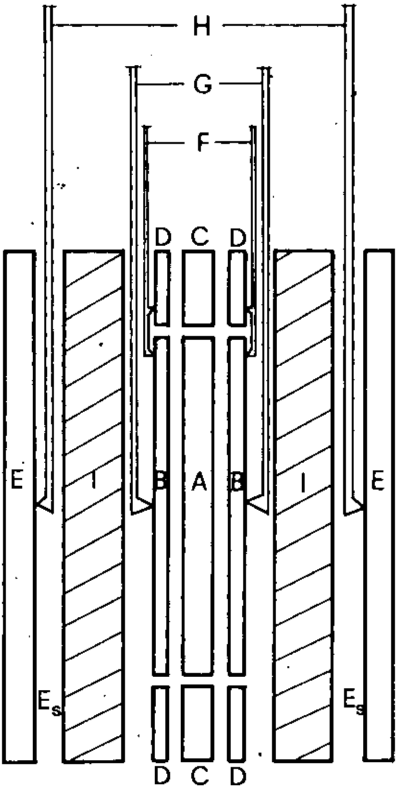

Fig. III d-1

Guarded hot plate apparatus

A- central heater
B- central surface plates — central section of heating unit

C- guard heater
D- guard surface plates — guard section of heating unit

E- cooling units
E_s- cooling unit surface plates
F- differential thermocouples
G- heating unit surface thermocouples
H- cooling unit surface thermocouples
I- test specimens

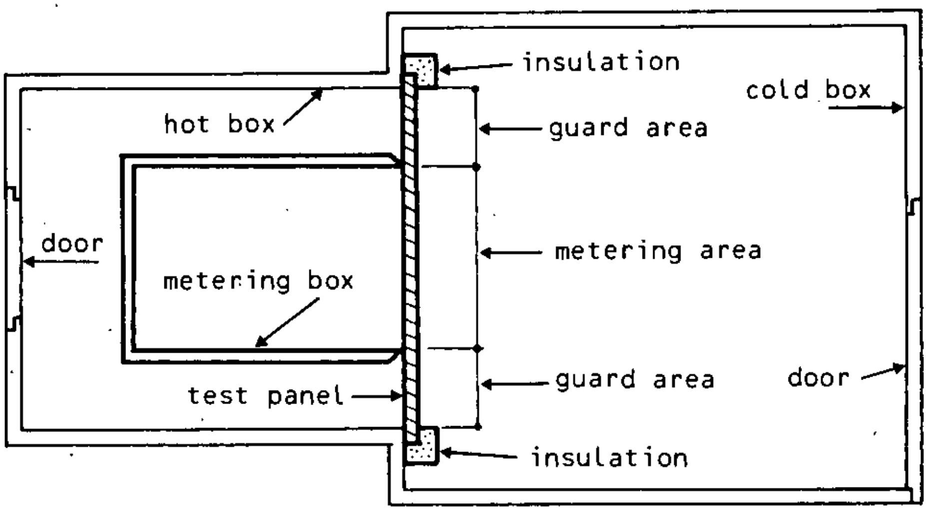

Fig. III d-2 Guarded hot box apparatus

Unfortunately, the two methods presented above cannot be applied to determine thermal conductivity of wet materials, which are the ones used in reality. The reason for this is that the establishment of steady state conditions, required for the tests, modifies the humidity content of the materials.

In order to perform measurements of thermal conductivity of materials in the transient-state, it is not necessary to develop new experimental devices: the "guarded hot plate" apparatus may be used (Fuet et al., 1979, D'Eustachio and Schreiner, 1952, Hooper and Lepper, 1950). In fact, the thermal conductivity of the sample is obtained by analyzing the temperature reaction on the face of the sample affected by an imposed flux. Such an analysis is made possible thanks to the various solutions of the heat equation under specific boundary conditions (see, e.g., Carslaw and Jaeger, 1959). The use of the guarded hot plate in the transient-state reduces considerably the duration of the measurements and thus makes it possible to deal with wet materials. However, this requires an apparatus that can produce cyclic boundary conditions, and the determined value of the conductivity will be valid only for the cyclic frequency of the boundary conditions.

Another transient-state method, named "the heated wire method" has been developed by T.N.O. (Holland) and is based on the theory of cylindrical temperature fields. A constant heat flux is sent into the material through a wire embedded in it. Then, the temperature gradient in the area around the wire (a function of the thermal properties of the material as well as of time and position) is measured. As the temperature at that point varies linearly with the logarithm of time, one can calculate the conductivity.

The main advantage of this method is that it is the only one which has lead to the development of a device which can be used for in situ measurements. This device is called the "λ -probe" (Erkelen, 1960, Hooper and Chang, 1953). It is a needle-shaped instrument that can be inserted into a small hole drilled for this purpose through the wall. This instrument makes it possible to monitor the temperature at different depths in the wall. One can then perform measurements in a non- destructive manner, whereas, formerly, samples had to be extracted from the wall.

A wire heater is dwelled, together with a temperature transducer, in the material under test. Temperature measured near a constant heat source after a certain time is used to calculate thermal conductivity of the material. Fig.

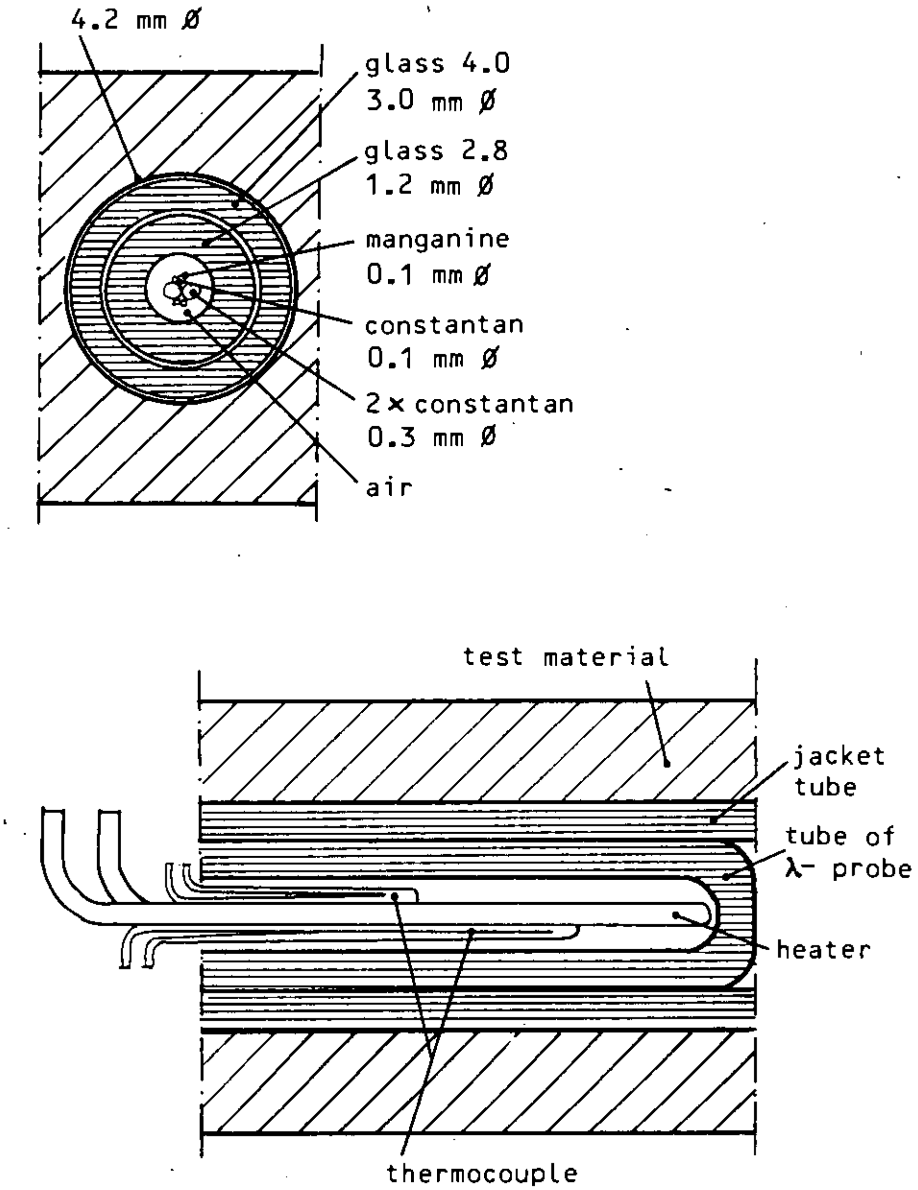

Fig. III d-3 The λ- probe

IIId-3a shows the λ -probe. The heater is a double-folded constantan wire 0.3 mm thick. Glued to this wire are constantan- manganine thermocouples (0.1 mm wire) in the lengthwise direction. In order to save space, each set of thermojunctions has a common constantan wire (see fig. IIId-3b). The whole is then incorporated in a small glass tube with an external diameter of 2.8 mm.

- walls: steady-state parameters

This section is devoted to field measurements of the thermal performance of walls. In steady-state conditions, the parameters which characterize the thermal behaviour of a wall are its thermal conductance and its overall heat transfer coefficient, also called U-value. They are defined in Ch. Ib.

A method of determining the U-value of a building component is to test a representative section in a guarded hot box: the measured and calculated values are generally in good agreement when there are no air cavities within the construction. When there is not sufficient information about the composition of the wall, it is, however, better to perform on-site measurements.

i) U-value of walls

The most common method for the measurement of the U-value of walls makes use of special devices called Heat Flow Meters (HFM) (ASTM C518, Gier and Dunkle, 1954): the basic principle of this apparatus consists in detecting and amplifying the temperature gradient of an auxiliary layer inserted in the thermal circuit.

Most HFM's consist of a thin, thermally and electrically insulating layer which acts as a support to a (e.g. copper-constantan) thermoelectrical circuit. The solderings of the two metals are placed alternatively on the hot side and on the cold side of this sheet. These thermocouples, thermally in parallel and electrically in series, detect and amplify the temperature difference between the two faces of the layer when it is crossed by a thermal flux. The whole probe is generally covered by an aluminium layer to improve the homogeneity of the thermal flow.

The heat flow meter must be calibrated (e.g., by means of a guarded hot plate) to make it ready for on-site measurements: the output voltage is generally a linear function of the heat flow. While (Devisme and Marechal, 1979) the thermal resistance of the heat flow meter is responsible for the temperature difference between its two faces, its thermal capacity is responsible for the difference between the in- and out- going heat fluxes. Therefore, a material has to be chosen having both a sufficiently high thermal resistance and a low thermal capacity.

The definition of the U-value refers to steady-state conditions, and therefore is not directly applicable to field measurements, where steady-state conditions can never be achieved. However, if the energy flowing across the wall, $\dot{q}$, is recorded for a time long enough, the amount of energy stored in the wall can be neglected. Outdoor radiation has also to be taken into account. An approximate way of doing this is to identify the outdoor temperature with the sol- air temperature. Leaving the exact definition of the temperatures till a later stage (see below), we have:

$$U = \int_0^\infty \dot{q}\, dt / \int_0^\infty (T_i - T_o)\, dt \qquad \text{(III d-1)}$$

where

T_i = indoor temperature

T_o = outdoor temperature

$\dot{q}$ = heat flow across the unit area

Measurements cannot actually be carried on for an infinite time. One has therefore to study the errors which may occur because of the finite time used for the integration. These errors depend on the wall construction and weight as well as on the amplitude of the temperature difference during the measurement. The integration time (in eq. IIId-1) to achieve a 10% precision ranges from a few hours up to almost ten days depending on the considered wall (see fig. IIId-4).

Three quantities have to be measured in order to obtain the U-value:

- inside (surface) temperature
- outside (surface) temperature
- inside heat flux

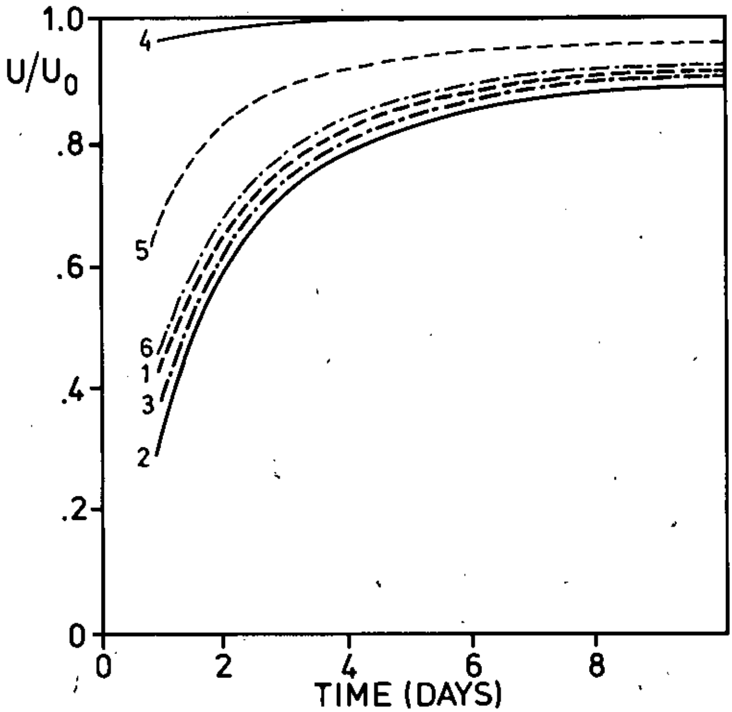

Fig. III d-4 The development of the ratio U/U_o in time during a measurement of the U-value of a wall with a heat flow meter. U is the measured U-value and U_o is the correct U-value (after EMPA 1981).

Table III d-1

U-value and specific mass of walls examined in Figure IIId-4.

N	Type of wall	U ($W/m^2 °C$)	Mass/area (kg/m^3)
1	Brick wall	1.10	407
2	Brick wall	0.90	505
3	Two-shell brick wall	0.40	367
4	Sandwich wall	0.40	8
5	Concrete wall with inside ins.	0.60	387
6	Concrete wall with outside ins.	0.60	387

The measurement of the quantities in parantheses yields the value of thermal conductance. *In theory the heat flux could be measured outside as well* as inside, because the two integrals of heat flux should coincide in the long run. However, this is very often not true, especially when the wall includes an air layer; moreover, the strong outdoor radiation field would emphasize the difference between the HFM radiative properties and those of the wall on which the HFM is inserted.

Since the wall construction is not homogeneous, temperatures and heat fluxes will not be constant over its surface. In this case, an infrared scanner can be extremely useful to assess the thermal state of the wall and choose the points where the measurements should be carried out (Roberts and Reinke, 1982). Particular care should be taken when installing the sensors: for U-value measurements, a wall shaded from direct solar radiation should be chosen. Otherwise, sol-air temperature, defined in Ch. Ib, should be chosen as the representative outdoor temperature; this, of course, cannot be directly measured.

For conductance measurements, where the surface temperatures are required, the temperature sensors should be as small as possible and should be embedded into the wall, under a thin layer of plaster. In this way the short-term temperature fluctuations, due to the turbulence in the boundary layer, adjacent to the wall surface, are automatically averaged, and the problems related to the representativity of the sensor position are diminished.

The use of heat flow meters involves some specific problems, such as:

- additional thermal resistance of the sensor itself;
- alteration of the wall thermal field;
- unsteady-state conditions occurring during the measurements, while the HFM has been calibrated in steady-state conditions;
- difference between radiative properties of the HFM and the wall.
- calibration depends on the properties of the wall the HFM is on

A way of minimizing the second effect listed above is to surround the HFM *with a material having the same thickness and thermal conductivity* as the sensor material. The third drawback can be by-passed if a low-capacity material is employed for the HFM, thus minimizing the heat stored by it. The fourth problem can be partially avoided if the HFM is embedded into the plaster and coated with the same painting as the wall. For further information on these topics see e.g.

Lau and Norberg (1979), Flanders and Marshall (1982).

ii) surface heat transfer coefficients

Surface heat transfer coefficients, h, (SHTC) can be measured using the same experimental setup as for of U-values. The measured quantities are:

- inside (or outside) air temperature, T_a
- inside (or outside) surface temperature, T_s
- inside (or outside) heat flux, $\dot{q}$

The (radiative + convective) SHTC is given by:

$$h = \dot{q} / (T_a - T_s) \qquad \text{(IIId-2)}$$

Since the boundary layer has no thermal capacity, the SHTC can be determined instantaneously. On the other hand, the SHTC is not, as counductance, a constant property of a wall, because it depends on variable boundary conditions such as air temperature, air velocity, solar and atmospheric radiation, etc... Moreover, as experience shows, the SHTC has little physical meaning, since it refers only to the air and surface temperatures, while surface heat transfer is influenced also by other quantities, particularly radiation from the surroundings.

The accuracy with which "h" can be determined depends mainly on how close the radiative properties of the HFM are to those of the wall. The need for precise sensors is even stronger here than for U-value measurements, since the temperature difference in eq. III d-2 is very small.

iii) U-value of windows

The on-site measurement of U-values of windows is not a procedure to be recommended, mainly because of the disturbance introduced by radiative exchanges. Moreover, the U-value of windows depends greatly (and, for single-panel glazings, exclusively) on the surface heat transfer coefficients, which are affected by meteorological factors, varying, in their turn, with time. For these reasons, the procedure presented above can lead to large errors, especially when the window is directly flooded by the sunlight. In this case, the HFM will never be able to reproduce the radiative properties of the glazing itself, especially not its transmissivity.

It is thus advisable to make use of data from laboratory measurements or a theoretical analysis. A mobile apparatus for direct measurement of the energy performance of fenestration systems has been recently developed by Klems and Selkowitz (1981). The so-called Mowitt (after Mobile Window Thermal Test) provides a number of capabilities, e.g.:

- full-scale testing of windows of various sizes and types;
- dynamic performance measurements using real weather conditions, including solar gain;
- flexibility in simulating interior building environments of different weight, insulation, and leakiness.

On the other hand, it should be stressed that the MOWITT does not perform field measurements, but rather operates upon full scale test samples. An interesting feature of this apparatus, based on the principle of the guarded calorimeter, is that it makes use of particular large-area, high-sensitivity heat-flow sensors (Klems and Di Bartolomeo, 1982). This kind of heat-flow sensor is based on alternate current resistance thermometry. The first prototypes, having size of 0.09 m^2, showed linear response, a sensitivity of about 35-40 mV/(W m^{-2}), with a minimal detectable flux of 0.08 W/m^2.

The procedure adopted by Caluwaerts and Verougstraete (1979) for laboratory measurements is also presented. The experimental apparatus is of the "guarded-hot box" kind and has been used to test a number of windows, having different number of glazings and different frames, in different environmental conditions. The following qualitative conclusions can be drawn:

- the U-value is influenced by outdoor conditions, especially by temperature and air velocity;
- the U-value is slightly affected by the heating system, except in the case when floor heating is used, where a relevant decrease has been noticed.
- the U-value is strongly affected, beyond the number of glazings, by the type of frame; PVC, wood and aluminium show respectively growing U-values.
- the window position in the wall opening seems to be irrelevant.

A supplementary heat resistance is provided by curtains (0.03 m^2/W) and outside roller blinds (about 0.25 m^2/W). When there is a radiator under the window, one has observed the effect (Dubbeld 1978) that, compared to a single-glazed window with window sill, the U-value of the window increases with 15% if the sill is removed, decreases by 21% if there are curtains above the radiator or the sill, and increases by 8% if there is a long curtain in front of the radiator.

- walls: unsteady-state parameters

The analysis of time-dependent thermal response of building walls is a useful tool to determine their behaviour under actual transient-state heat loads. Two different approaches can be adopted, both making reference to some theoretical method yielding the flux response of a wall once the properties of each layer are known:

- determine the unsteady-state parameters of the wall.
- validate experimentally the results of the method by comparing the measured flux and the calculated one.

Not all methods are suitable for the first approach; for example, the response factor method makes use of too large a number of independent parameters, compared with the accuracy with which fluxes and temperatures are known. On the other hand, the second approach can always be applied, but yields only indirect information on the wall thermal performance. The determination, in the laboratory, of the parameters of the Fourier transform analysis, and the "Envelope Thermal Test Unit" method belong to the first category.

i) determination of the parameters of the Fourier transform analysis

The Fourier transform method provides four complex coefficients A_ν, B_ν, C_ν, and D_ν, (defined by Eq. Ib-8) for every frequency considered in the thermal oscillations. These coefficients depend on $T_{i\nu}$ and $T_{o\nu}$, the indoor and outdoor air temperature, and on $\dot{q}_{i\nu}$ and $\dot{q}_{o\nu}$, the indoor and outdoor heat fluxes. The measurement of these coefficients can be performed in the laboratory, according to the procedure developed by Codegone, Ferro and Sacchi (1966) and briefly outlined here.

For the measurement of parameter A_ν, two identical wall elements are placed close to each other so that, e.g., the outside surfaces are in close contact, and equal temperature sinusoidal oscillations are imposed on the inside surface of the walls. Therefore, since $\dot{q}_{o\nu} = 0$, the coefficient A_ν is given by $A_\nu = T_{i\nu}/T_{o\nu}$.

For the measurement of parameter B_ν, using the same experimental set-up as before, a thin layer of known thermal capacity and high diffusivity is inserted between the two symmetrical wall elements in close contact with the outsides. By imposing equal temperature oscillations on the inside surfaces and recording the surface temperatures, one gets:

$$B_\nu = (T_{i\nu}/T_{o\nu} - A_\nu)/\ (\dot{q}_{i\nu}/T_{o\nu})$$

The two wall elements are reversed so that the inside surfaces are in contact. In this case, since $\dot{q}_{i\nu}=0$, the coefficient D_ν is given by $D_\nu=T_{o\nu}/T_{i\nu}$. The last coefficient, C_ν, is calculated from the relation $A_\nu*D_\nu - B_\nu*C_\nu=1$ (see ch. Ib), or by inserting a thin layer between the walls, in this case in contact with the insides.

ii) the Envelope Thermal Test Unit Method

The Envelope Thermal Test Unit (ETTU) is a portable modification of the "guarded hot box" (Condon, Carroll and Sonderegger 1980). It can be used both for field and laboratory measurements. It provides the dynamic thermal properties of walls, with reference either to a dynamic simplified model using a set of Equivalent Thermal Parameters (ETP´s) (Sherman, Sonderegger and Adams, 1982), or to the Fourier transform method described above.

The basic principle on which ETTU is based is that a regulated heat flux is applied on one or both sides of the walls, and the resulting surface temperatures are measured. The ETTU consists of two identical "blankets" which are placed in close thermal contact with the wall to be tested. Each blanket is made of a pair of electric heaters separated by an insulating layer of low thermal capacity. Temperature transducers are placed in each heater layer. Heat is provided to the inner (primary) heaters, while the outer (secondary) heaters act as guards.

A microprocessor-controlled data acquistion system is used to drive the system and record the system temperature responses. The analysis is restricted to the central region of the blanket to reduce the effect of transverse heat flow. The secondary heaters are driven by a servo-control which drives their temperature towards the primary heaters temperature, thus minimizing the heat provided by the blanket which is not contributing to driving the wall.

iii) experimental validation of the transfer function coefficients

Using the response factors method, the internal surface heat flux is given by eq. Ib-9. The unknowns are the sets of coefficients c, b, d; all other quantities can be measured using the procedure outlined for the measurement of the U-value.

There are several numerical methods to solve the equations above, but it should be stressed that the system may be ill- conditioned, thus yielding very different results for small variations of the coefficients. A better approach (Cli et al., 1979) consists of two steps:

- the c, b, d coefficients are computed according to the procedure outlined by Mitalas and Arseneault (1967) or using the pre-calculated values reported in the ASHRAE Handbook of Fundamentals (1981);
- the heat flux convolution, calculated using the measured temperatures in eq. I b- 9, is compared to the heat flux values, measured by the HFM technique previously described.

- measurement of radiative properties

i) radiative properties of building materials

The radiative properties of building materials, defined in Ch. Ib, do not differ significantly from one material to the other; moreover, the values provided in the literature may often be confidently applied. In some special cases it may, however, be useful to determine experimentally the radiative properties of building materials. In this case, different approaches and instruments must be used whether one is dealing with shortwave or longwave radiation.

The transmittance of shortwave (solar) radiation (0-4 μm) can be measured using the same instruments as those presented in ch. IIIb for solar radiation measurements. With two solarimeters (pyranometers) placed on the two sides of a glazing, and parallel to it, one can measure the incoming global solar radiation flux outside I_0 and inside I_i the window. The ratio I_i/I_0 can be defined as the shortwave transmittance, τ_s, of the glazing.

Reflectance can be measured, as before, using two solarimeters, one facing the wall, and the other facing the opposite direction. If I_r is the shortwave (solar) radiation reflected by the wall and I_0 the one impinging on the wall, we have $\rho_s = Ir/Io$

The third radiation coefficient, α_s (absorptance), can be easily deduced from the relation $\rho_s + \alpha_s + \tau_s = 1$ (see ch. Ib).

The value of the shortwave radiation coefficients will depend on the incidence angle of direct solar radiation, and therefore on the ratio of direct to (diffuse + reflected) solar radiation.

The transmittance of longwave radiation (4 - 100 μm), τ_ℓ, is generally assumed to be negligible both for glazings and opaque walls. The longwave reflectance, ρ_ℓ, is defined analogously to short- wave reflectance. However, an instrument for longwave radiation measurement (pyrgeometer) facing the wall will read not only the reflected component, but also the emitted radiation, I_e :

$$I_e = \varepsilon * \sigma * T^4$$

where

ε = the emissivity of the surface

σ = the Stefan-Boltzmann constant

If I_{e+r} is the value given by this instrument, and if I_o is known from a measurement performed with the same type of instrument, we have $\rho_\ell = (I_{e+r} - I_e)/I_o$ and $\rho_\ell = (I_{e+r} - \varepsilon\sigma T^4)/I_0$, and, since $\rho_\ell + \alpha_\ell + \tau_\ell = 1$ and $\varepsilon = \alpha_\ell$ (see Ch. Ib), we get

$$\rho_\ell = (I_{e+r} - \sigma * T^4) / (I_o - \sigma * T^4)$$

As before, applying $\rho_\ell + \alpha_\ell + \tau_\ell = 1$, absorptance can be immediately found.

ii) thermography

The term termography is. used to characterize the process which makes visible and quantifies the thermal state of a given object. The basic physical principle on which it is based is the relation existing between the surface temperature of a body and the infrared radiation it emits.

The instrument employed is the infrared scanner which, generally, records the radiation of wavelengths between 2 and 5.6 µm, or between 8 and 14 µm. These two intervals have been chosen because they correspond to two atmospherical "windows" where the transmission of infrared radiation is nearly independent of the humidity content of the atmosphere.

Once the radiation emitted by the object under observation has crossed the atmosphere, it is localized with the help of suitable objectives (just like in photography, it is the objective which determines not only the size of the image field, but also its spatial resolution). The objectives must be made of materials transparent to infrared radiation (e.g. silicium or germanium) and are optically treated in order to increase their transmissive power.

Once localized, the emitted radiation is projected on to the infrared detector by means of a scanning mechanism (2 silicium prisms optically treated and driven by 2 synchronous motors in the AGA camera).

The detector is a semi-conducting material (indium antimonide In Sb for systems working in the range from 2 to 5.6 µm or mercury cadmium tellurium Hg Cd Te for those working in the range from 8 to 14 µm), which has the property of converting the incoming infrared radiation into an electrical signal, the intensity of which varies with the energy of the incident signal. In order to guarantee a high thermal resolution (e.g. 0.1 K at a temperature of 30^{o}C for the AGA 780 camera) such detectors are placed in a Dewar vessel and cooled with liquid nitrogen. Next, the electrical signal emitted by detector is electronically treated, in order to obtain, on the screen of an oscilloscope, the thermal image of the object under consideration. This thermal image can be photographed with an ordinary camera, thus obtaining a thermogram.

Certain types of scanners reproduce the temperature distribution both on a grey scale (ranging from black to white) and on a colourscale. In the black-and-white thermal image, portions, which are darker in the grey scale, represent surfaces of a lower temperature than portions of a lighter grey colour. In a colour-thermogram, each shade of colour corresponds to a certain temperature interval. A clear picture of the distribution of temperature over the surface is obtained.

The basic difference between a thermal image and a photographic one is that the latter reproduces the reflected radiation within the visible range, while the thermal image reproduces both part of the reflected radiation and part of the emitted radiation.

A thermal image often has a coarser structure and the contours are more diffuse than those of a photographic image. This is primarily due to the difference in resolution, but also to the fact that the boundaries of the surface are sometimes less definite because of thermal conduction.

It is evident from the working process of the infrared scanner that only relative temperature differences in the image field can be determined. If the actual temperature of the surface is to be determined, it is necessary to know the actual temperature of a reference point on the surface under test; the emissivity of the reference surface and of the entire object, and finally, the temperature function and calibration curves of the camera.

A correction due to the attenuation of thermal radiation in air (primarily caused by the absorption which occurs in the molecules of gas, and by the absorption and dispersion which occurs in particles) should be necessary whenever measurements are made over distances greater than 10-20 m (see fig. IIId-5). Thus, for the measurements made over the distances common in thermography indoors, the influence due to the distance is negligible.

According to investigations made in Sweden (Pettersson and Axén 1980), the probable error in determining differences in surface temperatures with an IR scanner in the range of room temperatures can, by assessing the errors in the components along the chain of measurements, be estimated to 10% of the measured temperature difference, but not better than 0.5 K.

Finally, in order to correct a misleading interpretation, we want to stress that thermography does not directly give the thermal resistance or airtightness of the construction. In cases where the thermal resistance or airtightness are to be quantified, additional measurements, as those indicated in the preceeding sections, must be made.

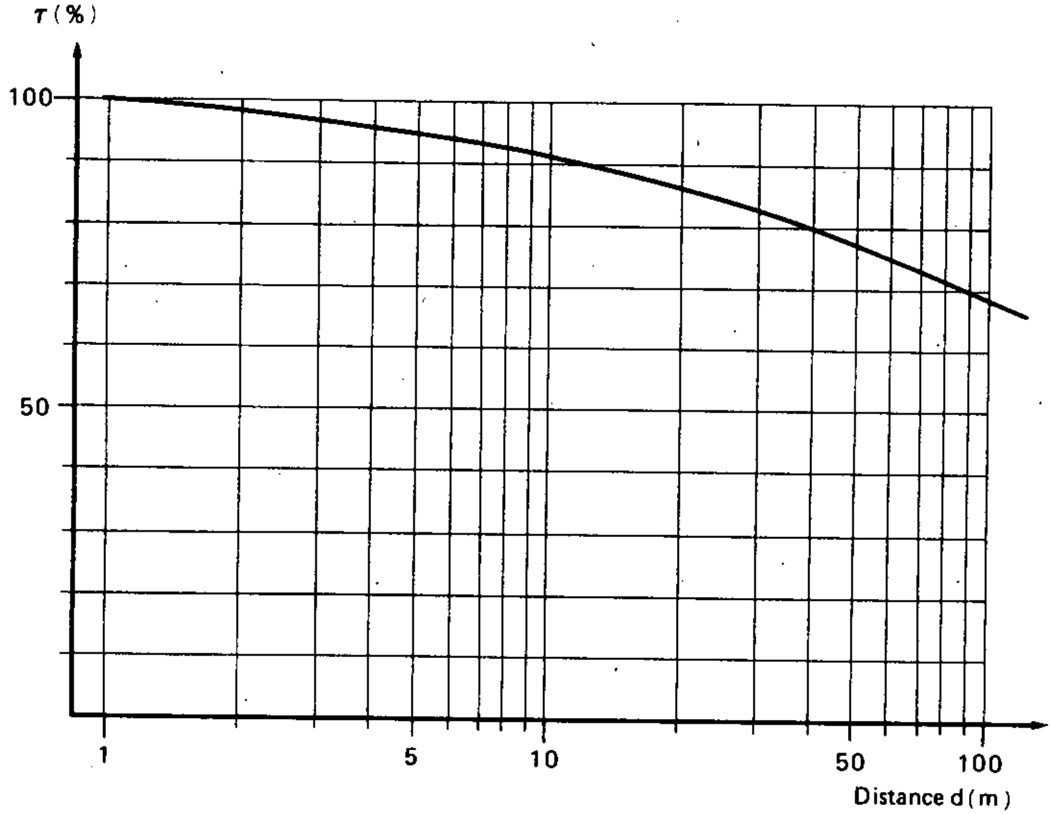

Fig. III d-5 Transmissivity (τ) for infrared radiation in air as a function of the distance (d). Typical curve.

The already mentioned publication (Pettersson and Axén 1980) developes a complete analysis of the requirements which must be satisfied when buildings are subjected to thermography. Moreover, this publication also gives the rules for the interpretation of thermograms and the use of comparative thermograms. It deals also with the problem of correct camera setting for the quality of the thermal image, and with the reliability of this method, i.e. the possibility of locating and determining with satisfactory accuracy defects in the insulation and airtightness of a building. Therefore we need only report the main recommendations for the use of thermography.

Thermography is to be carried out in such a way that the least possible interference occurs due to external climatic factors. Measurements should therefore take place indoors. Outdoor thermography is to be applied only for preliminary measurements over large wall areas. In certain cases, for instance when thermal insulation is very bad or when the pressure indoors is higher than that outdoors, these measurements outdoors can provide valuable information. The following conditions should be satisfied:

1) For at least a 24- hour period before starting thermography, and while it is in progress, the difference in air temperature across the building element must be at least 10 K. At the same time, the difference between the indoor and outdoor temperature should not vary by more than 30%. When thermography is in progress, the air temperature indoor should not vary by more than 2 K.
2) For at least 12 hours before starting thermography, and as long as this is in progress, the building element in question shall not be exposed to sunshine to such an extent that it can influence the results.
3) The pressure drop across the construction shall be 5 Pa.

Of course, these rules regarding conditions during measurement limit the *period when thermography can be carried out.*

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CHAPTER III e

Air infiltration

Contents

Keywords

air changes per hour (ACH)
air infiltration
airing
bypasses
constant concentration technique
constant flow technique
container sampling
decay technique
gas analyzer
heat recovery
leakage area
leakage site
pressurization
standardized techniques
tracer gas
ventilation
wind induced air infiltration

III e Air infiltration

- importance of air infiltration to retrofits

By air infiltration we will here mean the uncontrolled leakage of air into a building through openings in the building envelope such as cracks and interstices, and through ceilings, floors and walls. Exfiltration is the uncontrolled air movement out of the building. Generally air infiltration is applied to both inward and outward uncontrolled air movement.

By ventilation is here meant the process of supplying and removing air by natural or mechanical means to and from any space. Such air may or may not be conditioned.

In many cases one has to consider also air flows in the interior of the building through bypasses. By this is meant the unintentional openings within the building that allow air to move from one space to another. Examples include openings around plumbing and exhaust stacks that provide a path for lining space air to enter the attic. Such openings are often a main air infiltration component.

Reviewing the studies of infiltration in Europe and North America, energy losses due to air infiltration and ventilation in existing housing is generally stated to amount to between 20 and 40% of the energy used for space heating. Infiltration rates in the housing vary from approximately 0.1 ACH for the tightest of new housing to several ACH for leaky, older dwellings. Recent data (Grot 1979) collected in several hundred low income, older residential houses located in the United States indicate an air exchange rate very close to one air change per hour (ACH), the value used in many ASHRAE calculations. However, the air infiltration level can vary significantly from house- to- house and location- to- location. Normalizing for leakage area, fig. III e-1 illustrates the variations across the United States due to weather/location factors.

The air infiltration component of heat loss is often the most cost-effective to correct in an overall retrofit strategy, provided proper detection methods are used (such as infrared scanning combined with depressurization). Simple measures may often be taken to reduce air infiltration levels to those

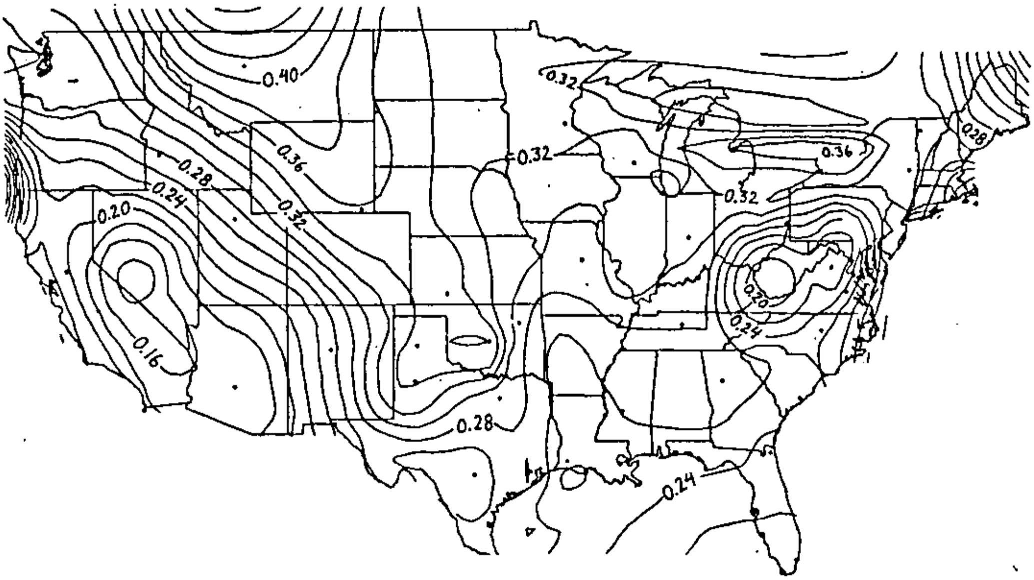

Fig. III e-1 Heating season average infiltration for the United States (48 of 50) expressed as air flow per equivalent leakage area, ELA (m^3/ h,cm^2). Data from the contour may be translated to ACH for an individual house by multiplying by the ELA and dividing by the house volume, e.g. 0.30 translates to 0.83 ACH for a 360 m^3 (150 m^2) house with a 1000 cm^2 ELA.

associated with reasonable energy loss and the maintenance of desirable, indoor air quality.

Air infiltration often takes place through cracks and holes that are present because of poor building components and practices, and the settling of the buildings as they age. Traditionally, windows and doors have been considered the most important sites of such air infiltration. However, testing by several groups (Tamura 1975, Caffey 1979, Collins 1979, Harrje et al. 1979) has revealed that, although important, leakage in frame construction associated with these components tends to constitute a fourth or less of the overall equivalent leakage area (an area that would provide equivalent flow through an otherwise tight envelope). Construction using plastic vapor barriers and extremely tight masonry construction would tend to alter this breakdown and place more emphasis on door and window leakage.

Construction features that are associated with the way in which walls, ceilings and floors join each other, and how electrical and plumbing components pass through the envelope, have been proven to be even more important. Two questions need to be resolved:

1) where are the specific leakage sites in each housing style within a country?
2) how can the undesired air leakage be reduced to an acceptable level through an economical and structurally sound retrofit procedure?

Without such retrofitting the air infiltration in the homes will remain very susceptible to changing weather conditions as shown in fig. III e-2.

The identification and relative magnitude of the leakage sites have been investigated in a number of new and old American houses (Tamura 1975 and Caffey 1979) as shown in Tables III e-1 and 2. Here the leakage of the floor -wall joint is very evident as are the problems associated with electrical outlets and duct systems. (The electric outlet leakage seems unnaturally high, but the table is used to illustrate that many components can provide air leakage. These components could also be grouped differently since openings where interior walls meet ceiling are noted as soleplate and electrical outlet leakage, for example).

These data are shown as an illustration that leakage may result from a variety of sites including doors and windows. Control of such leakage must be achieved if the triple goals of low energy use, suitable comfort and a healthy indoor environmet are to be attained.

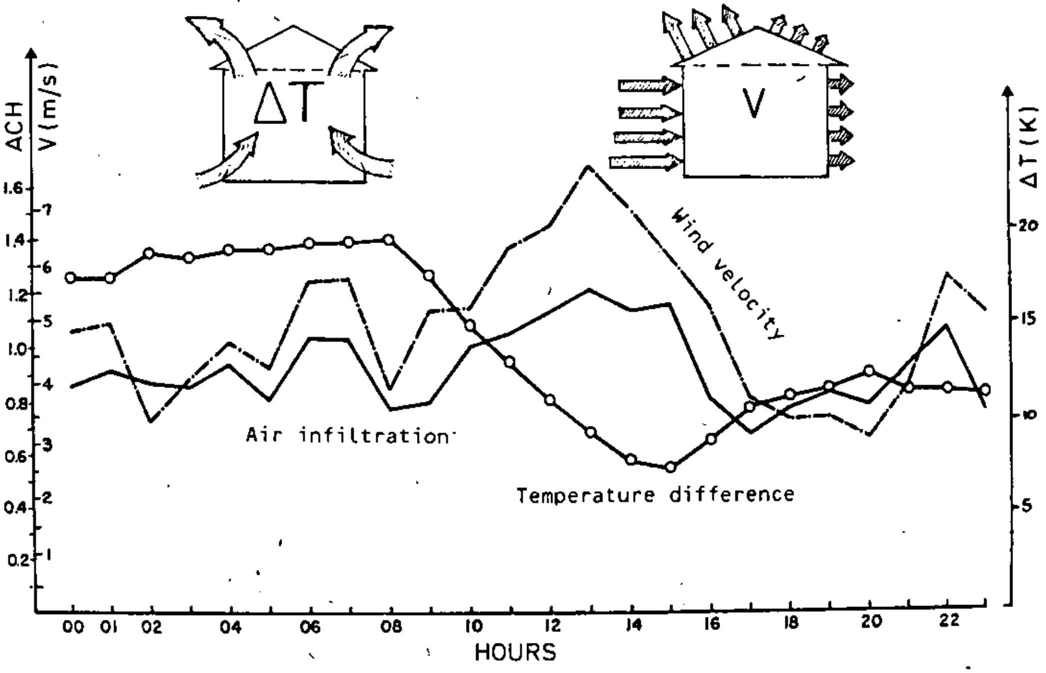

Fig. III e-2 Wind (v) and temperature (ΔT) induced infiltration recorded on automated monitoring equipment.

TABLE III e-1

Infiltration test results (after Caffey 1979)

Location of Leak	Leakage per item (m^3/h,unit)	Number of units	Total leakage	Percent of total	Cummulative
Soleplate	20.2/m crack	53 m crack	1070	24.6	24.6
Electrical wall outlets	13.6/outlet	65 outlets	883	20.3	44.9
A/C duct system	587/system	1 system	587	13.5	58.4
Exterior window	39.5/window	13 windows	513	11.8	70.2
Fireplace	239/fireplace	1 fireplace	239	5.3	75.7
Range Vent	226/range vent	1 range vent	226	5.2	80.9
Recessed spot light	56/light	4 lights	200	5.2	86.1
Exterior door	66.7/door	3 doors	122	4.6	90.7
Dryer vent	122/dryer vent	1 dryer vent	122	2.8	93.5
Sliding glass door	74/door	1 door	74	1.7	95.2
Bath vent	56/bath vent	1 bath vent	56	1.3	96.3
Other			152	3.5	100.0
Total			4348 m./h		

TABLE III e-2

Total leakage rates of typical houses (after Tamura 1975)

House type/Exterior finish of house	Total Leakage (m^3/h)	Ceiling (%)	Outer walls (%)	Doors/Windows (%)
One story stucco	1160	65	16	20
One story stucco	1100	57	21	22
One story brick	2410	16	65	19
One story brick	2620	34	42	24
Two story brick	2170	8	77	15
Two story brick	2240	11	66	23

The plot in fig. III e-1 is indicative of variations predicted for heating season average air infiltration. Where detailed air infiltration measurements have been conducted both during the heating and cooling seasons, it is evident that summer air infiltration rates tend to be substantially less (order of half the winter rates). This is because the inside -outside temperature differences are reduced as well as the average wind in many instances. Under mild weather conditions housing of only average tightness can experience very low air infiltration rates. This poses the vital question: can such variable air infiltration levels, highly dependent on weather, provide the necessary ventilation and proper indoor air quality throughout a typical year?

The documentation of total air change rate including air infiltration and ventilation through the full heating (and cooling) season is almost nonexistant, apart from a few studies (Owen Corning and de Gids 1977).

The role of the occupant of the building on the air exchange rate cannot be overlooked as an energy flow item. Occupant attention to those house items controlling ventilation is critical here. Questions arise: Are windows and doors closed properly, making full use of latching mechanisms? Are vents periodically checked for proper closure? What are the use patterns of vent fans in bath, kitchen and window areas? Is airing excessive or unnecessary? Thus, the house has a variable leakage rate from the occupant- related activities (see ch. II e, IV c and Socolow et al. 1980).

A major concern of those who have studied air infiltration is whether tightening the envelope of existing structures or improving the tightness of new buildings will result in indoor air quality problems. Excessive increases in humidity may be a warning sign that ventilation, whether natural or forced, is inadequate. When moisture levels saturate building materials, additional problems result, e.g., loss of insulations properties, rotting of wood structure, mold and odour problems, etc. For a further discussion on air quality problems see ch. Ic.

- tracer gas measurements

i) properties of tracer gas

The use of tracer gas, as the name implies, provides a method by which the air in the building can be identified so that an accounting can be made as to how much outside air replaces it. This method is then used to measure the ventilation rate in buildings or parts of a building. A wide choice of tracer gases is available, but the choice is strongly reduced when the agreement with the following criteria (Bargetzi 1977, Honma 1975) is checked:

- the gas concentration must be measurable with good accuracy, even when highly diluted
- the gases present in the indoor air should not affect the tracer gas analysis
- the gas should be cheap and easily available
- the gas should not be hazardous when breathed in the concentrations used for measurements
- the gas must not be flammable or explosive
- the gas density should be as close as possible to that of the air (unless one can demonstrate that the achievment of uniform mixing is not a problem)
- the gas should not be normally present in the ambient air

The most common choices, according to the previously listed criteria, are sulphur hexafluoride (SF_6) and nitrous oxide (N_2O), also known as laughing gas.

ii) tracer gas techniques

The general equation of concentration versus time of a gas diluted in the air of a limited space is:

$$C(t) = C_b + F*(1-\exp(-n*t))/(n*V) + C_o*\exp(-n*t) \qquad \text{(IIIe-1)}$$

where

$C(t)$ = concentration, function of time t (in hours)

C_b = background concentration of tracer gas in ambient air

F = tracer gas flow, m^3/h

n = rate of ventilation, air changes/h

V = volume of the space, m^3

C_o = initial concentration of tracer gas

The rate of ventilation is the unknown of eq. IIIe-1, which can be solved after it has been simplified using three different experimental procedures:

1) decay technique
2) constant flow technique
3) constant concentration technique

1) When the decay technique is applied, a small quantity of tracer gas is added and mixed with the air in the building, circulating the air by waving a fibre board sheet, using one or more floor fans, using the warm air system in the home, etc. After seeding, the concentration decay is observed over time. If $C_b = 0$ and since $F = 0$ during the measurements, eq. III e-1 yields:

$$n = (\ln C_0 - \ln C(t))/t \qquad \text{(III e-2)}$$

The rate of ventilation n represents the slope of a straight line when ln C(t) is plotted against time. However, it has been demonstrated that a more accurate way of determining the air infiltration rate is to use the expression obtained by integrating the (exponentiated) eq. III e-2 (Sandberg 1982):

$$n = (C_0 - C(t))/\int_0^t C(t)dt$$

where

$\int_0^t C(t)dt$ is the area below the concentration curve in a (t, C(t)) plot.

The use of tracer gas techniques can involve anything from a short term check of an hour or so, to long term monitoring of a week or even a year or more. For the short term tests, the detector can be brought to the site and (after seeding with the appropriate amount of tracer gas) the concentration decay monitored over a period of two hours.

Another approach is to seed and then gather samples of the building air in bags or bottles. Sampling before and after retrofits can be done in this manner. These containers are then analyzed "back at the lab". This approach allows sampling at a number of field locations (over the same time and weather period if desired) with one laboratory maintained detector. Additional details are provided on this technique because of its simplicity in the evaluation of building retrofits. The method used in the case of bottle sampling is almost identical to that used with the bag samples. The step- by step process used in the National Bureau of Standard study (Grot, 1979) is shown in fig. III e-3. One variation is that the tracer gas, SF_6 in this case, may be also provided in

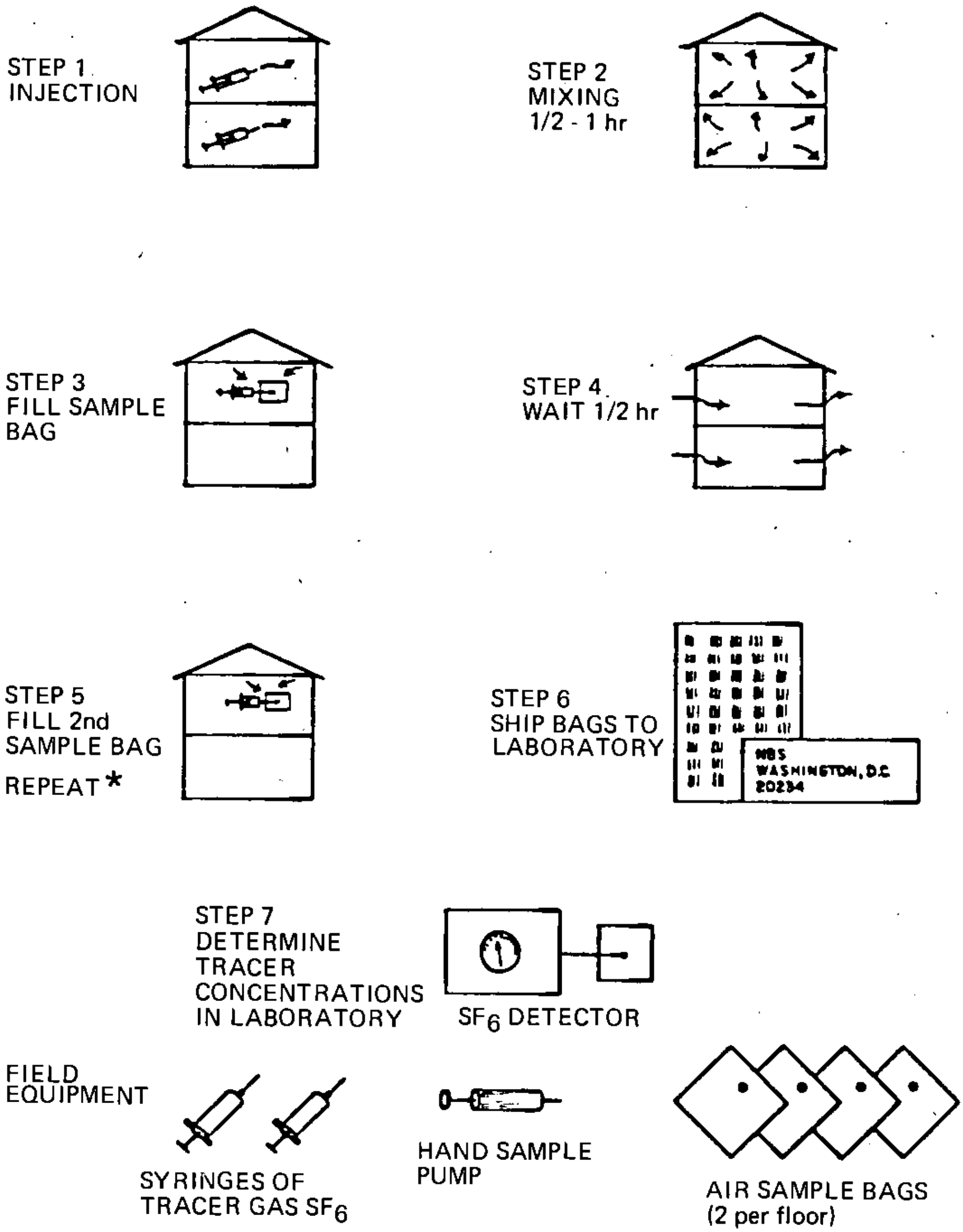

Fig. III e-3 Procedure for bag sampling (after Grot 1979) bottle form together with empty sample bottles.

One can proceed as follows: loosening the.cap on the SF_6 bottle one need only walk around the house squeezing the bottle to achieve seeding of the SF.. Periods when wind speed tends to be low are normally chosen for the test. Outside and inside temperatures are recorded as well as wind speed. With a warm air system one can use the furnace blower to finish the mixing process. If the ducting system does not couple with the outside air, the furnace blower may be used throughout the test period. If such coupling is suspected, a measurement with furnace blower on, intermittently, or on over the test period, will immediately reveal such coupling by registering an elevated air infiltration rate. The normal on cycles (e.g., 20 minutes out of the hour) of the furnace have proven to be more than adequate to maintain reasonably uniform gas concentrations in the house. One or more floor fans may be necessary with hydronic ar electric baseboard heating.

Following the initial mixing period, bottles are filled every half hour with representative air samples (six numbered bottles over 1/2 hours with times noted). Squeezing the bottles first from one side and then 90^{0} away, for ten squeezes, fills the bottles with room air. One central location in the house has usually proven adequate. Returning the bottles to the lab, by mail if necessary, one is ready for analysis using the equipment as shown in fig. III e-4. Each of the bottles has a natural rubber gasket and the plastic cap has been drilled so that the SF_6 detector probe, which is adapted to a hypodermic needle, can be inserted into the bottle (the gasket acts as a septum with many reuses possible). As air is withdrawn from the bottle at a controlled rate (as measured by a sensitive flow meter), pressure must be exerted on a bottle to avoid injestion of room air. This is achieved by a weighted clamp. SF_6 concentrations are recorded for each of the six sample bottles (double or triple readings can also be taken as a check on possible error) together with the previously noted time and temperature data. A simple hand- held calculator program provides the air exchange rates over the five periods.

Automated monitoring requires more complex equipment. Such equipment, if it uses discrete sampling to observe the tracer gas concentration decay, requires that periodically new tracer gas must be injected and that the readings must be recorded on a regular basis. An example of such an automated system that has been developed for a variety of air infiltration measurement applications is shown in fig. III e-5 (Harrje et al. 1975 and 1977). The most recent developmet in this type of equipment uses a micro-computer to control

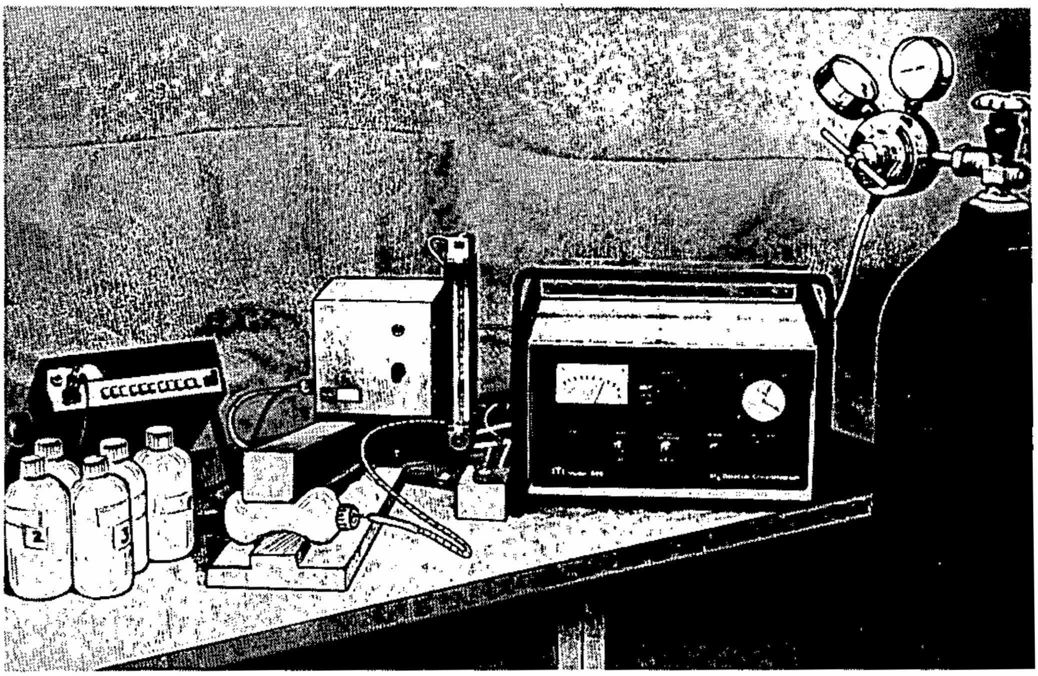

Fig. III e-4 Equipment for bottle sample analysis for air infiltration. Bottle squeezer, flow meter, SF_6 detector.

sampling from a variety of building locations (Grot et al, 1980).

The main advantage of the decay technique is its simplicity both in the ease of preparation of the test and in the analysis of the results. To provide accurate results, however, uniform mixing of the tracer gas with air in the test volume must be provided. However, this is true for all three techniques.

2) Another approach using tracer gas utilizes a constant flow technique (see Harrje, et al., 1977). This means the tracer gas is steadily injected, thereby minimizing mixing problems between tracer gas and the house volume under measurement. Since the concentration is not constant, a volume term will be present and the eq. III e-1 becomes:

$C(t) = F*(1 - \exp(-n*t))/(n*V)$

which yields:

$n = F/(C*V) - \exp(-n*t)/(C*V)$ (III e-3)

The time rate of tracer gas concentration is recorded using an appropriate detector. That portion of the record where the concentration changes are small represents the condition where the second term in eq. III e-3 represents a small correction. The system can run for days and thus give continuous infiltration measurements. One disadvantage of the system is that large changes of the air infiltration rate will drive the gas analyzer off scale thus loosing the data (Sherman et al. 1980).

As previously discussed, long term averaging of air infiltration is necessary for proper accounting of associated energy loss. A simpler, low-cost version of the constant flow system is being used to meet this need (Sherman et al. 1980). The system makes use of two sampling pumps. One slowly pumps a bag of tracer gas (SF_6) into the home over a period days; another pump slowly fills a bag with house air containing a representative concentration within the range of the detector. Measurements of SF_6 to 0.001 ppm allow high sensitivity and a large dynamic range.

Adding a micro-processor to a constant flow system allows adjustment to avoid the off-scale problem previously mentioned. Grot et al. (1980) refer to "continuous flow" infiltration monitoring in describing this system. As in the tracer gas decay automated system, the micro-processor plays an active role and calculated values are stored.

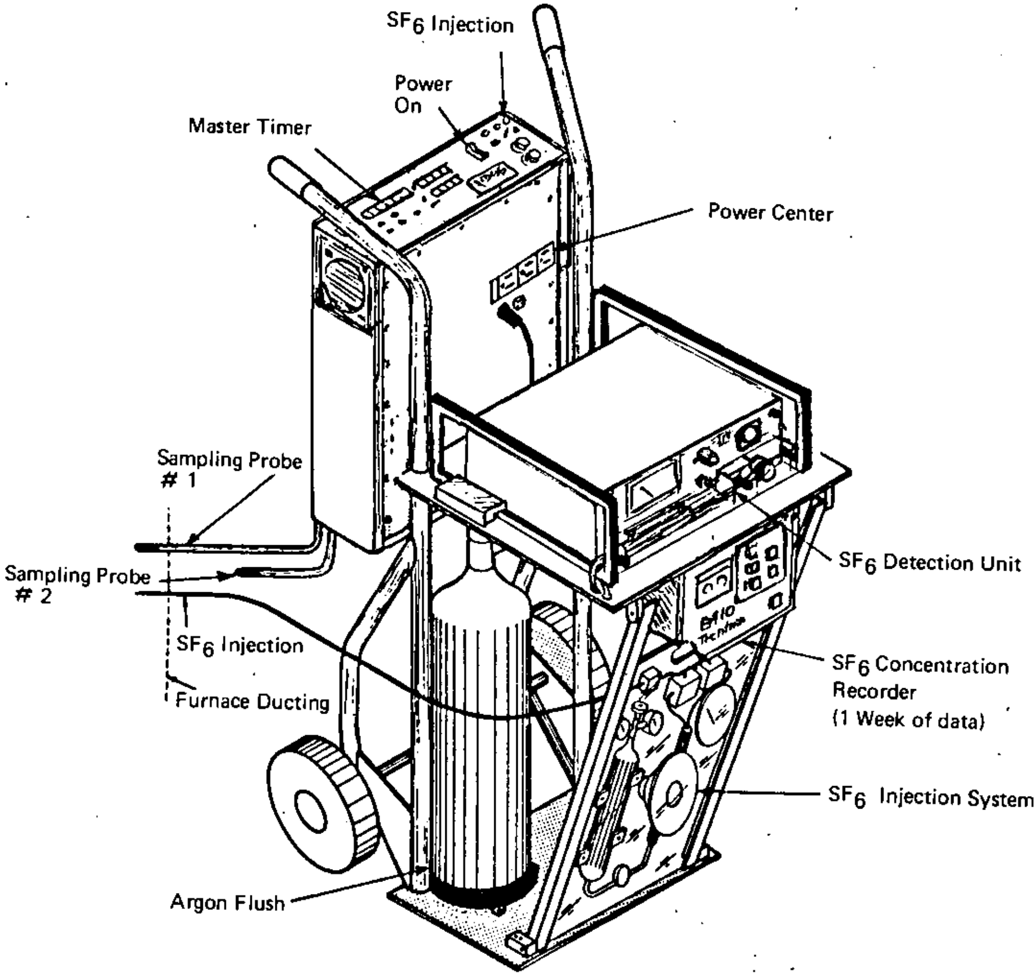

Fig. III e-5 Automated air infiltration unit

The main advantage in the use of constant flow technique is that it allows for the continuous measurement of the air infiltration rate, whereas the decay technique provides an average value over a period (a period that can be less than one minute, however).

Among the disadvantages of the constant flow technique one should mention the larger amount of gas consumed during the measurements, and a requirement to estimate infiltration rates to keep the tracer concentration levels within suitable bounds.

3) The ultimate system for air infiltration measurement would maintain a constant concentration of tracer gas. This is referred to as the constant concentration technique. In this case eq. III e-1 becomes: $n = F/CV$. However, this requires a feedback-type design where the rate of injected tracer gas is directly proportional to the building air exchange rate.

This is a difficult problem to solve. Developments on such new measurements systems have been reported (AIC 1980). In multi-zone buildings, whether zoned houses or more complex structures, it is necessary to maintain constant concentrations to analyze multi-chamber interactions. Some of the systems are measuring as many as ten zones simultaneously. An alternative solution is to use a variety of tracer gases and detectors.

iii) measurement equipment and Standards

All three experimental procedures previously described need the same basic equipment, not necessarily at the test site, that is:

- a cylinder with tracer gas, provided with a valve
- a gas analyzer
- tubes (rubber or plastic) for suction and/or injection of gas
- a recording device, or, at least, a watch.

The gas analyzer itself is by far the most sophisticated part of the experimental apparatus. For example, to detect SF_6 one version of the equipment includes a portable gas chromatograph, coupled to an electron capture detection system. The gas chromatograph separates the SF_6 from other background gases, including oxygen, and the detector supplies the quantitive information as to the actual gas concentration. The sensitivity of current equipment allows concentrations below 0.001 ppm, thus the amount of SF necessary to seed a typical house is less than 40 cm^3 (Harrje et al., 1975). Such equipment is rather expensive.

In contrast, the gas analyzer used with N_2O is based on the principle of measuring the change in the infra-red absorption characteristic of the air/N_2O mixture; it usually works with tracer gas concentrations up to 1000 ppm.

Detectors for other tracer gases can use such principles as thermal conductivity or chemiluminescence. In general it can be stated that all detectors are of comparable complexity and cost.

Determination of the air leakage rate in building has necessitated the generation of standards as to methods. In the United States such a standard has been developed (ASTM 1980). This is a "standardized technique for measuring air change rate in buildings under natural meteorological conditions by tracer gas dilution". The Standard cautions that it does not cover individual building component contributions to air change rates and that a knowledge of the principles of gas analysis and instrumentation is required. The Standard points out that "current state of the art does not possess analytical techniques to extrapolate precisely measured air change rate to meteorological conditions different from those prevailing during measurement". Safety precautions concerning the maximum allowable concentration of tracer gas are stressed. In order to insure that maximum concentration allowances are not exceeded locally, the Standard suggests concentrations be targeted no higher than one quarter of the maximum.

The Standard indicates that release of the gas, in order to insure proper mixing, is dictated by the building and air handling system(s). Forced air systems help promote good mixing, while in many other situations floor fans must be deployed. Homogeneity of mixing determines when sampling for air exchange rate can begin. The Standard states that mixing is sufficient when samples from a number of locations in the volume to be measured differ by less than 5%. In residential structures "two or more samples from widely separated locations are required. In multi-storey structures, two widely separated samples per floor are required". Sampling networks are also described which allow one to blend air samples prior to concentration analyses.

Calibration of the gas analyzer is emphasized in the Standard using "standard mixtures of at least two different concentrations in the range anticipated for the actual test, unless manufacturer's specification allow single point calibration".

According to the Standard "insufficient data exists for purposes of precision and accuracy determination. A reasonable estimate of the uncertainty in a given air change rate determination is of the order of 10% or less". Indoor-outdoor temperature difference and wind speed and direction are often strong functions of the air change rate and should be taken into account "when interpreting or comparing air change rate data".

- pressurization of buildings

An approach to rating the tightness of a building envelope makes use of pressurizing, or depressurizing, the building, and measuring the air exchange rate under these artificial conditions.

Several countries use this approach. Efforts to correlate these measurement with tracer gas measurements have been made (Blomsterberg and Harrje 1979, Kronvall 1980, Sherman and Grimsrud 1980, Nylund 1980). Used as a leakage rating method, the pressurization technique provides a pressure vs flow graph for the building being inspected and achieves this goal in minutes.

This may be done at any time of the year since natural infiltration only plays a minor role under these artificial test conditions. For retrofit performance testing this is an important advantage (fig. III e-6).

A powerful fan or blower is used to pressurize or depressurize the structure. The variations include fans with calibration sections included and others where the calibration is done in the laboratory and fan speeds and pressure differences are translated into air flow rates. Some of the designs make use of the windows as an access point whereas other designs use the door opening as a means for mounting the "blower door".

Sweden has made use of pressurization techniques to monitor tightness in new housing. These samples provide data to show that leakage does not exceed the three ACH "standard" at 50 Pa pressure difference level to rate houses although it is recognized this condition is far removed from any natural weather effects.

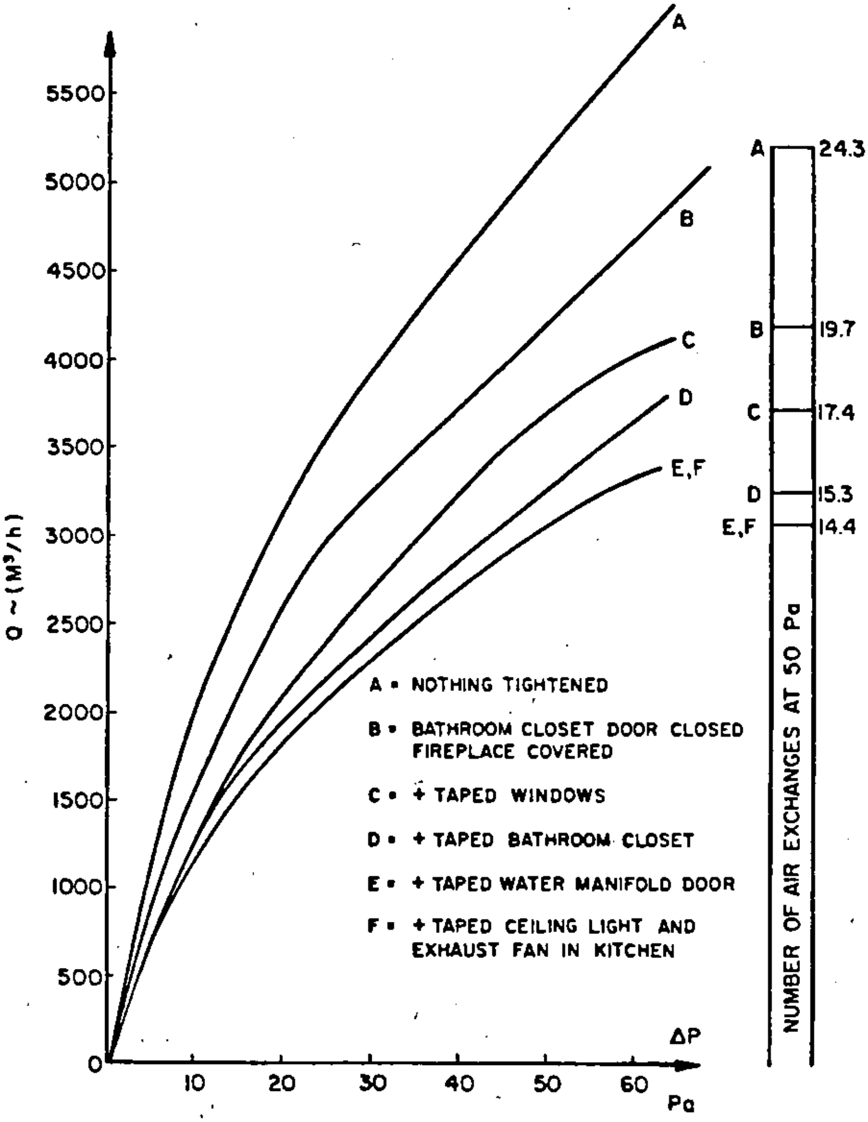

Fig. III e-6 Air leakage vs pressure difference illustrating steps to reduce air infiltration.

One such equipment design, the Blower Door, is shown in fig. III e-7. An important feature that was previously mentioned is that not only can this approach point out when a home is too leaky and monitor the improvements, it can also point out when the house is too tight.

Values of tightness approaching the Swedish Standard mean that forced ventilation is necessary to avoid problems of indoor pollution and excessive moisture.

Following the proposal for the formulation of a Standard (SP 1977), some further information is here given, both on the test equipment and conditions:

- the fan must be controllable and have sufficient capacity to produce a 55 Pa pressure difference
- a flow meter to measure the air flow through the fan is required (calibrated units such as the blower door use rpm to determine air flow)
- a micromanometer for measuring pressure differences between 0 and 55 Pa with an accuracy of 2 Pa is required
- the fan and flow meter should be able to be reversed
- the indoor and outdoor temperatures should be measured, along with the wind direction and velocity. Extremal values for performing the test are 8 m/s for wind velocity and 30 K for the temperature difference
- all ventilation openings should be sealed before the test (including fireplaces and drain taps). In contrast, the U.S. testing has allowed vents and stacks to remain open since natural ventilation takes place through these openings. This should be taken into account in comparing tightness values from one country to the other.
- all doors and windows facing outside should be closed
- all internal doors should be kept open during the test.

It should be also taken into account that tests performed with over pressure in the building will generally give different (and often higher) air change rates compared to tests when the building is underpressurized. A common solution is that of taking the average of the two results. Finally, corrections should be made on the volume flow due to indoor and outdoor temperatures (Kronvall, 1980).

The location of air infiltration sites makes use of the abilities to pressurize and depressurize the house. Using pressurization in the living space and forcing warm air into the attic (heating season example) one can use infared

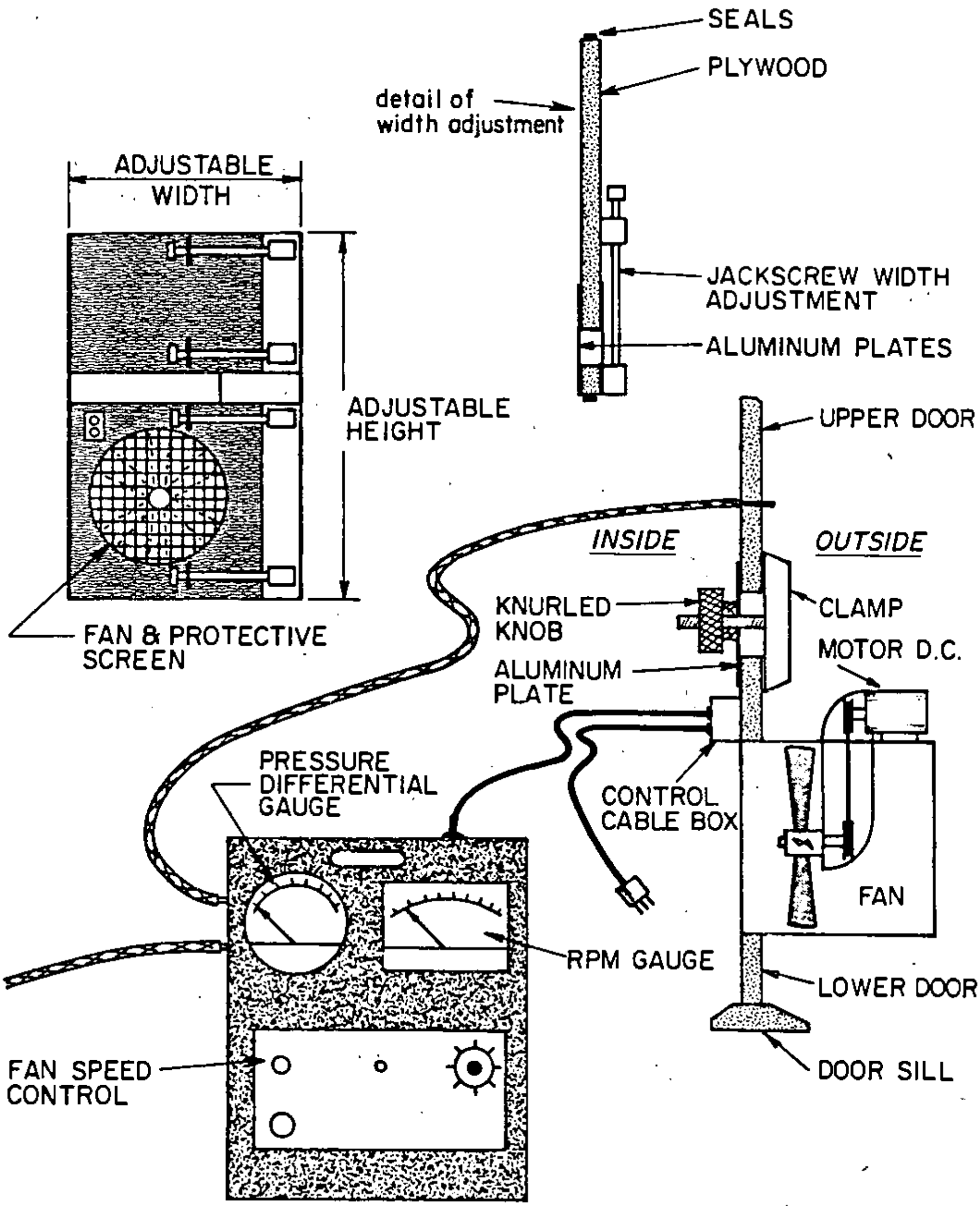

Fig. III e-7 Blower door and control panel scanning to detect the leakage sites. Often these locations are associated with plumbing and electrical penetrations of the envelope. However, even interior partitions can leak air to the attic. Depressurizing the house draws cold air through cracks in the envelope, as shown in fig. III e-8a and 8b, these heat leakage areas are the result of cold air moving into the walls (fig. 8a) or across the ceiling between floors (fig. 8b)(Ruriel and Rudy, 1980). These are of course just two illustrations of heat leaks. Many of the leakage sites listed in Tables III e-1 and 2 can be easily detected with infrared. A handbook has been produced illustrating such leakage problems (Pettersson and Axen 1980).

Where temperature differences are inadequate for proper infrared scanning (less than 5 K), one can substitute smoke tracers to seek out leaks. If one pressurizes the house, any leak causes the smoke to stream toward the opening. The smoke tracers work well in evaluating window leak sites, a location where infrared scanning is sometimes difficult because of emissivity variation of the materials involved (aluminium, glass, plastic, etc.)

If the generation of an indoor airborne pollutant is known over time, it may be used as a natural tracer for determining air infiltration. Radon may offer this opportunity. CO_2 generated by the occupants may also hold out possibilities (Turiel and Rudy, 1980). Indeed, the proposed new ASHRAE ventilation guidelines allows a choice as to when to supply outside air based upon staying below prescribed pollutant concentrations. Monitoring is of course necessary in this approach.

Use of methods that would integrate the effect of air exchange rate over time could prove useful in providing an average air exchange rate before and after a retrofit. One simple injection -collection technique has already been described. Remember, however, for this technique to work the generation rate and extinction of the pollutant must be a constant or, at the very least, follow a well-prescribed pattern. For radon this is not likely as radon outgassing from soil is widely variant.

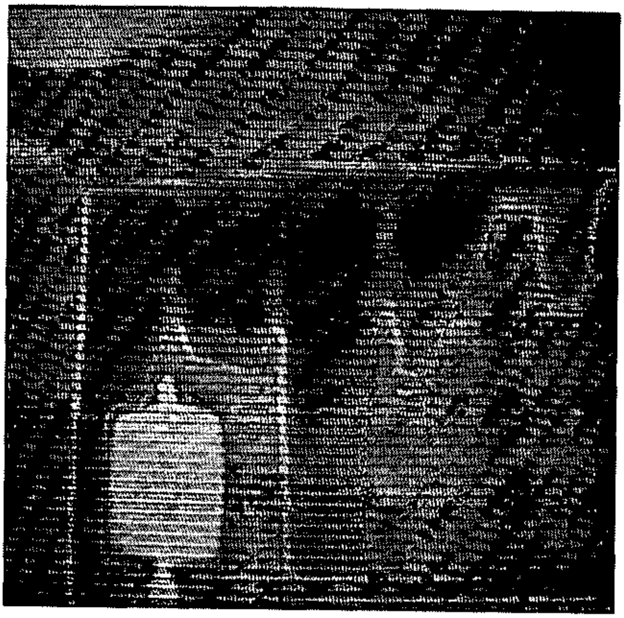

Fig. III e-8a Heat leakage path from attic shown behind interior wall.

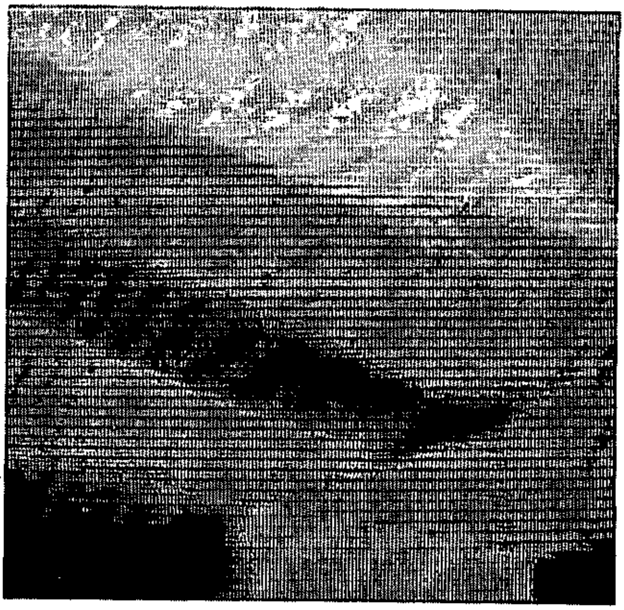

Fig. III e-8b Heat leakage from across ceiling (between 1st and 2nd floor) - also shown as heater duct path.

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CHAPTER III f

Energy conversion and energy flow in heating systems

Contents

Key words

air flow
boiler
boiler efficiency
combustion efficiency
control system
efficiency of use (part load, average, cyclic, or seasonal efficiency)
energy consumption
energy conversion
furnace
heat delivery
heat distribution
heat emission
heat terminals
mass flow
temperature
thermostat
ventilation systems
volume flow meter

III f Energy conversion and energy flow in heating systems

- general introduction

This chapter analyzes the measurement of those quantities, related to the energy conversion and distribution in heating systems, which are particularly relevant for the retrofit effect evaluation.

Measurements of the energy conversion efficiencies, defined in ch. I d, are always very important, whether the heating system has been retrofitted or not. Whenever the heating demand of a building has been diminished, for example, by improving the insulation, the capacity of the existing heat generating equipment (boiler + burner) becomes excessive. Consequently, the efficiency of the heating system will generally decrease. Furthermore, the distribution of heat to the individual rooms or dwellings will be altered, and may become inadequate from the comfort point of view.

The above considerations point out the need for <u>readjusting</u> the <u>heating</u> system capacity and controls in order to obtain a full benefit both energy- wise and comfort- wise, from house retrofits.

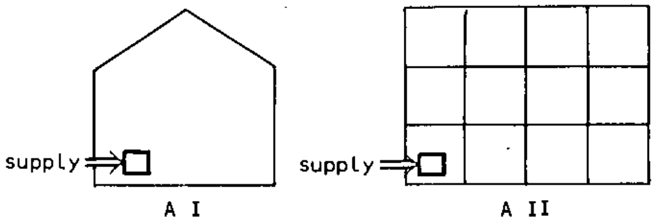
The measurement of energy distribution in a heating system may be important in the following types of investigation:

1) studies on the behaviour of occupants
2) studies on the control system
3) validation of computer models in which the heating demand of each dwelling or room is calculated.
4) assessment of the effects of retrofits (e.g., installation of thermostatic radiator valves) on the heating system.

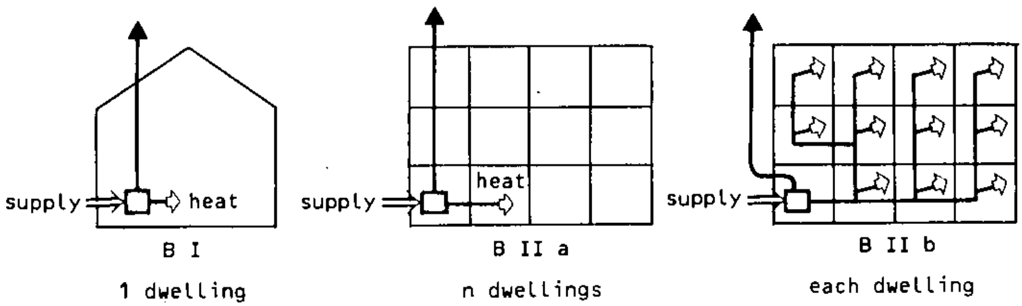
A general classification of the types of measurement of interest is shown in fig. III f-1 and Table III f-1. The aim of the investigation will determine:

1) the type of measurements
2) the duration and sampling time of the measurement

A Measurement of the total energy consumption



B Measurement of the total energy consumption and heat supply to the dwelling(s)



C Measurement of the total energy consumption, heat supply to each dwelling and heat supply to each room

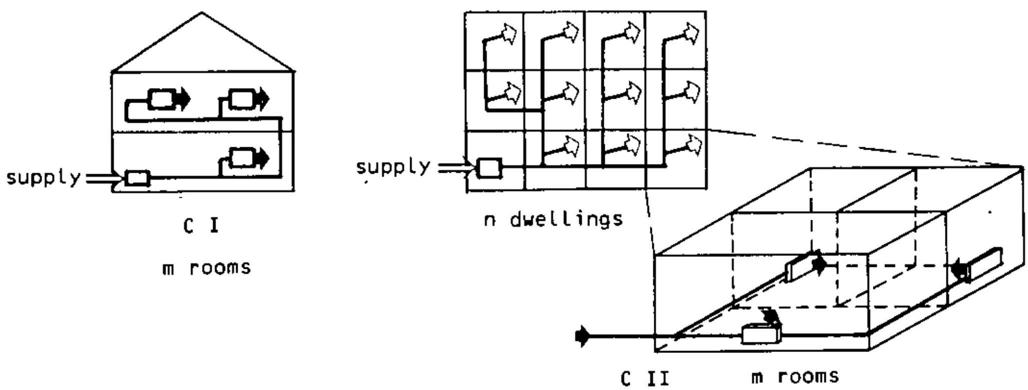


Fig. III f-1 Schematical division of the measurements

TABLE III f-1

Possible measurements on heating systems, depending on the aim of the study

aim of the investigation	type of measurements AI	AII	BI	BIIa	BIIb	CI	CII	duration of the investigation	Maximal sampling time
total direct effect+ indirect conservation+ occupant influence	+	+	+	+	+	+	+	1/2 heating season	1/2 heating season
measurement of boiler efficiency	-	-	+	+	+	+	+	"	"
measurement of heat supply to a dwelling	-	-	+	-	+	+	+	"	"
occupant behaviour in a dwelling	-	-	+	-	+	+	+	"	1 month
occupant behaviour in a room	-	-	-	-	-	+	+	"	"
measurement of separate effects of direct and indirect conservation	-	-	-	-	-	+	+	"	"
check on control system operation	-	-	+	+	+	+	+	1 week	1 minute
check on dynamic one-room dwelling model	-	-	+	+	+	+	+	"	1 hour
check on dynamic multi-room dwelling model	-	-	+	-	+	+	+	"	"

Notation as in fig. III f-1 + feasible measurement
- not feasible measurement

- energy consumption

To determine the energy conversion of the boiler, the measurement of the energy supply as a function of time is always necessary. The measurement of the energy supply will be discussed for each type of fuel. The heating value of the fuel has always to be known.

The supply of electric energy can be measured with a kWh meter (also called electricity meter). Electricity meters are electro- mechanical devices, which multiply current and voltage in phase and then integrate the result. They can in general be bought from the local Electricity Board, reconditioned meters can also be found. Calibration can be performed by the local electricity board, or, directly, using a dynamometer. For continuous recordings opto- electronic devices, as for gas meters, can be used. The accuracy is about 2 % depending on the status of the kWh meter.

If electricity is measured in order to determine the heat emission of an electric terminal, and the heat emission is constant with time, it suffices to measure the on- time with an electric hour or minute counter. The accuracy is about 2%.

Whenever a rough evaluation of oil consumption is required, this can be determined using a measuring beaker or tank. For more accurate measurements, volume flow meters especially designed for oil are available, having an accuracy of 2 to 5%. For continuous recordings semi- positive displacement meters are widely used, because they are cheap, robust, and accurate.

Gas meters provided by the local Gas Supply authorities are generally of the reciprocating diaphragm type, and have a mechanical meter. For continuous recording, they can be modified using opto- electronic devices that can read the number of revolutions of the dial mechanism by counting the reflections from painted marks or the passage of holes drilled in the disc. Since gas is also used, in some cases, for sanitary water heating and cooking, an extra meter could be needed.

The accuracy of gas meters ranges from 2 to 5% depending on, among other things, the variation in gas temperature. Whenever the gas meter cannot be applied, the gas consumption may be determined by measuring the on-time of the boiler. By running the boiler at full load for a certain time, the relation between gas consumption and time can be determined. The elapsed time can be measured by an hour or minute counter operated by the space thermostat or the boiler thermostat.

The mass of coal used over a given period can be determined by weighing. Special attention must be given to the determination of the heating value of coal. Continuous recording is impossible. The accuracy ranges from 5 to 10%.

The mass of wood used over a given period can be determined by weighing. The heating value of wood depends on the type of wood and its water content, and is, therefore, hard to determine. The same problem is encountered when waste products are burned.

- energy conversion in the boiler

The energy conversion efficiency of the boiler (or furnace) can be defined by two different parameters:

i) steady-state efficiency
ii) efficiency of use (average or cyclic efficiency)

i) steady state efficiency

The steady-state efficiency of a boiler is given by (see eq. I d-2):

$$\eta = (H_1 - H_4)/Q_i \qquad \text{(III f-1)}$$

where

H_1 = enthalpy of heated fluid leaving the boiler
H_4 = enthalpy of heated fluid entering the boiler
Q_i = heat content of fuel

or as

$$\eta = 1 - Q_j/Q_i - (H_f - H_a)/Q_i$$

where

Q_j = convective and radiative heat losses from the heat generator
H_f = enthalpy of combustion gases and vapour entering the chimney
H_a = enthalpy of air entering the boiler

The term Q_j/Q_i is often denoted by L_j (the jacket loss factor), while the term

$(H_f-H_a)/Q_i$ (the flue loss factor) is denoted by L_f. The latter is partly due to incomplete combustion, and is often further divided into L_{inc} (the incomplete combustion loss factor), and L_c, the remainder of L_f (the chimney loss factor). Thus, $L_c=L_f-L_{inc}$. The efficiency can now be written:

$$\eta = 1- L_j - L_c - L_{inc} \qquad \text{(III f-2)}$$

The two expressions III f-1 and III f-2 correspond to two different ways to determine the steady-state efficiency of a boiler:

- direct balance method
- indirect balance method

When the direct balance method is used, one starts by expressing H_1 and H_4 of eq. III f-1 as:

$H_1 = \int c_p \; \dot{m} \; T_1 \, dt = c_p \, m \, T_1$
and
$H_4 = \int c_p \; \dot{m} \; T_4 \, dt = c_p \, m \, T_4$
where
$\dot{m}$ = mass flow rate of heated fluid
c_p = heat capacity per unit mass of heated fluid
T_1 = temperature of fluid leaving the boiler
T_4 = *temperature of fluid entering the boiler*
and

$Q_i = \int \dot{m}_i \, H \, dt = m_i \, H$
where
m_i = mass of fuel
H = heat content of fuel

The supply water (or air) temperature (T_1) and the return water (or air) temperature (T_4) should be measured, as well as the quantity of water (or air), m, flowing through the boiler and the quantity of fuel, m_i. Fluid temperature measurements and flow- rate measurements are discussed separately in other sections of this chapter.

When the indirect balance method is applied, the boiler efficiency is indirectly determined through its energy losses (see eq. III f- 2). Since for tuned- up heat generators the losses *due to incomplete combustion are generally* negligible, it is possible to apply a formula (Gumz 1962), valid for complete combustion, for the calculation of L_c:

$$L_c = (A + B/CO_2 + C*W)*(T_f - T_a) \quad (\%)$$

where

T_f = flue gases temperature

T_a = air temperature

CO_2 = volume content of carbon dioxide in %

W = mass water content of fuel per unit mass of fuel

and

A,B, and C are constants, depending on one or more of the variables composition and mass of the flue gases, specific heat of water and air (dependent on the temperature), enthalpy content of the fluid (temperature dependent), etc. For oil the following average values have been given (Gumz 1962): A= 0.0064, B=0.49, and C= 0.0044.

For solid and liquid fuels, the CO_2 and O_2 volume contents are related by (with an error of a few per cent, for gas the application of this relation may result in errors of 20 % or more):

$$CO_2 = (1 - O_2/20.8)*(CO_2)_{max}$$

where $(CO_2)_{max}$ is the maximum volume content of CO_2.

The quantity $\eta_c = 1 - L_c$ is often referred to as "combustion efficiency". Summing up, the quantities which have to be measured are:

- air temperature
- flue gases temperature
- CO_2 or O_2 content in flue gases

For temperature measurements see following sections in this chapter. As for the CO_2 content, the following methods can be employed for the analysis:

- chemical methods (Orsat measurement equipment, portable absorption analyzers)
- physical methods (conductivity method, paramagnetic method (for O_2), infrared method (for CO), etc.)

The Orsat equipment is not suitable for quick analyses in the field. On the other hand, the portable analyzer, based on the absorption of CO_2 (or O_2) by a solution, provides a rapid and sufficiently reliable information. The most suitable instruments are, however, the so called fuel- efficiency monitors (FEM), which allow the instantaneous measurement of both flue gases temperature and O_2 content by means of electric transducers.

The jacket loss factor (L_j) can be estimated from *Table III f-2* as a function of the boiler nominal power Q_n (Andreini and Pierini, 1980).

TABLE III f-2

Jacket loss factor at full load for small boilers

Q_n(Gcal/h)	0.5	0.7	1.0	1.5	2.0	3.0	4.0	5.0	7.0	10.0	15.0	20.0
(MW)	0.6	0.8	1.2	1.7	2.3	3.5	4.7	5.8	8.1	11.6	17.4	23.3
L_j (%)	4.1	3.0	2.1	1.5	1.2	.95	.80	.70	.55	.50	.45	.40

ii) efficiency of use

Since the efficiency of use is not constant in the heating season, it should be determined at different loads. Accuracy oscillates between 2 and 10% depending on the precision of the measuring devices used. If the volume flow of *the heating medium cannot be measured, the efficiency of use may be derived from* the degree of use of the boiler and from values of the efficiency of use determined in a laboratory as a function of load.

The degree of use is the fraction of time in which the boiler is used at full load. The determination of the efficiency of use in the field can be carried out using a method (Dittrich 1972) (direct method), which requires the measurement of efficiency and standby losses.

Standby losses can be measured by channeling the water flow from the boiler through an insulated bypass close to the boiler. Therefore, heat is delivered by the boiler only to maintain the water temperature of the boiler and the energy consumption is equal to the standby losses.

The measurements must be done at the normal operating temperature. The standby losses, L_s, will be expressed as a percentage of the full load of the boiler. If the fuel supply is constant in time then:

L_S = (burner "on" time/ total time)*100
The efficiency of use is now (Uyttenbroek, 1980):

$$\eta_u = (1 - L_s/B)/(1 - L_s/100) * \eta_d$$

where

B = degree of use in % of time of the heating season
η_d = boiler efficiency (determined through the direct method)
η_u = efficiency of use

This method is suitable for boilers operating at constant supply water temperature, but cannot be applied to boilers controlled by a room thermostat. In general, experimental data indicate that there is a small difference between efficiency of use and steady-state efficiency above a degree of use of 30%.

For a lower degree of use a greater difference can be expected. In many countries an average B value of 30% over the heating season is normal. After a retrofit, B will be even lower. Therefore the efficiency of use will decrease. Fig. IIIf-2 (Bergen, 1980) shows typical curves of efficiency vs. load, for three types of boilers. Special attention must be paid in the following situations:

1) periods with a B value less than 30%;
2) modulating burners for decreasing B values will show: lower η_u for induced draught burner and higher η_u for ventilator burner (Anglesio, 1980);
3) ventilator burner with condensation: for lower water temperature higher η_u.

- energy flow in water heating systems

The total heat supply to the pipes can be derived by measuring the water volume flow and the temperature increase across the boiler. Such measuring equipment is already included in some installations for collective heating. In such cases water heat flow meters are used. Techniques for measuring volume flow and temperature separately are described below.

For volume flow measurements, volume flow meters inserted in the water distribution system are used. This implies that an extra flow resistance is introduced, which reduces the water flow rate. To limit this effect a type of flow meter with low resistance should be chosen. It is possible, however, to compensate the pressure loss due to the volume flow meter by increasing the pump head. One may than proceed as follows:

1) measure the water temperature difference (ΔT) across the boiler and the outflowing water temperature (T_1) (e.g., by a thermometer placed in the boiler) when the boiler is on;

2) fit the volume flow meter in the return pipe upstream the pump;

3) keep the boiler on until the water temperature has reached the value T_1 again. Measure ΔT once more and regulate the pump pressure by varying its speed or by bypass regulation, until the pressure regains the same value as before.

By using this procedure the pressure loss over the flow meter is compensated only for one given volume flow. Different water flow rates cause different pressure losses and, consequently, require a different pump head. By setting the radiator valves in the normal positions, the measuring error due to pressure loss across the flow meter is minimized. In order to compensate such pressure loss correctly in all circumstances, a second pump connected in series with the volume flow meter may be used (see fig. III f-3). The number of revolutions of the pump is always controlled in such a way that the pressure difference across flow meter and pump remains zero.

The accuracy of volume flow meters is about 2 to 10%, depending on the minimal volume flow rate. Since the water distribution system is often very dirty, it should be possible to clean the volume flow meter during operation of the heating plant or to install a filter upstream the measuring device.

During temperature measurements in the water distribution system, the temperature of hot water flowing through a pipe is not constant over the pipe section because of cooling down at the pipe wall. The highest temperature may be expected in the centre of the pipe (see fig. III f-4).

For exact measurements of the water temperature, a sensor is placed in the pipes. By producing a strong turbulent flow at the sensor, the temperature gradient becomes smaller and a more accurate measurement is obtained. A more homogeneous temperature distribution may be expected if the pipe is insulated externally upstream over a great length, thus decreasing the cooling down at the pipe wall. In this case, it is sufficient to measure the temperature of the outside pipe surface underneath the insulation. If a thermometer socket is used, it is in small diameter pipes usually placed in a bend (see fig. III f-4). The sensor must be placed as far as possible into the socket. If thermocouple wire is used, galvanic contact should be avoided. It is recommended to kink the thermocouple wire a couple of times before bringing it into the socket, to prevent heat conduction through the supply wires to the thermocouple (see fig. III f-4).

If the temperature is measured by means of thermocouples at the pipe, first insulate the pipe with tape, then place the thermocouple and wind the wire a couple of times around the pipe, cover once more with insulating tape and finally insulate the pipe.

When measuring the heat emission from terminals, the following general relation holds for the heat emission of a radiator or convector:

$$\dot{q} = K * \theta^{\beta} = \dot{m} * \Delta T * c \qquad \text{(III f-3)}$$

where

θ = difference between the mean terminal temperature and the room temperature

$\dot{m}$ = mass flow through radiator or convector

ΔT = temperature difference between supply and return water

c = heat capacity per unit mass of water

$\dot{q}$ = heat emission

K = nominal heat emission for radiator or convector (W/K^{β})

β = exponent, usually taking a value around 1.3

For θ we may use

$$\theta = (T_s + T_r)/2 - T_a \qquad \text{if } (T_r - T_a)/(T_s - T_a) > 0.7$$

and (III f-4)

$$\theta = (T_s - T_r)/\ln((T_s - T_r)/(T_r - T_a)) \qquad \text{if } (T_r - T_a)/(T_s - T_a) < 0.7$$

where

T_s = temperature of supply water

T_r = temperature of return water

T_a = temperature of room air

From eq. III f-4 it follows that the mass flow and the heat emission of the radiator, or convector, can be derived from the room temperature and the temperature of the supply and return water if K is known.

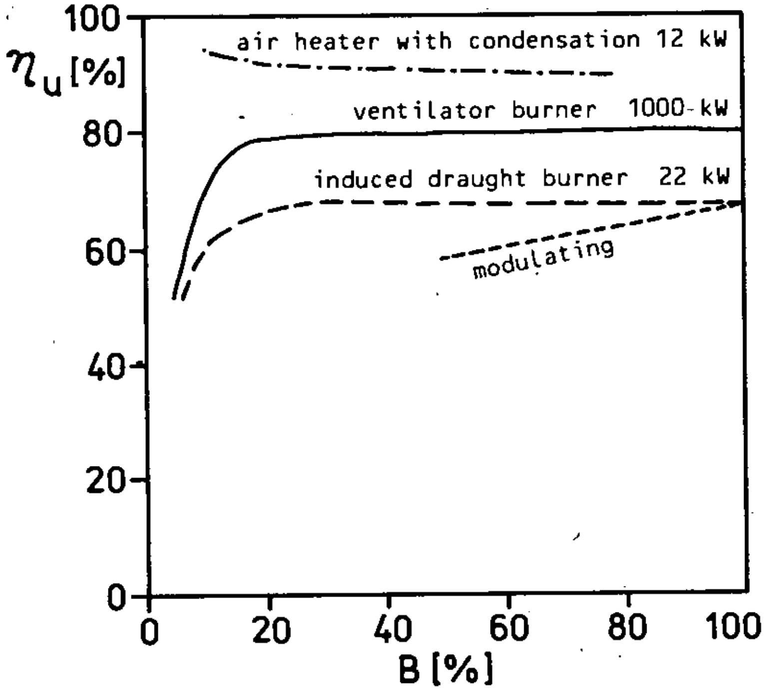


Fig. III f-2 Efficiency of use (η_u) for several types of boilers (after Bergen 1980)

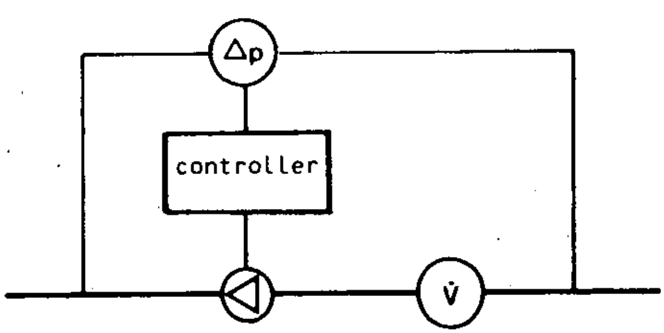


Fig. III f-3 Volume flow meter with pressure compensation

This measurement only gives an approximate result, because, due to different radiator heat emission, the value of K may in practice be different from the given value, if it has been determined in the laboratory. If the total heat emission is determined separately, however, the heat distribution over the different radiators or convectors can also be found from the total heat supplied by the boiler, which is equal to the total heat emission of all radiators or convectors q_{tot}, which can be determined from the relation:

$$q_x = (K_x * \theta_x^{\beta})/(K * \theta^{\beta}) * q_{tot}$$

where

index x refers to a single terminal

As in this approximation it is assumed that the total heat emission is equally distributed among all radiators or convectors, it is implicitly assumed that the heat emission of the pipes is also evenly distributed. In some special cases, the heat output will change, for lower water temperatures, to $\dot{q} = K' * \theta^{\beta'}$, where K' is a new value of K, and β' may take a value up to 1.5.

For the determination of the heat distribution in a dwelling over a long period, heat emission meters are also used. The amount of evaporated liquid in a capsule placed on the radiator is a measure of the total amount of heat emitted in a given period. The accuracy is 10 to 15%. Depending on the measuring period desired, a more rapidly evaporating fluid may be used, which at the same time increases the accuracy. Even if no heat is emitted by the radiator there will be evaporation, the extent of which is determined by the room temperature. This "background" evaporation must be deduced from the figure given by the evaporation meter.

Generally, for floor heating, a modulating regulation is applied. The amount of heat emitted must be derived from a volume flow and a temperature difference measurement. The heat distribution to the rooms above and below can be determined by means of heat flow meters (see ch. III d). The measurement may be carried out before or after the threeway mixing valve (see fig. III f-5) on $\dot{V}_1$ and T_1, or $\dot{V}_2$ and T_2, respectively. Measurement of $\dot{V}_2$ and T_2 is preferred, because $\dot{q}_2$ has always a higher value than $\dot{q}_1$. The measurement results will show whether $\dot{q}_2$ depends on the position of the valve or not; in the latter case a measurement of T_2 will suffice.

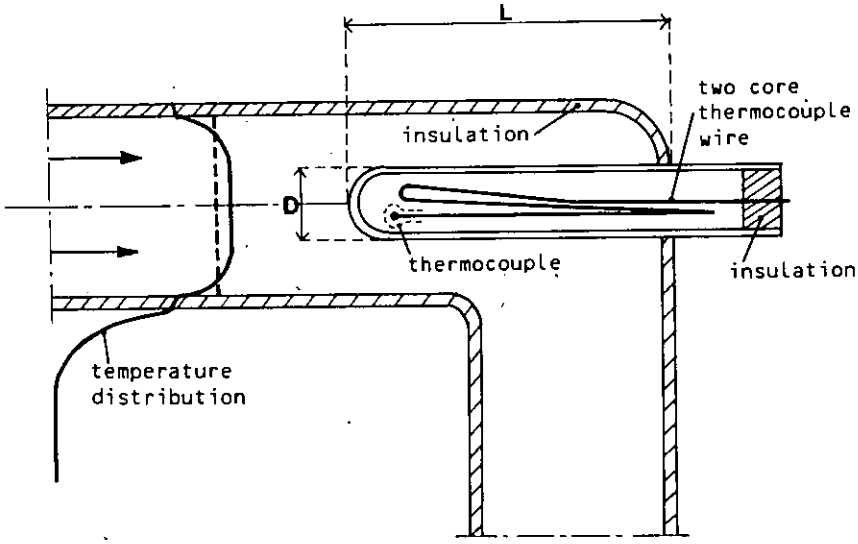


Fig. III f-4 Thermocouple in a thermometer socket in a pipe and the temperature distribution in the pipe. The ratio L/D should be taken greater than 10.

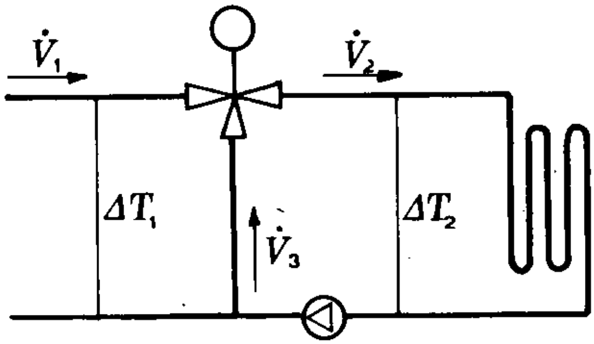


Fig. III f-5 Measurement of heat emission from floor heating. The flow V_1 and the temperature difference ΔT_1 or V_2 and ΔT_2 can be measured.

- energy flow in air heating and ventilation systems

In this section we will treat the measurement of flow and temperature in air heating systems. However, the methods described here can in general also be applied to measurements in mechanical ventilation systems (for measurements of air flow rates see also Svensson 1983).

The heat supply to an air system can be determined from a volume flow measurement in a duct and a temperature difference measurement over a heat exchanger. For temperature measurements in air systems, the following sensors are considered:

- fluid thermometers
- resistance thermometers
- thermocouples.

For recordings, or for the determination of mean values over a longer period, only the last two sensors can be applied. (See ch. IIIb). Chemical integrators may be used for the determination of mean value. To account for temperature differences in the pipe section several measuring points are required for each section.

There are several methods for measuring the air flow in ducts. Some of them are specially designed for laboratory measurements and are seldom used in the field. However, as the applicability of these methods to field experiments is not generally assessable, we will give a brief description of all of them. Depending on the experimental setup, the following methods can be used:

1) traverse air velocity measurements
2) pressure drop measurements
3) tracer gas method

1) The first method is based on the well known equation

$$\dot{V} = \bar{v} * A$$

where

$\dot{V}$ = air volume flow rate

$\bar{v}$ = average air velocity over the cross section

A = cross section area

Provided that A is known in advance, this method requires the measurement of air velocity in a number of points over the duct section in order to achieve a reliable evaluation of its average value $\bar{v}$. The points can be chosen either to be representative of equal surface areas (in this case, the greater the number of areas, the better the accuracy), or to be directly representative of the mean velocity in the duct (see Fig. III f-6).

In both cases the average velocity in the duct will be given by the arithmetic mean of the measured values at each point. The recommended sensor for the air velocity measurement is a Pitot static tube measuring both static and total pressures (also called Prandtl tube); alternatively hot wire anemometers, calibrated to take into account the effects of air temperature, can be used. Elbows, wyes or dampers will disturb the flow. Therefore the Pitot tube should always be located at some distance (3 to 7.5 diameters) downstream.

A large number of commercially available devices belong to the second group. They are usually based on the static pressure drop across a calibrated equipment. Cross tubing and calibrated diaphragm flowmeters are some examples.

2) An easily applicable and inexpensive technique is the one in which pressure is measured at two points on the external and internal side of a 90° elbow (see Fig. III f-7). Knowing the duct diameter and the pressure difference one can from a suitable flow diagram read the air volume flow rate.

3) The tracer gas method has been recently developped (see fig. III f-8). A tracer gas (e.g. N_2O) is injected at a constant rate $\dot{V}_g$ into the duct. Its concentration is then measured downstreams. The air flow rate $\dot{V}_a$ is then given by

$$\dot{V}_a = \dot{V}_g/(C_s - C_b)$$

where C_s is the measured concentration and C_b is the background concentration.

The distance between the tracer gas injection and sampling points ranges from 10 to 80 times the duct diameter, depending on how many flow disturbances there are present; the greater the disturbance (e.g. a ventilator), the smaller the distance has to be.

For the measurement of air flow rate across exhaust openings (*outlets*) the following methods can be used:

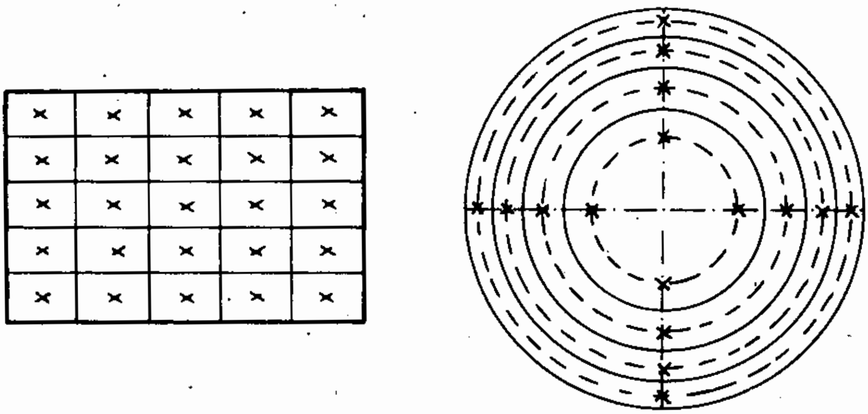


Fig. III f-6 Measuring points (x) in rectangular and circular duct sections.

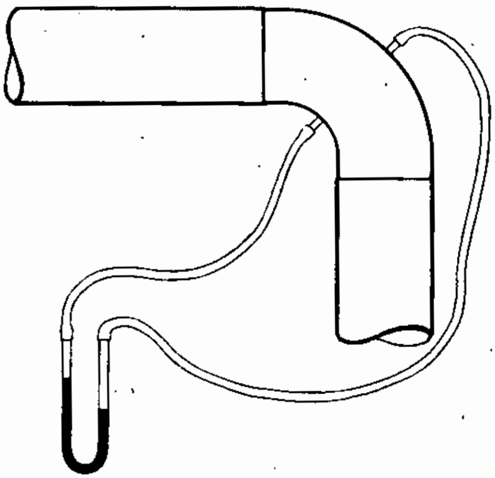


Fig. III f-7 Placement of pressure probes at a 90° elbow.

1) traverse air velocity measurements
2) pressure drop measurements
3) air velocity measurements with calibrated hoods

1) In this case, air velocity is measured at a certain distance from the grille (generally 2- 3 cm) at a small number (usually 4) of points over the section. The volume air flow, $\dot{V}$, is given by:

$$\dot{V} = k*\bar{v}*A$$

where k is a correction factor, $\bar{v}$ is the average measured air velocity and A is the cross- sectional area. The value of the correction factor depends on the *damper position as well as on the grille size.*

2)The second method is used for circular inlets. It makes use of a probe (a capillary tube) which is inserted behind the grille. A micromanometer then measures the pressure drop across the tube. *The volume air flow can be obtained* from the pressure drop using suitable diagrams, in which the slit width appears, as a parameter.

3) Specially shaped <u>hoods</u> are commercially available in which a hot wire anemometer is placed. The hood can be applied to circular inlets. The volume air flow can be determined as a function of the measured air velocity by means of a diagram established by previous calibration (see fig. III f-9).

For the measurement of air flow across supply openings <u>(inlets)</u> the following methods can be used:

1) plastic bag methods
2) pressure difference measurements
3) air velocity measurements with calibrated hoods .

1) The first method is very reliable and yet quick and simple. A plastic bag is tightly applied to the outlet (see fig. III f-10). As the air flows into it, the bag starts swelling until the inside-outside pressure difference *reaches* a suitable value (e.g., 3 Pa). At that moment the volume air flow will be given by the simple equation:

$$\dot{V} = V/t$$

where V is the bag volume at the corresponding pressure difference and t is the time elapsed from the beginning of the swelling. A reliable device for time

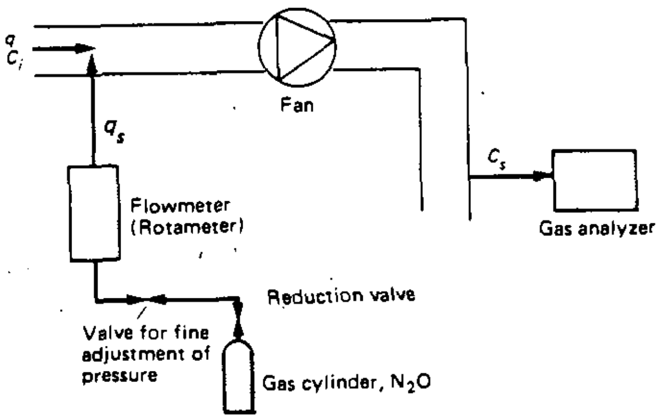


Fig. III f-8
Flow measurement with tracer gas technique.
q = air flow rate
C_i = initial tracer gas concentration in the duct
C_s = gas concentration in the sampling cross section
q_s = injected tracer gas flow rate

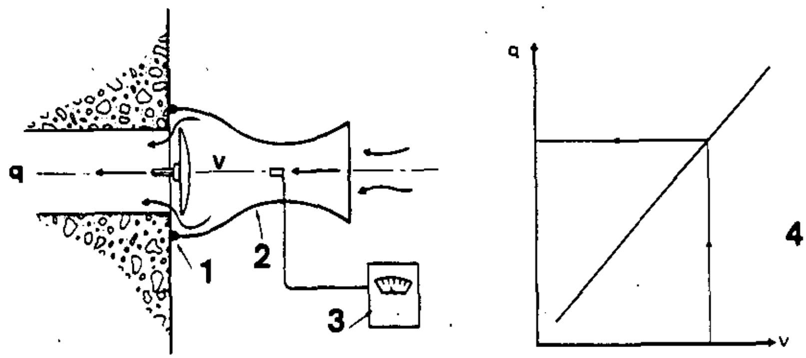


Fig. III f-9 Measurement of air flow in outlet with calibrated hood.
1) sealing 2) measuring hood 3) indicator instrument
4) calibration curve of airflow rate q vs velocity v .

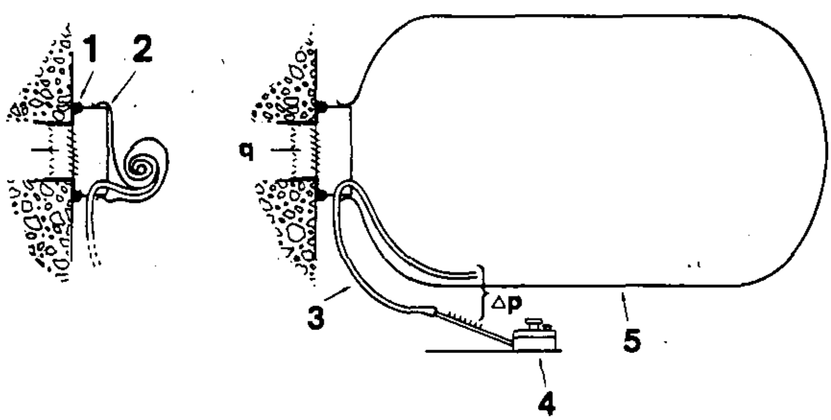


Fig. III f-10 Measurement of air flow rate at inlet with bag method.
1) sealing 2) frame to which the plastic bag is fastened
3) measuring tube (5 mm) connected to microanemometer
4) microanemometer 5) plastic bag with thickness 0.03 mm

measurement is needed. To achieve a good accuracy, the elapsed time should not be smaller than 10 seconds.

2), 3) The methods based on pressure difference measurements are very similar to those described above. Calibrated hoods can also be used for outlets, provided that a straight extension duct (longer than 3 times the diameter) is applied between the grille and the measurement device.

The rate of heat supply to a room by an air system is given by:

$$\dot{q} = \dot{V} * \rho * c_p * (T_i - T_r)$$

where

$\dot{q}$ = rate of heat supplied by the air system

$\dot{V}$ = air volume flow through the grille(s)

ρ = density of supply air

c_p = heat capacity of air

T_i = supply air temperature

T_r = room temperature

In order to determine the rate of heat supply to a room, $\dot{V}$ and $(T_i - T_r)$ must be measured.

- the control system

In a two- or multiposition control system, a thermostat emitting electric on/off signals through one or more control contacts is placed in a representative room of the dwelling. This thermostat turns the burner on or off in one or more steps. It is also possible that in each room, or in each dwelling of a multistorey building, the hot water supply is controlled by an electric shut- off valve.

In order to increase the control capability, two- position thermostats are generally provided with a thermal feed back resistance connected in series or parallel to the load (see fig. III f-11a and 11b). By measuring the pressure over the excitation coil, it can be determined whether or not heat is supplied. Depending upon the aim of the measurement, the output signal can be processed by:

1) continuously recording equipment

2) impulse counters
3) minute counters

If one wants to know how a boiler thermostat connected in series with the room thermostat works, two measuring signals may be used (see fig. III f-14).

By measuring the fuel consumed during one period, the energy consumption can be directly derived by measuring the burner on- time. For a thermal feedback resistance connected in series, it should be considered that parallel connection of a measuring device to the load induces an increase of current (see fig. III f-13a). This causes an increase in the thermal feed back. It is recommended to use a measuring instrument with a high input impedance so that the extra load current is negligibly small. To be able to check the operation of the thermal feed back, one may proceed as follows:

1) adjust the thermostat at a low temperature and let it cool down for about 30 minutes, so that the sensor cools down to room temperature.
2) turn the thermostat slowly up to a position where it just switches on. The value at this position corresponds to the room temperature at that moment.
3) a temperature rise of the sensor will then only occur by excitation of the thermal feed- back resistance. At this stage, the thermostat may not be heated by internal sources.
4) determine the time before the thermostat switches off. If the efficiency of use of the boiler is sufficiently high, this time may not be shorter than about 5 minutes. For comfort reasons this time, depending on boiler capacity and the size of the installation as well, may not be longer than about 15 minutes. If these conditions are not satisfied, the thermal feed- back will have to be adjusted once more.

Modulating control works with continuously variable signals in the control circuit. Generally, these signals can easily be measured and recorded if they are transmitted electrically or pneumatically. When electrical signals are used, it should be remembered that the input impedance of the measuring instrument must be sufficiently high to prevent weakening of the measuring signal. When pneumatic signals are used, pneumatic-electric converters may be used.

The measurement of the signal is not easy if the sensor, the automatic control device, and the correcting valve are built as a unit (as in thermostatic radiator valves). In this case, only the input and output signal of the whole

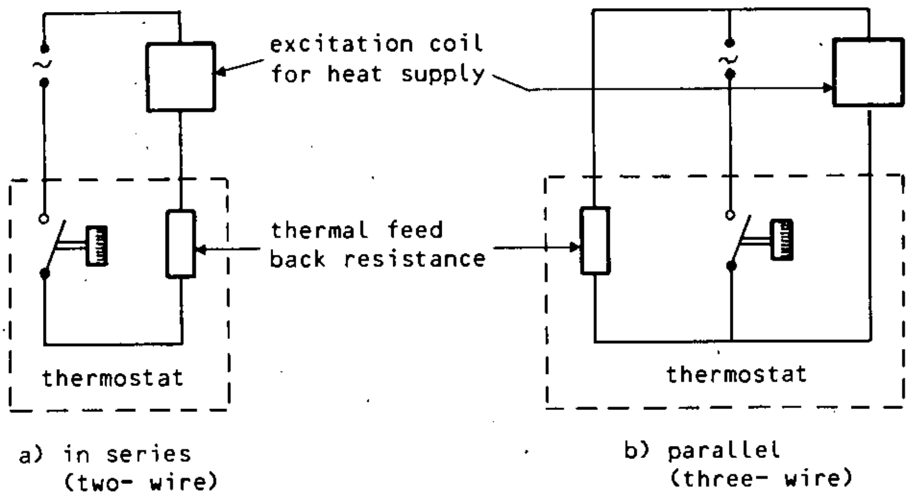


Fig. III f-11 Connection possibilities of a room thermostat with thermal feed back.

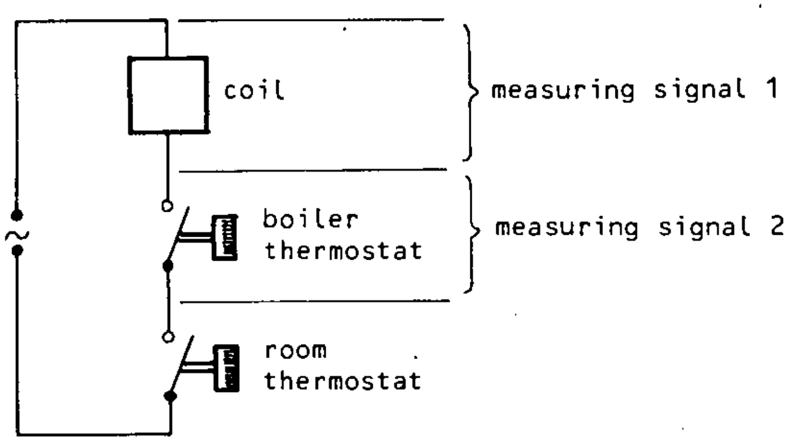


Fig. III f-12 Measurement of thermostat signal control circuit can be measured. For a thermostatic radiator valve, room temperature and water temperature are the input signals, and water flow rate or heat emission rate of the radiator is the output signal. Control strategies include mixing control and quantity control. In mixing control, the flow rate of the heating medium is virtually constant. In quantity control the flow rate of the heating medium (or of the fuel supply) is variable.

In weather- dependent control, water temperature is controlled by the outdoor conditions (sun, wind, temperature, precipitation). The operation can be checked by measuring the output signal of the outdoor sensor(s) and/or by measuring the water temperature.

Night set back is realized by lowering the value of the room, water or supply air temperature below the daytime setpoint. This can be done manually or automatically by means of a time switch. In installations with weather-dependent control, night set back can be attained by reducing the firing line. In installations with room temperature control, automatic night reduction can be achieved by excitation of a heating element in the thermostat or by adjustment of a special night thermostat.

The occupants' operations on set point as well as the weather conditions are in principle measurable with technical devices. However, it is not always necessary to monitor the occupant's unknown action directly. It is often sufficient to measure the effect caused by the action. For example, information on the position of the radiator valves can be gained by measuring the water temperature behind the valve or the temperature drop across the radiator. Information about the boiler thermostat, and the room thermostat position, or about the use of night temperature set-back can be gained from the supply water temperature. Information on the number of radiator valves opened can be derived by measuring either the rate of increase of the water temperature when the burner is on, or the temperature rise across the boiler.

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CHAPTER III g

Data acquisition systems and Installation rules

Contents

III g Data acquisition systems and Installation rules

- general introduction

The modern data collection system used in building energy monitoring can be expected to be electronic in nature. This chapter discusses the interconnection of the system components so as to minimize error, interference and costs while providing an acceptable level of reliability.

The major components of a data acquisition system are:

1) sensors or transducers,
2) signal conditioners
3) multiplexers or scanners
4) data form converters
5) recorders
6) data processors

All data acquisition systems possess each of these components to one degree or another. The level of sophistication that one employs in acquiring data depends entirely on the design of the experimental project which is being undertaken. Though all data gathering efforts must have each of the above components, the actual configuration of the final data acquisition system depends on the goals and resources of the project. Factors to be considered include:

1) number of data points
2) frequency of readings
3) size and nature of the structure
4) separation of the system components
5) whether or not the system is computer based
6) end-use and ultimate destination of the data
7) variables to be measured
8) sources of interference
9) reliability of the power lines

Many installation problems can be precluded by a judicious overview of system design philosophy and selection of system components, especially sensors. Furthermore, care must be exercised to avoid creating interference sources from system control relays, solenoids etc.

- sensors and transducers

The purpose of sensors and transducers is to produce an output which is detectable and corresponds to the physical quantity which is to be measured. The output of sensors can be visual, mechanical, or electrical in nature. The visual and mechanical output sensors such as bulb thermometers, dial bi-metallic strip thermometers, gas meters, water meters, electric meters, etc. are commonly used for manual data acquisition and as backup to automated systems. Some of these types of sensors can be modified to provide pulsed or digital electrical outputs. Pulse output sensors are usually quantity measuring devices such as turbine meters, totalizing wind speed anenometers, automated gas and water meters, tipping bucket rain gauges and automated electric meters.

Electrical transducers can have outputs which are changes in voltage (thermocoupless, heat flow meters, solar flux meters, generator type wind anenometer), resistance thermistors,(RTD´s), current (certain pressure transducers, electro-chemical cells), or capacitance (certain pressure transducers, moisture meters).

The general problem of designing a data acquisition system is to be able to interface this wide variety of sensors to a recording system. The relationship between the physical quantity and the output of the sensor can be either linear or nonlinear. Simple relationships are usually preferable. It is important to ascertain whether the relation between the physical quantity measured, and the output of the transducer, is dependent on environmental factors (especially temperature). The choice of a sensor should be based on

1) accuracy
2) reliability
3) ability to be interfaced with scanning equipment
4) initial cost
5) cost of installation

- signal conditioning

The output of some transducers, especially those of the self excitation type, can be directly interfaced to the data logger or data scanning system; however, most transducers require some sort of signal conditioning before they can be interfaced to a data logger. The most common type of signal conditioning is amplification and this is often included in a data logger. This is required if the level of the output of the transducer is too low to be accurately registered by the recording system. Some systems incorporate a self- selecting amplification sheme, called autoranging, in which the system selects the optimal level of amplification. This is usually done at the expense of speed and cost.

Where several decades of input signal level must be accomodated, a viable alternative is to use a logarithmic amplifier for signal conditioning. This is especially desirable when the data are to be digitalized by an A/D converter after multiplexing, and ultimately processed by a digital computer.

Two other types of signal conditioning often required are the conversion of resistance changes of certain transducers to voltages, and the conversion of currents to voltages. If the transducer has a pulse output, these must be converted to a voltage for most data loggers. This can be accomplished by either a frequency- to- voltage converter, if instantaneous rates are desired, or by counter circuit and D-D converter if a totalized output is dictated by the design of the project. If the average value of an analogue transducer is desired, this can be accomplished by an integrator. This technique greatly reduces the amount of data processing required if there is no need for more frequent data.

An electronic integrator produces an output which is proportional to the time integral of the input signal. An integrator can be used only if the transducer has a linear output. An integrator usually consists of a voltage-to- frequency converter and a counter. A counter consists of a pulse shaper circuit, a contact bounce suppressor (when designed to accept input from mechanical contacts), and sometimes a predivider to reduce the pulse rate, and a counting circuit. The output of the counting circuit is usually digital. If the data logger cannot accept digital input, a digital to analogue converter must be employed. A slight variation of a counter is a timer. A timer gates a pulse train of fixed frequency into a counter when a switch closure or digital voltage is applied to its input.

For the monitoring of the status of discrete events, an encoder is often used if the data logger does not directly accept digital signals. This allows the status of several different devices to be monitored on only one data channel.

- data scanners

In order to convert the signals from each transducer, or signal conditioner, the output of each device must be directed to the data converter or reading device. The switching is accomplished by multiplexers. Today most multiplexers are one of three types: reed multiplexers, FET multiplexers and CMOS multiplexers. Each type has its particular advantages and disadvantages. The reed multiplexers can sustain high common mode voltages and do not leak; however, they have a more limited operational life and speed. The FET multiplexers have a longer life, but are susceptible to leakage and may fail in the closed state, thus affecting readings on other channels. The CMOS multiplexers are quite popular; they are less susceptible to leakage and will fail in the open state, not affecting other channels. They are however more easily damaged by excessive voltages.

The number of devices which a scanner can monitor is determined by the number of channels it has. In selecting a scanner, one should consider not only the number of channels it has but also:

1) the nature of the control of the accessing sequence
2) the type of clock used
3) the possibility of remote control
4) the expandability of the number of channels at a later date without factory modification
5) the ease of operation
6) the level of the signals it can handle
7) its effect on the output of the transducers
8) the environment in which it can be used.

The manner in which the channels are accessed can be either random, periodic or continuous. In the random mode a group of channels will be selected on command from the operator, in the periodic mode these channels are selected at a fixed interval of time, in the continuous mode the channels are scanned as fast as the system allows. The clock should be judged as to its accuracy and stability. In most energy monitoring applications the clock should have a calendar or a Julian day counter.

The provision for power- failure protection should be considered. There are several ways to provide this protection. An uninterruptible power supply can be used for the whole system. However, this can be very expensive and at times can be a source of power failure itself. In one wants power fail protection, one should first choose a total system which uses as little power as possible and has few high power consuming devices which are used frequently. Another strategy is to protect only those parts of the system whose function is critical. For example, the clock could have a battery backup or the memory of a computer could be power- fail protected. Another strategy is to provide enough power for an orderly power- down in order to protect recorded data from being destroyed.

A power -up routine can then be used to resume data acquisition when stable line power is restored. It should also be decided if meaningful data can be collected during a power failure. Also the most frequent power failures are of short duration, and it is usually only economical to protect the system from this class of failures. In all cases the system should be protected from very short transients on the power line. Before installation the quality of the electrical service should be checked. The data acquisition system should not be connected to circuits which have heavy equipment on them which frequently start and stop. It is also advisable to install line filters on power lines to minimize the effects of line transients.

Many scanners can be controlled remotely by either parallel or serial interfaces. These allow later use of the scanner with a computer. The expandibility of the scanner to larger configurations should be determined; though there is a practical limit for the number of sensors which can be connected to one scanner. If low level signals are being scanned, the accuracy with which these can be switched by the scanners must be determined. If sensors with high output impedance are used, the effect of the bias currents of the multiplexers (and data converters) must be assessed.

- data converters

The conversion of the signal from the transducer to a form in which it can be read, and recorded, is accomplished by a data converter - either an analogue to digital converter or a digital to analogue converter, depending on the nature of the sensor signal and the recorder input. The most typical type of data converter used in building energy studies is an analogue to digital converter. The digital to analogue converter is usually reserved for control and analogue display functions. One notable exception occurs in data collection systems when only a few channels consist of digital data. The cost effective approach is to add D/A converters to the digital channels instead of providing separate multiplexing and interfacing to the few digital signals. The two most popular types of A/D converters are the successive approximation A/D converter and the dual slope integrating A/D converter. The successive approximation A/D converter is faster than the dual slope integrating A/D converter; however, it usually requires a sample and hold amplifier. The dual slope integrating A/D converter has inherently more noise rejection.

The data rate in most building performance monitoring systems is slow enough to permit the use of the dual slope integrating A/D converter. Besides the inherent advantages of automatic zero and noise rejection, selection of the integration time to equal an integer number (1 or more) of cycles of the power line frequency can achieve a 40 to 60 dB rejection ratio of power line frequency noise pickup. Even higher rejection ratios can be attained for harmonics of the power line frequency. Practical throughput rates of 4 to 8 conversions per second can be attained.

In selecting an A/D converter, one must judge its precision, resolution, drift, input impedance, bias currents, its ability to accept bipolar inputs, its ability to accept differential signals, its normal mode rejection characteristics, its common mode rejection ability and the number of significant digits. If an A/D converter has a readout, it is called a digital voltmeter.

At present there are many systems which incorporate all or some of the functions of signal conditioners, data scanners and data converters described above. These systems are referred to as data loggers or data acquisition systems. Many of these now have microprocessors and permit a wide variety of signal conditioning, a certain amount of data reduction, and some programming of its functions. If such a system satisfies the requirements of a monitoring project, it is usually advisable to incorporate it in the data monitoring instead of attempting to interface individual components. However, none of these systems are specifically designed for building applications and therefore usually require some adaption to specific projects.

- data recorders

The output of a data acquisition system can be stored on analogue paper tape, analogue magnetic tape, digital paper tape and digital magnetic tape. In general any media recording analogue data requires vast amounts of data rejection, often much of this by hand. Such media have been used in the past as primary data storage means. However, at present they are best suited for application as a backup medium to be employed in case of failure of the primary, suited for single channel operations which require high speed and dynamic range.

The most commonly used storage medium in modern data acquisition systems is the digital magnetic tape; though with the advent of computer based data systems this could be replaced by magnetic discs. Magnetic tape records can be either seven or nine track tapes used on large main frame computers or digital cartridge or cassette recorders. The important criteria for these recorders are reliability and the existence of a reader for the media on the main frame computer on which the data are to be analyzed. It is important to consult with the operators of the computer on which the data are to be analyzed to determine the compatibility of the media and the data format with existing devices and software on the computer.

- computer based data acquisition systems

The data acquisition approaches described above have been used to adequately measure the energy performace of buildings; however, certain deficiencies should be recognized. The system is relatively expensive and more data are collected than is needed for most applications, adding to the data processing costs. With the advent of the microcomputer, it is now possible to develop building monitoring systems which perform realtime analysis of the data collected and, therefore, produce physically meaningful results faster and at a lower data processing costs. There are several schemes for interfacing a microcomputer to a data gathering system. Standard parallel and serial interfaces can be used to interface counters, data scanners, signal conditioners and data loggers to the microcomputer. However, with the establishment of standard data busses for microcomputers, such as the S-100 buss, it is possible to use standard interface cards on the computer buss for a large variety of sensors. The addition of a microcomputer to a data acquisition scheme also allows the intelligent control of the experiment and the possibility of recording and monitoring only what is of interest at a specific time.

Figure III g-1 shows a configuration of microcomputer-based data acquisition system which provides not only the information required on the standard components of the building energy use and environment, but also includes a tracer gas system for monitoring the air infiltration of the building. It would be difficult to do this level of monitoring without a microcomputer.

Another approach using the computer as part of the monitoring system has been developed at Princeton University. The adoption of the home computer into a data acquisition system seemed a logical and cost effective direction. The built in display allows for the instantaneous readout of data and system monitoring. The system uses programming with simple commands that allow the homeowner to restart the data taking after a major power failure with a few simple commands typed into the built- in keyboard.

There are numerous ways to link sensors to signal conditioners, signal conditioners to scanners, scanners to data converters etc. These devices can be linked together by hard-wire communication path or by telemetering. In principle, the simplest and least complicated means should be used. For linking systems together, there are many slave and master concepts which can be used to link remote subsystems to a central facility.

There are advantages to this type of system if it is functioning properly. However, the failure of one or two critical components can bring the whole system to a halt. With the advent of low priced microprocessors, the trend has been toward distributed systems with the local data acquisition systems having on -site calculational ability, and being able to function alone. The interfacing of many smaller systems to a central data system can present many unforeseen problems if the system has not been field proven for an extended period of time. Also the time from which the first sensor is installed to when reliable data can be collected is quite long for a complex interdependent

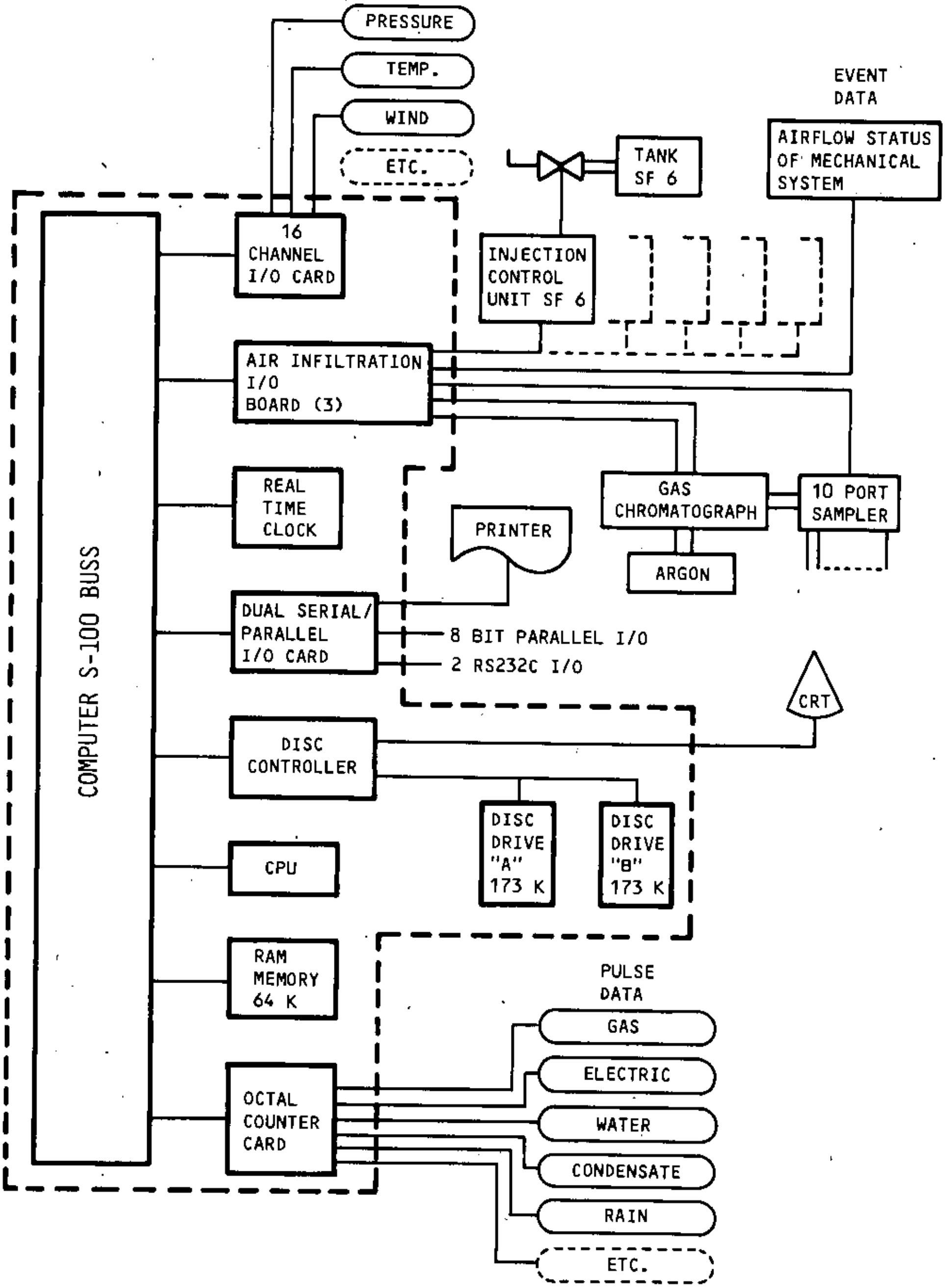

Fig. III g-1 Block diagram of the interfacing of each component with the computer system. For independent distributed systems, much meaningful data can be collected and the reliability and functioning of many parts of the system proven as each subsystem is activated.

There are data acquisition systems which can handle over 1 000 data channels. This type of system should be avoided if possible. In general, once an experiment requires more than 100 data channels, its design should be reevaluated. If that number of data points are required, the experiment should be divided into subgroups of basically independent submodules and individual data acquisition should be considered for each submodule.

- sensor connection

Various types of sensors are availabe for measuring variables. They range widely in cost, accuracy, precision, response time, size, excitation requirements (none to precision DC/AC voltage/current), output level (millivolts to volts) and output type (digital, contact closure, photo-interrupter, analogue voltage/current and analogue frequency/pulse). It will be necessary to bring a variety of signals from the variously located sensors to a central location where they can be processed and recorded. In addition, sensor excitation will have to be supplied from that location as required.

Certain introductory remarks can be best illustrated by closely examining the sensor selection for one type of measurement. A detailed discussion of sensor selection for all the variables is beyond the scope of this section.

As an example, temperature has been choosen, since it generally comprises 1/2 or more of the total measurements in building energy monitoring systems. High level output types, such as the sensor/transmitter types used in various processing industries, are precluded because their cost is about ten times that of the sensor alone. When sensor selection is limited to commercially available types that do not require individual calibration by the user, a choice among four types remains. These types are thermocouple, thermistor, integrated circuit (IC) transducer and resistance thermometer detector (RTD).

A detailed comparison of the technical characterics of the various type can be found in the literature(see Harrje and Cooper 1979 and also ch. IIlb). A linearizing network, either as hardware, software, or firmware, is required for all types except the thermolinear thermistor composite.

For thermocouples a low level multiplexer and high gain amplifier is required before the signal can be fed to an A/D converter. Thermocouple extension wire must be used to connect the thermocouple to the electronics package if a common reference junction is to be used. If individual reference junctions are provided adjacent to each thermocouple, then standard instrumentation cable may be used to bring the signal to the electronics package. Thermocouple extension wire is expensive, difficult and time consuming to work with, resulting in high installation costs. In electrically noisy environments it should be shielded and/or run in conduit. Where disconnects are required special thermocouple metal connectors are necessary which are also difficult to work with. Both thermocouple extension wire and connectors can introduce additional error, so that an overall worst-case limit of accuracy (and interchangeability) of 2 to 4 K can result. Only when high temperatures, above the range of other sensors, are encountered does the use of thermocouple appear justified.

Bead thermistors must be read by a resistance measurement. This requires that excitation in the form of a constant current be supplied by the electronics package. The resultant signal level is 0.4 to 0.5 VOC, large enough to result in significant system economies. A special low level multiplexer is not required. If the A/D converter is of the dual slope integrating type with a fixed signal integration time, and that time equals one or more periods of the AC power line, then ordinary 2 conduction speaker wire can be used to connect the thermistor to the electronics package.

The wire gauge should be selected so that the loop resistance of the speaker wire (at its highest temperature) is sufficiently small compared to the thermistor resistance at the highest temperature to be measured so as to keep the resultant error within acceptable limits. If the data acquisition system is known, and the approximate temperature of the wire is known, then a software correction can be made for the wire resistance. Otherwise, a four terminal resistance measurement will have to be made. This will require a 4 conductor cable (2-signal, 2-constant current supply) and a differential input multiplexer and A/D converter (see also ch. III b).

- interference

Building energy monitoring systems may be subjected to all types of interference from a variety of sources and physical locations because of their spatially distributed nature. Interference is classified as electric, magnetic, electromagnetic or conducted, thus describing the major means of coupling the interference into the data acquisition system. Although electric and magnetic interference is limited to nearby sources, the electromagnetic and conducted types may originate from remote sources. While most sources generate all four types simultaneously, most of their energy is concentrated in one or two types.

Common sources of interference in buildings include fluorescent lamps, power wiring, electric ignition for combustion devices, universal motors, power distribution transformers, relays and solenoids, building controls, appliances, business machines, data processing equipment, medical equipment, wireless intercoms, telephone equipment, walkie-talkies, CB and HAM radio transmitters, electric arc welders, neon signs etc. Commercial and industrial buildings will obviously contain more varied and higher powered interference sources than residential buildings and private homes.

Many sources of interference can originate from outside the building being monitored. These may include any sources previously mentioned, especially when connected to the same power line, as well as any high power sources located in nearby structures.

Mobile radio transmitters (police, emergency, commercial, CB etc.), Walkie-Talkies (security patrol) as well as commercial broadcast antennas and high voltage power transmission lines must also be considered as potential interference sources.

Electric interference can be expected from devices operating at high voltages, and/or frequencies. It is capacity coupled via the electric field into exposed circuitry. Reduction is achieved by electrostatic shielding of the exposed circuitry with a high conductivity metal, usually aluminium or copper. Often successive layers of insulated shielding are used to achieve the desired isolation. Connection of the innermost shield to the signal common or signal ground must take place at the electronic package because of the spatially distributed nature of a multiple input system.

Magnetic interference can be expected from devices operating at high current and/or frequencies, or containing coils wound on ferro-magnetic cores. Power distribution wiring is, of course, also a prime source. Reduction of low frequency interference is achieved by magnetic shielding of the exposed circuitry with soft iron or steel. Grain-oriented high permeability alloys, such as μ-metal or permalloy, may sometimes be used. Table IIIg- 1 (Nalle 1965) lists the attenuation various shielding materials provide for DC/low frequency magnetic fields.

TABLE III g-1

Magnetic field reduction by shields

Shield material	Ratio	Field reduction
No shield	-	0 dB
1/2 inch OD aluminium tube	1:1	0 dB
1/2 inch OD copper tube	1:1	0 dB
1 inch rigid steel conduit	138:1	42.8 dB
1 inch ID BX armor-steel	28:1	28.8 dB
3/4 inch ID BX armor-steel	22:1	27.0 dB

Where coupling between coils or transformers is involved, additional attenuation can be achieved by orienting their magnetic axes in mutually perpendicular directions. Electrostatic shields are effective against high frequency magnetic fields because the induced eddy currents give rise to magnetic fields that cancel the external field within the shield. The external magnetic field and the induced eddy current density decrease exponentially with the distance from the surface. The depth of penetration, or skin depth, is defined as the distance into the conductor at which the eddy current density = 1/e times the density at the surface. The skin depth d has been given to (Belden Corporation)

$$d = 5033 * \sqrt{r/(pf)}$$

where

r is the resistivity in ohm/cm

p is the relative permeability
f is the frequency in Hertz

At $20^{O}C$ this becomes $6.62/\sqrt{f}$ cm for copper and $8.16/\sqrt{f}$ cm for pure aluminium. The above equations assume that the conductor (shield) is thicker than 10*d, the radius of curvature of the surface is greater than 10*d and does not vary rapidly along the surface. Thus, an aluminium shield would have to be at least 11 cm thick to provide effective magnetic shielding at power line frequencies, but only .0017 cm thick at 1 MHz.

Electromagnetic interference can be expected to be radiated from any device containing an electronic oscillator. In addition, any device containig an electric arc (gas, lamps, welders, commutators, mechanical contacts) can be expected to radiate.

The lumped and distributed circuit constants of the device, along with the modulation, will determine the frequency spectrum, while its physical dimensions compared to the wavelength(s) will determine its efficiency as a radiator. Properly grounded electrostatic shielding, as well as RF bypassing of critical circuit elements, are used for reduction of the interference.

CAUTION: Long ground leads can increase the electromagnetic interference by acting as antenna systems in themselves. In some situations, the ultimate solution may have to be determined by trial and error. Detection can take place in dirty or corroded metal to metal contact points (such as connection of a ground wire to a pipe) as well as semiconductor p-n junctions. After detection, the interference can appear as the average value of the half-wave rectified RF signal or as the modulation envelope, depending upon the frequency response of the data collection system following detection.

Conducted interference can be expected from the building AC power lines, and can originate from any device operated from those lines. Reduction is achieved by installing power line filters for the data collection system. If they are of the plug- in type, shielded line cords should be used on the appropriate system components.

Conducted interference can also be introduced by physically grounding the data collection system at more than one point. Ground potential differences, ranging from tenths of a volt to volts, can exist throughout a building or building complex. Their exact character will vary, depending upon what electrical equipment (and where) is in operation simultaneously. In addition, DC potential differences can exist through the galvanic action of any dissimilar metals used in the plumbing system(s).

Care should be excercised during installation to insure that inadvertant grounding of shields, signal common leads, sensors etc. does not occur through either direct (high or low resistance) connection or high stray capacities.

Interference can enter various parts of the data acquisition system: the sensors, instrumentation lines, electronics package (signal conditioners, multiplexer, A/D converter, data recorder etc.) or data (digital) communication link (if present). Various parts of the system are more susceptible to different types of interference:

1) sensors: conducted, electric, magnetic.
2. analogue data lines: all
3. electronics package: conducted, electromagnetic.

Sensors are often the entry point of conducted interference because of accidental grounding during mounting, thus creating a "ground loop". High impedance sensors can also introduce ground loops by capacitive coupling to ground. Low level output sensors are the most vulnerable, and modern data amplifiers include guard ciruits to cope with this situation. Where magnetic shielding of a sensor is required, shield- μ tape can often be used to form a shield in-place. It is available in a variety of widths, thicknesses and alloys. If electrostatic or electromagnetic shielding is also required, the tape can be obtained with copper foil physically bonded to, but electrically insulated from, the magnetic alloy.

Analogue data lines generally use twisted-pair shielded wire with an overall insulating jacket. Aluminium- polyester shielding is used extensively because of its 100% coverage, as compared to 60% to 80% for most braided shields. Braided shielding is time consuming and difficult to work, while the bare drain wire of aluminium- polyester shielding is fast and easy to work. This type of construction provides excellent protection against electric and electromagnetic interference while relying upon the twisted pair construction for protection against low frequency magnetic fields. With low signal levels, it may be necessary to enclose the instrumentation cable in conduit to obtain adequate low frequency magnetic interference rejection. Table III g-2 compares the effectiveness of various methods (Nalle 1965).

TABLE III g-2

Magnetic noise reduction by wire twisting

Test	Ratio	Magnetic Noise Reduction
Parallel wires	-	0 dB
Twisted wires, 10 cm lay	14:1	23 dB
Twisted wires, 7.5 cm lay	71:1	37 dB
Twisted wires, 5 cm lay	112:1	41 dB
Twisted wires, 2.5 cm lay	141:1	43 dB
Parallel wires in 2.5 cm rigid steel conduit	22:1	27 dB

This type of cable is available in many combinations of pairs, shielding, insulating materials, gauges and double shielding. A discussion of the various types of insulations and shielding can be found in the literature (Belden Corporation).

At the input to the Electronic Package low-pass filtering should be used to restrict the bandwith of the incoming signals to minimum required by the data. Signals outside this range can, by definition, only be noise. Simple single section R-C filters can be effective in reducing the conducted interference entering the electronics package. High output impedance sensors may, with the cable capacitance, form a suitable filter.

Most interference conducted into the Electronics Package will come from the AC power lines. This can be removed by installing suitable power line filters. Other vagaries of the power line can cause poor system performance. These are poor regulation, high voltage spikes, and lack of integrity. All of these can be overcome with the addition of an Uninterruptable Power System (UPS). While originally available only for high power systems, UPS are now manufactured in low power ratings for the microcomputer market. A dedicated power line should also be used to prevent unnecessary power interruptions.

The ideal way to eliminate interference is to suppress it at its source. This approach is not feasible in building energy monitoring except, perhaps, with one or two grossly offending devices. The economic and political reasons for this are obvious. From a technical standpoint, the basic device design will be different if interference suppression is a design objective. In practice, an interference reduction of about an order of magnitude might be achieved by retrofitting an existing device. This will usually consist of adding power line filters to reduce conducted interference. Occasionally, units may be found with their grounding connection broken, badly corroded or absent.

A second way to minimize interference is by judicious layout of the installation. A walk-through of the building should be conducted to locate potential interference sources. In that way, close proximity of system components to these sources can be avoided during initial system layout. Where unavoidable, appropriate interference reduction methods can be included in the initial planning.

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APPENDIX III

Errors, Representativity and Sampling of measurement points

Contents

App. III Errors, Representativity and Sampling of measurement points

- errors in direct measurements

It will not be possible to give an account of all possible sources of error that are inherent when using all the sensors described in ch. III. Here will only be given an example of errors that may occur in temperature measurements in the building interior.

For the error evaluation one has to distinguish between three kinds of error:

1) the error of the measured temperature at one certain position
2) the error associated with the representativity of these positions
3) sampling errors due to temperature fluctuations with time at these positions

1) The error of the first kind is due to properties of the measuring device. For some errors of this kind it is, in principle, possible to calculate a correction factor and thus reduce the size of the error. If this is not possible, one can in some cases estimate the size of the error. This can be done provided one knows, e.g.:

- the accuracy of the sensor
- the resolution of the voltmeter or amperemeter
- errors caused by heat conduction along wires
- the error resulting from non-linearity of the instrument

For other errors there is in general no way of performing a correction or estimate the size of the error. Errors of this kind include:

- errors due to a falty calibration
- errors due to use of the instrument in an environment different from the one where the calibration was performed (see below)
- the error caused by self-heating
- the error caused by heat radiation from surfaces
- the error caused by instability in the output voltage of the battery included in the instrument

- for surface temperature measurements the error caused by heat conduction.
- interference between measurement system and electro- magnetic environment

The error of the first kind will have a systematic as well as a statistical component. The systematic component of the error can be reduced in two ways. One possibility is to perform the calibration in an environment that as much as possible resembles the environment at the position where the actual measurement will take place. The instrument can, e.g., be calibrated in a room where the surfaces are kept at the temperature one expects that the surfaces of the room studied will have when the measurement is performed. In this way the error caused by heat radiation from surfaces will be reduced.

The other way is to calibrate the instrument in an environment where the influence of the factors listed above is reduced as much as possible. In this case the correction of the measured value has to be performed after the measurement through a calculation of the estimated deviation from the "true" value. In both cases the systematic error will be reduced, but it will not disappear.

If the remaining systematic errors (or their upper limit) can be estimated (after calibration and/or correction as described above) it is possible to assign an inaccuracy to the measurement procedure. If the individual remaining errors are denoted by ε_i, two usual measures of this inaccuracy are the probable error ε defined as

$$\varepsilon = \sqrt{\Sigma\varepsilon_i^2}$$

or the maximal error ε_{max} defined as

$$\varepsilon_{max} = \Sigma|\varepsilon_i| .$$

2) The error of the second kind also has a systematic and a statistical component. The systematic component is associated with the choice of positions of the sensors. Assume that n observations of the temperature at a certain position have been made. Furthermore assume that these observations constitute a sample from a normally distributed population. The normalized average temperature multiplied by n will then follow Student's t-distribution t(n-1). This can be used to calculate a confidence interval of the average temperature.

The same method can be used to treat m simultaneous observations at the different sensor positions, if it can be assumed that the average temperature is the same at every such position, e.g., on a partition wall. The normalized average temperature will then follow the distribution t(m-1).

3) Finally assume that m sensors can be regarded as randomly distributed in space and the temperature fluctuations at each sensor position follows a normal distribution with the same scatter, but with a different average, for the different positions. A simultaneous observation of the temperature at the m positions is performed n times. The normalized average temperature of all these observations multiplied by $\sqrt{nm}$ will then follow the distribution t(nm-m).

For a discussion on errors in direct measurements see, e.g., Doebelin (1966) or Abernethy- Thompson (1980)

- errors and representativity in non direct measurements

In general the errors will not be known when data are collected from archives and records unless one has access to two records with partly overlapping data. Such data can be compared to give an idea on how correct and consistent data are. Another possibility is to compare part of the data set to real conditions which have not changed since the construction of the data set.

The most common source of error in observational studies is the influence of the observer on the behaviour of the occupant.

When survey techniques are used, an underlying assumption is that the respondent has the intellectual capability to respond to complicated phenomena, he can verbalize his response and is aware of the effect of the environment on his the behaviour. The respondent may have an inclination to give the answers he believes are the wanted answers. Other sources of error in this case have to do with the way the questions are formulated and presented. Questions and responses can be misinterpreted. There is always the possibility that the interviewer influences the occupant, he may unintentionally nod agreement or smile. Another source of error is that the answer will often depend on at what time of the year the interview is performed. It might be difficult to ask the occupant about his behaviour during the heating season in the summer.

The most difficult problem when using survey techniques is the problem of validity. Here it might often be advantageous to make a distinction between external validity (degree of agreement between a measured value and the "true value") and internal validity (degree of agreement between an entity as used in a model and the operational definition of this entity).

The question of external validity can often not be answered as the "true" value is not known. Instead this becomes a matter of judgement when experience of real conditions obtained by other means are compared to the results of the actual investigation. The question of inner validity is often more a practical question of what approximations can be allowed while still retaining the crucial features of the studied entity.

The sample of the population questioned, or investigated, in projects to determine the behaviour and habits of occupants has seldom been representative of the population in a strict statistical sense.

The number of variables becomes very large if one tries to typify dwellings. On the other hand, the investigators have striven to get a sample that in some respects is typical, even if they have not succeeded in getting one that is really representative. In most cases, therefore, the major features of the results from investigations of this kind can be trusted but minor details of the results should not be accepted uncritically.

Often no single method can reach all sources of information but several data gathering techniques have to be used to collect all relevant information.

For a discussion on errors and representativity in non- direct measurements see, e.g., Lang et al. (1974)

- sampling of measurement points

Here we will treat the topic of how to determine the sample size (choose a representative sample) when designing a sample survey from a population. It will be shown how the error is determined if the size of the sample is fixed, and how to choose the size of the sample for a wanted size of the error. It will also be assumed that the population is divided into groups, each consisting of several objects. For simplicity we will here ony treat the case of two groups, but all formulas below are easily generalized to the case of more groups. The following notation will be used:

N = size of population, $N = N_1 + N_2$
N_1 = size of first group of population
N_2 = size of second group of population
n = size of total sample, $n = n_1 + n_2$
n_1 = size of sample from first group
n_2 = size of sample from second group
x = measured entity
$\bar{x}$ = average of x
$\bar{x}_1$ and s_1^2 = average and variance of the values x_{1i}, $i = 1, n$.
$\bar{x}_2$ and s_2^2 = average and variance of the values x_{2i}, $i = 1, n$.

It is now clear that an estimate of the average of x, x, for the whole population is given by

$$\bar{x} = (N_1 \bar{x}_1 + N_2 \bar{x}_2)/N \qquad (A\ III - 1)$$

where $\bar{x}_1$ is an estimate of the average of the measured entity in group 1 obtained from the sample n_1 as

$$\bar{x}_1 = \sum_{i=1}^{n} x_{1i}/n_1 \qquad (A\ III - 2)$$

Obviously $\bar{x}_2$ is calculated in an analogous way. The variance of $\bar{x}$ will be $D^2(\bar{x})$

$$D^2(\bar{x}) = (\sum_{i=1}^{2} N_i(N_i - n_i)\ s_i^2/n_i)/N^2 \qquad (A\ III - 3)$$

where

$$s_i^2 = \sum_{j=1}^{n_i} (x_{ij} - \bar{x}_i)^2/ (n_i - 1) \qquad i = 1,2 \qquad (A\ III - 4)$$

Let ut now first assume that measurements have already been performed with given n, n_1 and n_2, and we want an estimate of the variance of the average $\bar{x}$. This variance can then immediately be obtained from (A III - 3).

Now instead assume that no measurements have been performed, but n has been chosen. One then wants to determine n_1 and n_2, $n_1 + n_2 = n$, so that $D^2(\bar{x})$ becomes as small as possible. As input one then needs the ratio of the variances s_1 and s_2 of the two groups. We assume that this ratio can be obtained from previous investigations or a qualified guess has to be made. If

(A III - 3) is differentiated with respect to n., one obtains the result that the minimum value of $D^2(\bar{x})$, $D^2_{min}(\bar{x})$, is given by

$$D^2_{min}(\bar{x}) = (\sum_{i=1}^{2} N_i s_i/N)^2/n - \sum_{i=1}^{2} N_i s_i^2/N^2 \qquad \text{(A III - 5)}$$

and the values of n_1 and n_2 are given by

$$n_i = N_i s_i\, n/\sum_{j=1}^{2} N_j s_j, \qquad i = 1,2. \qquad \text{(A III - 6)}$$

which can be written e.g. as

$$n_1 = N_1 n/(N_1 + N_2 * s_2/s_1)$$

which confirms that is suffices to know the ratio s_2/s_1 in order to determine n_1 and n_2. Lastly assume that the wanted value of $D^2(\bar{x})$ has been fixed. One then wants to determine n, n_1 and n_2. Solving (A III - 3) with respect to n one obtains:

$$n = n_1 + n_2^2\, s_2^2/(N^2 D^2(\bar{x}) + \sum_{i=1}^{2} n_i\, s_i^2 - N_1^2\, s_1^2/n_1)$$

Differentiating with respect to n_1 one obtains:

$$n_i = N_i s_i\, (\sum_{j=1}^{2} N_j s_j)/(D^2(\bar{x})\, N^2 + \sum_{j=1}^{2} N_j s_j^2), \quad i=1,2 \qquad \text{(A III - 7)}$$

and

$$n = (\sum_{i=1}^{2} N_i s_i/N)^2 / (D^2(\bar{x}) + \sum_{i=1}^{2} N_i s_i^2/N^2) \qquad \text{(A III - 8)}$$

which is in fact identical to (A III - 5). One can now see that to calculate n, n_1 and n_2 one needs to know the values of s_1 and s_2.

Example 1

A residential building contains 100 flats, 20 of which are situated at the gables of the building. Each flat has windows on two facades, one which is exposed to solar radiation and one which is not. The rooms on the sunny side are expected to have a higher temperature. One wants to know in how many flats the temperature has to be measured if one wants to minimize $D^2(t)$ where t is the average temperature of the building.

It has already been decided that in each flat where measurements are performed, the temperature should be measured at two positions, one in a room on the sunny side and one on the shaded side of the building. The average of these two temperatures is assumed to be the average temperature of the flat. In this case thus $N = 100$, $N_1 = 80$ and $N_2 = 20$. From previous experience it is also known that for buildings similar to the one above $s_1 = 1$ K and $s_2 = 2$ K. From (A III-6) one then immediately obtains $n_1 = 2n/3$ and $n_2 = n/3$. From (A III-7) one can now calculate that for $n = 6$ one gets $D_{min} = 0.5$ K while for $n = 24$ one gets $D_{min} = 0.2$ K.

Example 2

One wants to know the average rate of air exchange of a population of one million dwellings, 700,000 houses and 300,000 flats in residential buildings. Consequently $N = 1{,}000{,}000$, $N_1 = 700{,}000$ and $N_2 = 300{,}000$. Samples are to be taken at random from this population, and the air exchange rate measured for every dwelling in the sample so that the resulting error of the determined air exchange rate is not greater than 0.05 air changes/h. One then has to determine the sample sizes n, n_1 and n_2, $n_1 + n_2 = n$. As seen above one must then know the values of s_1 and s_2.

A pilot study is performed. The rate of air exchange is measured in ten flats and ten houses, chosen at random from the population. The values of s_1 and s_2 are estimated by (A III - 4). One obtains $s_1 = 0.5$ airchanges/h and $s_2 = 0.3$ airchanges/h.

One can now proceed to determine n, n_1 and n_2 using $D^2 = 0.05^2$ and the values of N, N_1, N_2, s_1 and s_2 as input to (A III - 7) and (A III - 8). One then gets $n_1 = 61$ and $n_2 = 16$. Disregarding the uncertainty in the estimated values of s_1 and s_2, one then has to measure the rate of air exchange in another 51 houses and 6 flats.

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PART IV

MEASUREMENTS AND DATA COLLECTION ON

OCCUPANCY AND HOUSEHOLD ENERGY

Contents

CHAPTER IV a

General introduction and data collection methods

Contents

IV a General introduction and data collection methods

- general introduction

Part IV deals with measurements of the occupancy related consumption of energy in a residential building. The first ch. IV a deals with the methods of measurement which can be applied, and their advantages and disadvantages. The second ch. IV b deals with factors affecting the occupant's consumption of household energy and tap water, and the monitoring of this energy consumption. The third ch. IV c treats operations by the occupant which affect the total energy consumption, but are not easily monitored. The last ch. IV d deals with simulation studies. Appendix IV contains a collection of data on the consumption of tap water and household energy. At the end of Part IV can be found the bibliography and references common for the chapters of Part IV.

In ch. III a different methods of collecting data have been discussed. In this chapter we will describe how these methods are applied to the measurement of the occupancy related energy consumption. Data collection from records, monitoring of a residential building, and the use of survey methods and observations will be discussed. It will also be discussed how published data on the consumption of tap water and household energy have been obtained and how reliable such data are. The background to this discussion is that data of the kind above can be used in a calculation of the energy balance of a residential building for the evaluation of a retrofit.

If one uses data collected from records, one will, in general, have only information about the consumption of energy by the "average household". This may be sufficient if one is using a simple model, or is studying the effect of a retrofit on a large number of households. Otherwise the energy consumption of the residential building will have to be monitored.

Data on domestic energy consumption are often presented as national averages. Sometimes data have been obtained from a representative sample of the population in a country. In other cases it has not been feasible to conduct a study in this way. Instead, one or more case studies have been performed and the results have been assumed to be representative of the whole population. The problem of representativity may then become acute.

When only one or a few residential buildings are monitored, it will in general be possible to get a sufficient breakdown of the end use of household energy. It will often be necessary to have a sufficient degree of breakdown if the results of the measurements are to be used as input to a model to simulate the thermal behaviour of the residential building in another environment, or if the results of the measurements are to be applied to other buildings. If this breakdown of the end use of domestic energy is not at hand, the problem of representativity may arise. It may then be of interest to estimate the total consumption of net energy in the household to be compared to a national average or the average consumption in other countries.

If, instead, data are collected from a large number of residential buildings, it will in general not be possible to obtain data on the end use of household energy. Therefore, it may in this case be of interest to estimate the energy consumed for purposes other than heating of the building.

Strictly speaking, all energy released by appliances inside a building should be regarded as a positive contribution to the heat balance of the building. However, in many cases this energy causes overheating and is quickly removed by the occupant, e.g., by increasing the rate of ventilation. When studying the energy balance averaged over a long period, it has therefore become common to regard only a certain fraction of the energy released by appliances as a contribution to the heating of the dwelling. This energy, and energy flows through the building envelope from impinging solar radiation, are often referred to as the "free heat".

It can be assumed that nearly all energy released by electric appliances like refrigerator, deepfreezer, TV sets, and illumination contributes to the heating of the dwelling. For hot tap water, a clothes-washer, and a dish-washer one has to estimate the amount of energy used to heat water and how much of this energy is released inside the building and how much is lost by the discharge water. When cooking and drying clothes, some of the used energy will increase the temperature of the air which is removed by the ventilation system. One must therefore, in this case, consider whether the rate of air change is increased when the occupant is cooking or drying clothes.

A summary of the discussion in App. IV on how to treat the energy flows associated with the use of appliances is given in Table IV a-1. In Table IV a-2 there is a summary of what data collection methods can be applied when collecting data related to the occupancy.

TABLE IV a-1

Treatment of occupancy related energy use

Energy from	Treatment of energy
generation of hot tap water	Used energy can be divided into: flue losses+ jacket losses+ distribution losses+useful energy which heats the water. Energy is lost by the discharge water. Flue losses: part of the energy is regained through heating of the chimney if this one is inside the building Jacket losses: can be neglected if the volume of the tank is small. Otherwise it will contribute to the heating of the building (sometimes only to the heating of the basement). Distribution losses: part of the energy is transferred to the plumbing. This can give a contribution to the heating if the pipes are inside the building and not in the building envelope. Useful energy: can be regarded as lost when water leaving for drain except for a small part which is taken up by the plumbing.
cold tap water	Temperature of inlet water raised by heat transfer from the building. This energy is lost when water is discharged.
cooking	Some energy "lost" because of overheating and increased ventilation, more when gas is used then when electricity is used. Consequently the operation of the ventilation system has to be considered (see ch. III e)
clothes-washing	Useful energy for water heating can be regarded as lost when hot water generation incorporated with washer. If the hot water is taken from the hot tap water, it can be treated as such.
dishwashing	Same comments as for clothes washing
clothes-drying	If hot air is produced, the indoor air temperature rises. Small part of this energy may be stored in the building fabric. Most generated energy will be lost by the air extracted by the ventilation system.
refrigerator& deepfreezer	Continuously working. Nearly all energy contributes to the heating of the dwelling
TV	Load varies much during day. Nearly all energy contributes to the heating of the dwelling
illumination	Load varies much during the day and during the year. Nearly all energy contributes to the heating of the dwelling.

- collecting data on energy for tap water

Monitoring domestic hot water systems becomes a difficult problem due, on one hand, to the complexity of human occupancy patterns, and to the variety of production and distribution devices on the other hand. The type of installation, and the accuracy of energy saving predictions, determine the level of monitoring chosen for these purposes. However, despite the difficulties, one should not ignore the effect of this supplementary energy package on the total energy balance of the house (in the context of a decrease in spaceheating demand due to insulation of the house and an increase in the "comfort" level of the occupants).

Various technical factors will determine what measurement devices can be used and their complexity:

1) type of primary energy used (oil, gas, coal,electricity)
2) type of appliance or system (appliance specifically designed for water heating or central heating, storage capacity etc.)
3) distribution system (for a single house or a group of buildings)
4) number and location of the draw- off points

In any case, hot water production can be treated as a heating system (individual or incorporated). Thus, it can be studied in terms of its efficiency of production, distribution, and regulation.

If no continuous monitoring is performed, but one still wants to estimate the energy consumed by production of hot tap water, and its contribution to the heating of a residential building, data have to be collected by means other than monitoring of the building. The data which are needed in a study of the effects of a retrofit will depend on what model is used and what kind of data analysis is to be performed. If a complex model is used, one will, independently whether the building is monitored or not, need information about

1) the demand profile (with a time-resolution as in the model)
2) the appliances used for generation of hot water
3) the domestic appliances using hot water
4) the amount of water consumed (hot and cold)
5) the temperature of the inlet water
6) the temperature of the hot water

Information about the consumption of tap water in dwellings can be obtained in several ways. Published data have mostly been obtained in one of the following ways:

1) A direct measurement of the useful energy by measuring the flow and the temperature of the hot water just before the tap. The net energy use required for the calculation of the energy balance of the building can then be obtained if the heat losses from the hot water storage and the plumbing is added to the measured useful energy. The flow of hot tap water can easily be monitored, or read of from a meter, in residential buildings with individual metering. These results will, however, not be directly applicable to buildings with collective metering, or no metering at all, as the consumption there is likely to be higher.

Experiments where direct measurements have been performed in general have to be regarded as case studies. Results from such experiments seldom represent any kind of "national average consumption". Data on the end use of water, and the net energy consumption for hot tap water, can be found in App. IV.

2) If the amount of primary energy, used by the heating appliance, and its efficiency are known, the net energy used for hot water generation can be calculated. If the hot tap water is produced in connection with the heating system, the appliance efficiency will vary throughout the year, and will, in general, not be known with a high degree of accuracy. This topic is discussed in ch. III f. Here we only mention that estimates of the efficiency of water heaters in residential buildings varies from 35 to 70% depending on the load, the kind of fuel that is used, and the kind of water heater (central heating or not) (Smith 1978, Wilson 1978, Hirst-Hoskins 1977, Over 1974, Whittle-Warren 1978).

3) If only electricity is used for hot water generation, the net energy can be determined directly.

4) Hot water consumption is often inferred from the total household water consumption. The hot tap water fraction of the total water consumption is measured in a few residential buildings. This fraction is then supposed to be typical also of other dwellings whose hot water consumption is to be estimated.

5) A fifth possibility of estimating hot water consumption is to perform a further breakdown of the end use of water as in the first method discussed above, but instead of direct measurements one uses survey techniques. A representative number of occupants are asked about how often and for how long they take baths and showers, how often they wash their laundry and at what water temperature, how often they wash up their dishes and how.

One will then have a more representative sample of occupants than when direct measurements are performed on a small number of dwellings. Instead, the numbers obtained are not very accurate and systematic errors can occur. An example of this will be given. In an investigation in Sweden (Dahlman-Åhlund, 1969) with the aim of determining the hygienic habits of people, it was found that men took hot baths 3 times a week and women 5 times. Only 10% of the interviewed people used a shower. In another investigation in Sweden (Edén-Persson, 1978) with the aim of determining the habits affecting the energy consumption, it was found that the people interviewed took less than one hot bath a week but 2.5 showers a week. In both cases the sample of people was not representative of the whole population, and the second investigation was performed ten years after the first, but the disagreement between the results obtained still seems to be rather too large.

6) The simplest way of estimating the energy losses of a building due to water heating is to measure the water flow, the water temperature at the inlet, and the temperature of the sewage water, provided of course that this can be done in practice.

This method is reliable if applied to multi-family dwellings with many flats where the temperature of the sewage water is rather constant. It is more difficult to apply to single-family houses where this temperature varies more.

Collecting data on the amount of cold water used in households in different countries from official records is difficult. At best, the gross consumption as given in official statistics is split up into industrial use, domestic use, distribution losses and "other" use. At worst, distribution losses, which are often of the order of 10% but in same cases may be as large as 30% (Coe 1978), and other use is included in the given consumption for domestic use and industrial use. Domestic use is, thus, not only water used in households, but also includes water used in shops, restaurants, schools, and offices.

- <u>collecting data on energy consumption by appliances</u>

Energy used by domestic appliances will in general be in the form of electricity or gas. It is generally rather easy to monitor the total consumption of electricity or gas by the household. Using a simple model, one can then make an assumption about how much of the net energy consumed by domestic appliances contributes to the heating of the dwelling. If a very <u>complex model</u> is used, one will, for the major energy consuming appliances, need <u>information</u> about

1) the demand profile (with a time-resolution as in the model)
2) the energy consumption by each appliance
3) how much of the energy consumed by the appliance contributes to the heating of the dwelling

If information about the energy use by appliances is to be gathered by monitoring, each major domestic appliance will have to be monitored separately. A discussion on the factors which have an influence on the energy consumption by appliances and how to perform a monitoring of domestic appliances, is given in ch. IV b.

Information about the average amount of energy consumed by domestic appliances is, if no monitoring is performed, in general collected in one of two ways. The first one is to investigate the energy <u>consumption per event</u>. This has been done in many laboratory tests. Knowing this, one then has to determine when, and often also how, the appliance is used. This is often done by pure guestimates, sometimes based on some simple survey.

The second way is a purely <u>statistical</u> one. Knowing the fraction of households which have a certain set of appliances (often referred to as a certain technology), and the total consumption (of electricity or gas) for this type of household, via a simple linear regression analysis one can determine the average energy consumption for many appliances. This is done in some countries. In other countries, however, the utilities collect data only on the fraction of households having a certain appliance. In this case the above technique cannot be used. One does in its place use a combination of guestimates on the energy consumption of each separate appliance and the change in penetration of a certain appliance, trying to match these two factors with the change in consumption of electric energy in a rather ad hoc manner. Even the statistical method cannot resolve the consumption of energy by appliances having the same penetration. Thus only the total consumption by TV, refrigerators and illumination can be determined, as each of them in most Western countries has a penetration above 90% .

In only a few cases, none of the two above mentioned methods has been used, but the estimates have been obtained by monitoring of the consumption of household energy in a representative sample of all dwellings (see Bonnard-Vuille- Saugy 1980).

Sometimes the energy consumed by an appliance using gas has been considered equal to its electric counterpart after taking into consideration its efficiency.

- collecting socioeconomic data and data on behaviour and habits of occupants

Socioeconomic data and data on the behaviour and habits of occupants can be collected for several reasons (see also ch. II a).

1) Data may be collected to make sure that the occupants of the test- and the reference buildings in a test- reference experiment are "identical". One does in general not know how individual variables affect the energy consumption, but rather one wants to eliminate differences in some variables as a possible explanation of the difference in energy consumption between the buildings.

2) One may collect data if one wants to generalize the results from a retrofit experiment on a few buildings to part of the national building stock. In this case one collects data to make sure that the occupants of the experimental buildings are representative for the occupants of the class of buildings to which the experimental building belongs.

3) Data can be collected in order to estimate the magnitude of some terms in the energy balance equation of the building. One then has to use a model where data are input to a numerical calculation.

4) One can collect data as a preparation for the launching of an energy- saving campaign. One can then be trying to find what motivates the occupants to save energy. One can also investigate what knowledge the occupants have about, or

how they operate on, already existing building systems. This can be used to prepare instructions to the occupant on how energy can be saved by a more efficient use of such systems.

It is obvious that socioeconomic data and data on the behaviour and habits of occupants can be of very different kind. They can, e.g., include:

- socioeconomic data (income, age, occupation, etc.)
- the occupants´ attitudes to and motivation for energy saving
- data on when the occupant is at home and in what rooms he spends his time
- data on the use of set points
- data on the use of ventilation system
- data on the occupants habits of airing, shielding windows, etc.
- data on use of appliances
- data on use patterns of hot tap water
- data on the occupants experience of the indoor comfort

Data collection methods for socioeconomic data and data on the behaviour and habits of occupants are described in ch. III a. The importance of collecting data of the kind listed above is stressed in many chapters of this document. Below is given a short discussion on how these methods can be applied in practice.

Data on where and when occupants perform some operations, like being at home, can be obtained in several ways. The first is the use of survey techniques. Occupants are interviewed, or fill in a form, answering the question about when they are at home. The second is based on diaries. A number of people are asked to keep an hour by hour record of one day´s activities. This technique has often been used in time- budget studies, i.e. studies of where, and how people spend their time. Observations can also be used. As this means that the experimenter has to spend some time in the home of the occupant, this method has seldom been used in practice.

Information of the kind above can often be derived from other sources. TV and broadcasting companies often devote considerable effort and resources to making time-budget studies for themselves, in order precisely to determine the times of day at which certain audiences will be free to watch or listen to their programs. This information can often be obtained with the population classified with regard to age, occupation, education, income, and geographical region.

A measurement of the habit of <u>window- shielding</u> is most easily performed by observation. Most occupants have rather rigid habits in this respect. A rather small number of observations is required to establish the nocturnal habits. The diurnal habits show a greater variation due to the presence of sunshine. However, if a few observations are performed on sunny and on overcast days, the diurnal habits will also be rather well known.

An alternative is the use of survey techniques. In general this will not lead to an improved accuracy compared to observations. In most cases it will be more time- consuming. Only few studies of this kind have been performed.

Several different methods of measurement can be employed to collect information about the habit of <u>airing</u>. It is of course possible to use direct measurements. Magnetic switches can record when a window is open or shut. Photocells can also be used for this purpose. A thermometer placed on the inside of the window or near the floor will sense the change in air temperature when a window is opened. In this case it might be more difficult to determine when the window is closed. Direct measurements will give a very detailed picture of when, and for how long, the occupant is airing. However, this technique can in general only be used when a comparatively small number of dwellings is being studied.

The number of open windows in a residential building can also be observed.Studies have been performed where an observer has been walking around a number of residential buildings during the day, observing the number of open windows on each facade once every hour for almost a year. Alternatives to this are to use TV cameras for the observation or to record the building facades by photographic means at regular time intervals.

In this case <u>observations</u> is a more flexible method than direct measurements. It can be used for intense observations of a small number of dwellings or for observations of a large number of dwellings in a limited number of occasions.It is, however, difficult to use observations if one wants to study the frequency of airing at night.

Survey techniques can also be used in this case. The occupant can be asked about how often and when he opens windows. The answer will then depend on the season. The occupant will in general tell about his behavior during the last days or the last few weeks. However, experience has shown that the answers are on the average comparable to results obtained by observations (provided of course that one takes into account the seasonal variation of airing). The information will not be so detailed as if direct measurements or observations are used.

Monitoring of the occupant´s choice of set- points is rather easy for some heating systems, e.g., electrical heating. For heating systems not allowing an easy monitoring, survey techniques can be used. In this case the use of survey techniques is facilitated by the fact that many occupants prefer the extreme possibilities when choosing set points, either completely on or completely off, or at a rather low or a rather high temperature, whichever is relevant for the heating system under study. Furthermore many occupants seldom change the set points (see ch. IV c). This of course also makes it easier to use observations.

Monitoring of the occupant´s use of building systems driven by electric motors, e.g. mechanical ventilation systems, is rather easy by simply recording the presence or absence of an electric current or a magnetic field.

TABLE IV a-2

Data collection methods for occupancy-related variables

Type of variable	Direct measurement	Survey methods	Observation	Records
Socioeconomic	No	Possible	No	Recommended
Attitudes	No	Recommended	No	No
Presence at home	No	Recommended	Difficult	Large sample
Use of set points and ventilation	Recommended	Possible. Only seasonal average	Difficult	No
Habits of airing	Small samples	Only for season	Recommended	No
Habits of shielding windows	Difficult	Only seasonal average	Recommended	No
Indoor comfort	Recommended	Possible	No	No
Demand profile of appliances	On-off recording easy	Limited accuracy	No	Difficult
Energy consumption by appliance	Recommended	No	No	Consumer tests
Penetration of appliances	No	Recommended	Limited accuracy	Only average
Demand profile of hot water	Recommended if dynamic model	Limited accuracy	No	Difficult
Consumption of hot water	Recommended	Difficult	No	Only average
Penetration of hot water appl	No	Recommended	Limited accuracy	Only average
Consumption of cold water	Easy	No	No	Only average

CHAPTER IV b

Household energy and domestic tap water

Contents

Keywords

accumulation of water heating system
capacity of appliance
demand profile
distribution of hot tap water
domestic appliances
efficiency of hot tap water production
efficiency of hot tap water storage
efficiency of hot tap water distribution
living and working patterns
metabolism
metering
monitoring of hot tap water
monitoring of domestic appliances
operations of the occupant
penetration of appliance
production of hot tap water
storage of hot tap water
tap water
variation in energy consumption
waste water

IV b Household energy and domestic tap water

- the occupant's use of tap water and appliances

This chapter deals with the operations of the occupant where tap water and domestic appliances are used. In the first section it will be discussed what factors influence the consumption of energy by tap water and domestic appliances. The following two sections deal with the monitoring of a residential building for the measurement of this energy consumption.

A discussion on different ways of obtaining data on the consumption of tap water and domestic appliances can be found in ch. IV a. A collection of data of this kind is found in App. IV. For a discussion about what variation can be expected in the occupants' use of hot tap water and domestic appliances, we refer to ch. I e.

The importance of the operations performed by the occupant must be judged relatively to their impact on the total energy consumption of a residential building. The energy used for tap water consumption and by domestic appliances may vary from ten per cent, for a badly insulated old building, to fifty, for an extremely well insulated modern residential building. The heat produced by the occupants through metabolism must also be taken into account. However, not all of the energy from these different heat sources, the so called "free heat", will contribute to the energy balance of the building. An estimate of the magnitude of this contribution is made in ch. I e.

It is important to realize that the consumption of tap water and electricity for domestic appliances varies with the time of the day and throughout the year. Some examples are given in fig. IV b- 1 through 3.

Many factors affect the consumption of household energy and tap water. The price and the form of metering is of importance for the consumption. In France consumption of hot tap water with collective metering may be 50% larger than with individual metering (CGE 1970). Similar numbers, 36 %, have been obtained in Munich in Germany (Coe 1978). In most countries there is a large variation in the numbers given for the amount of water and household energy consumed per capita or household. This is, however, partly due to the difficulties of collecting data of this kind (see ch. IV a).

Household energy consumption is also affected by the living and working patterns of people. These may be continuously changing like the number of persons in a dwelling. During the investigation on the effect of a retrofit one has to take these changes into account. Some examples are:

- children: an increase in hot water consumption
- husband and wife both work: less household energy consumption
- electric appliances have been replaced by more economic ones:less consumption
- introduction of new types of appliances: clothes driers and dish washers.

Therefore, apart from determining the energy consumption of the heating system in the building, one will have to determine other kind of energy consumption. When performing the retrofit, one has to check whether, and to what extent, this has any effect on the household energy consumption. If there is an important effect, it is advisable to measure it. Some examples of the effect of a retrofit are, in the case that extra insulation is added to the dwelling:

The temperature in the adjacent rooms increases,as a result more rooms are used
effect: higher electrical energy consumption (more lamps on)
The temperature in the kitchen may rise:
effect: more energy is used for cooling and less for heating.
Installation of, for instance, a better temperature control. The kitchen is colder in the evening and at night.
effect: less energy is consumed for cooling and heating.
Lower temperature of hot water.
effect: less energy is consumed for hot water.

The final energy consumption of domestic appliances depends on:
- their capacity
- penetration
- demand profile

In App. IV the average energy consumption for various types of household energy consumption in various countries is analysed. There is a great difference between the USA on the one hand and the European countries on the other. The high values for refrigerators, freezers and other appliances in the USA is caused by the hot climate and the use of cooling units in dwellings.

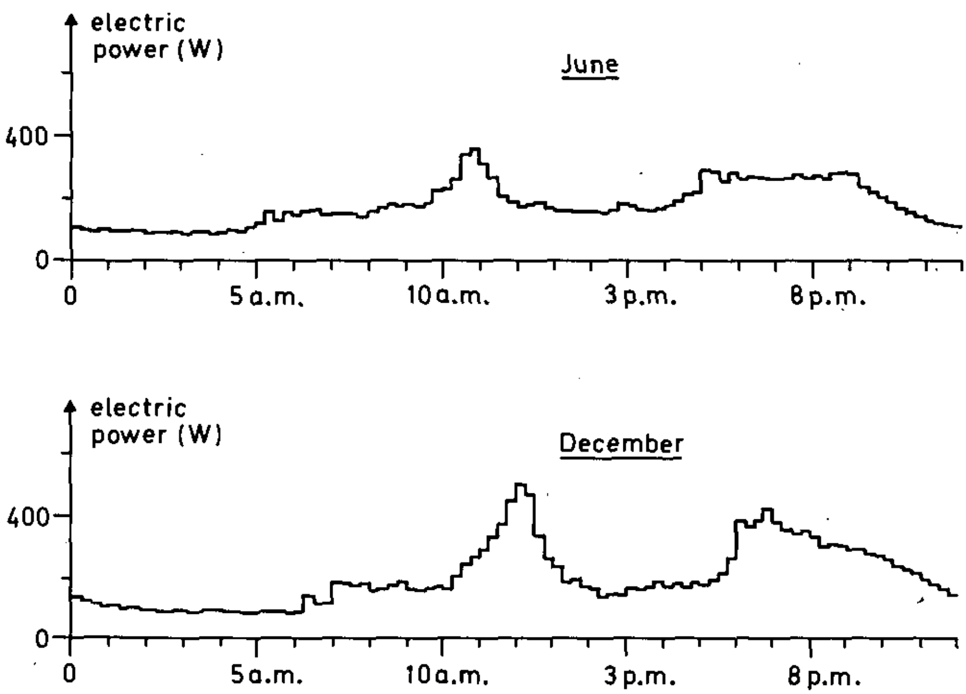

Fig. IV b-1 Load of appliances for a flat in the winter and in the summer (after Favre and Trachsel 1982)

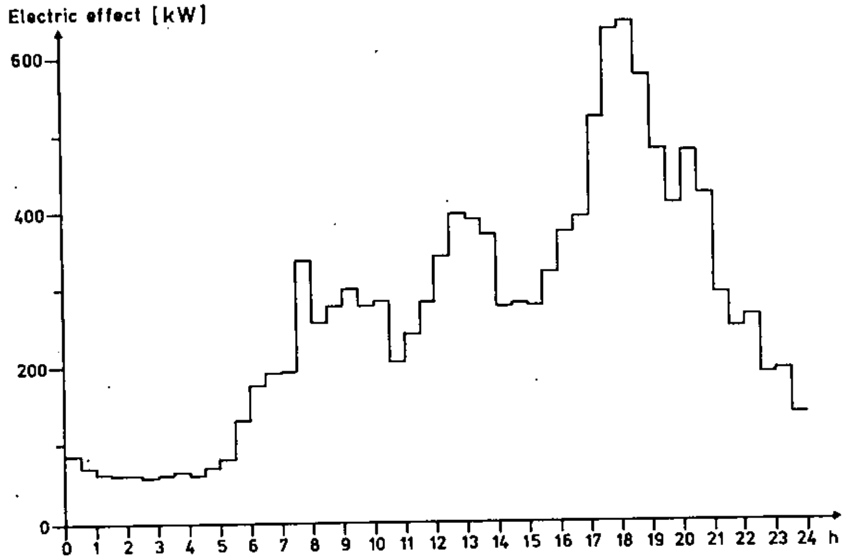

Fig. IV b-2 Heat requirement for hot tap water on days with heavy consumption, as measured in a building with 150 flats (after Svensson 1973)

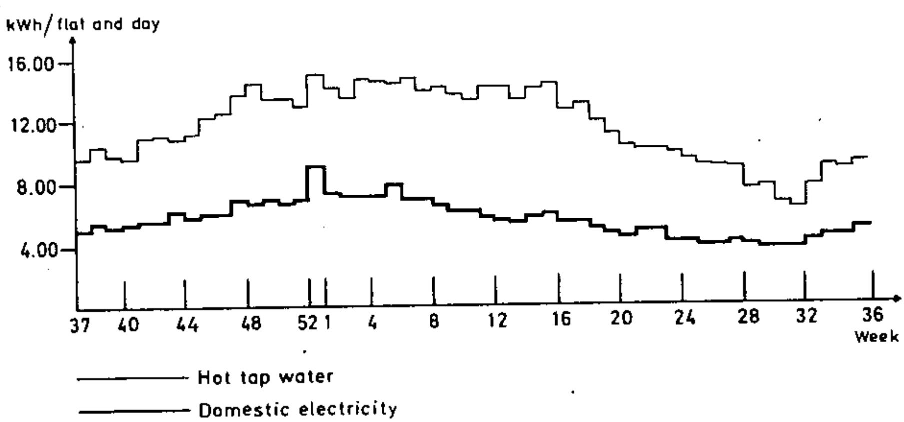

Fig. IV b-3 Energy consumption during a year of hot tap water and domestic electricity in 6 residential buildings with 113 flats (after Byggnadsenergigruppen 1974)

An important point is that in these data the penetration is the average for a country. In a certain retrofit project the penetration may differ considerably from this average. There may also be great variations of the demand profile. Here the size of the family and that of the dwelling play an important role. Therefore, it is advisable to determine the penetration and the operational period of use via an inquiry. To draw up an adequate inquiry it is important to know what appliances cause the greatest energy consumption in average conditions.

In many countries the following trends have been observed in the frequency of use, type of household appliances and the results thereof for the energy consumption:

(1)	hot tap water:	an increase in energy consumption.
(2)	cooking:	an increase in energy consumption.
(3)	a deepfreezer or refrigerator	the introduction of low energy types decreases the energy consumption
(4)	a dishwasher or a clothes drier	penetration is rising: this causes an increase in energy consumption.
(5)	lighting of the house	introduction of low-energy lamps causes a decrease in energy consumption.
(6)	a clothes washer:	the introduction of synthetic detergents allowing wash at 60°C to clean the "white" wash (this previously required 95°C to be adequately cleaned) also causes a decrease in energy consumption.

- monitoring of domestic hot tap water systems

i) systems

It may be useful to review some of the different production possiblities for hot water. Generally one can make the following classification:

1) Appliances specifically designed for water heating alone
   Electric or gas boilers are generally individual appliances. They can be:
   a) without accumulation
   b) with accumulation

In the first case water is "instantaneously" heated when a tap is opened (fig. IV b-4). In the second case a water storage volume is maintained at a given temperature (see fig. IV b-5).

2) Central heating appliances
For hot water production systems integrated with the main boiler there are two kinds of system
a) instantaneous or heat exchanger type (fig. IV b- 6) where hot water is produced instantaneously by means of a coiled tube incorporated in the main boiler or in a separate water tank, which is heated up by this main boiler.
b) appliances with storage which can be divided into
- incorporated storage (fig. IV b-7) : hot water production using a storage tank incorporated in the main boiler.
- separate storage
  . with heat exchanger (fig. IV b-8) : hot water production using a separate tank heated by a coiled tube linked to the main boiler.
  . cellular (modular) heat production system (fig. IV b-9) with separate double envelope cells.

There are 3 main types of distribution systems:

- local production of hot water at each tap point
- distribution to tap points from one central production unit (fig. IV b-10)
- circulation loop with return of unused water to production unit (fig IV b-11)

It may be interesting to focus attention on aging effects, which can affect measurements made over long periods (for example calcification).

ii) theoretical evaluation of the production, storage and distribution efficiencies

Since the system can be described as a heating system, one has to analyse the same efficiencies as in a heating system: production, storage, and distribution. In the case of central heating appliances, also producing domestic hot water, the losses can be divided into:

- losses at the heating appliance
- losses in the primary circulation pipework (between appliance and storage vessel)
- losses from the storage vessel
- losses in the draw-off pipework.

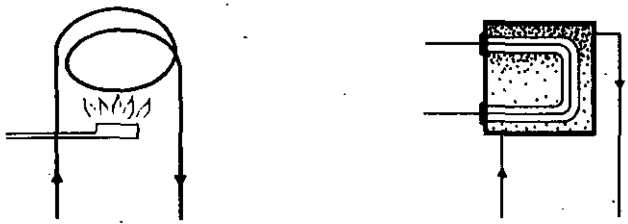

Fig. IV b-4 Individual appliances for hot water generation without accumulation. Gas (left) and electric (right)

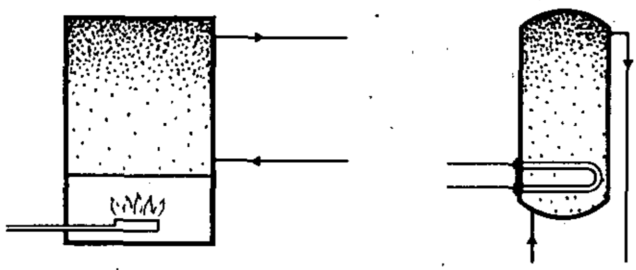

Fig. IV b-5 Legend as in fig. IV b-4 but with accumulation

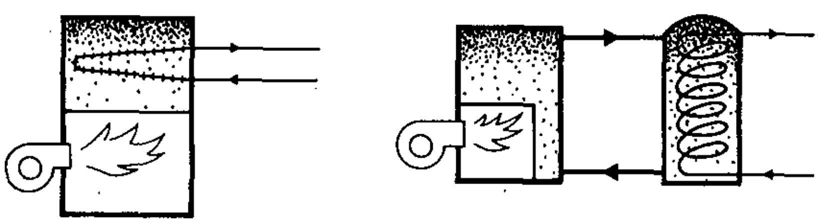

Fig. IV b-6 Central heating of hot water without storage. With coiled tube in the main boiler (left) and with coiled tube in a separate tank heated by the boiler (right).

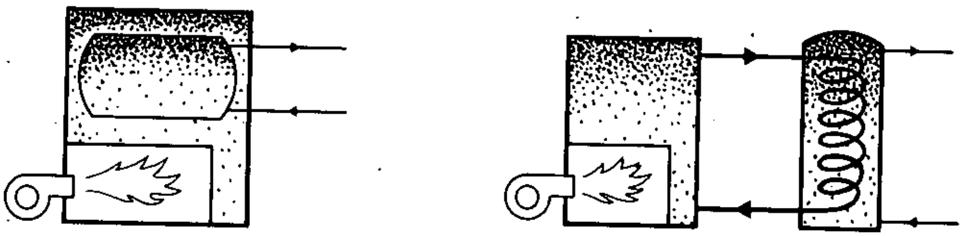

Fig. IV b-7 Legend as in fig. IV b-6 but with tank incorporated in the boiler.

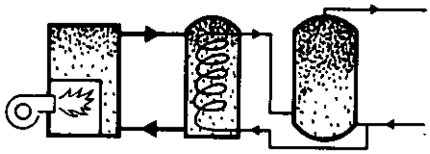

Fig. IV b-8 Central heating of hot water with separate storage tank and heat exchanger.

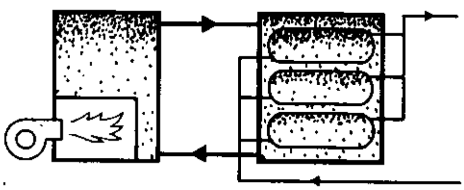

Fig. IV b-9 Central heating of hot water with separate storage tank and cellular or modular heat production system.

In some cases one or more of these losses are absent.

Knowing the losses of the heating appliance on an experimental or systematic basis, one can then determine the production efficiency of the system on the same basis as described in ch. I d and III f.

The storage efficiency depends on the nature and thickness of the insulated jacket, the mean temperature of the stored water, and the mean temperature of ambient air, and also on the geometrical configuration and the structural design of the vessel.

The distribution efficiency depends on the consumption profile (programme of draw-offs), the temperature of the hot water, and the geometrical features of the network (including length of pipework, its diameter and nature, and also the environment through which it passes: unheated or heated rooms).

The consumption profile is more complicated to estimate correctly: for each draw-off one needs to know:

- the time at which it occurs
- the volume of water
- the temperature of utilization
- the type of draw-off: one can distinguish two types:
  . draw-off without accumulation of water in sanitary fittings (e.g. showers)
  . draw-off with accumulation of water in sanitary fittings (e.g. bathtubs)

The following text contains a discussion on the kind of losses which can be distinguished (see fig. IV b-12).

1) In the case of a dead-leg distribution (fig. IV b-10) the losses fall into the following categories

- stand-by losses during the draw-off periods.
- stand-by heat losses between the draw-of periods.
  . draw-off with accumulation.
  . draw-off without accumulation.
- energy losses from the hot water via the pipework, after turning-on the tap

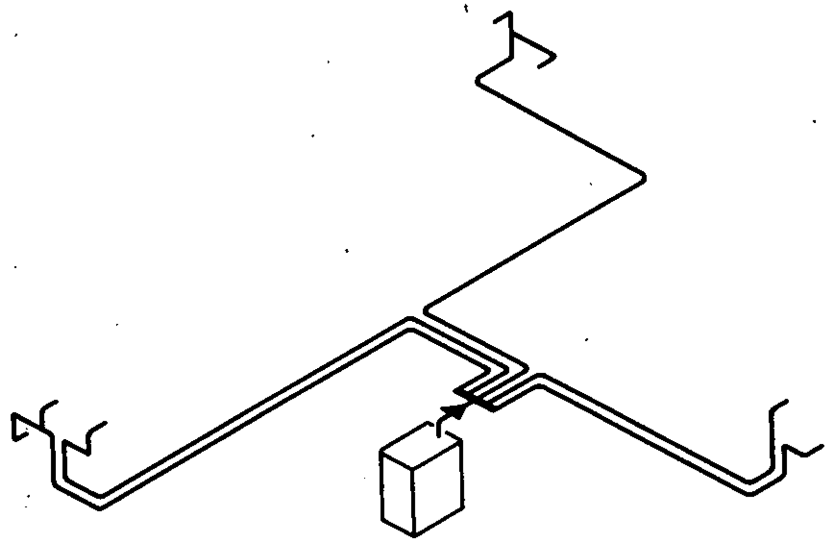

Fig. IV b-10 Hot tap water distribution system with individual distribution to each tap point (dead-leg distribution).

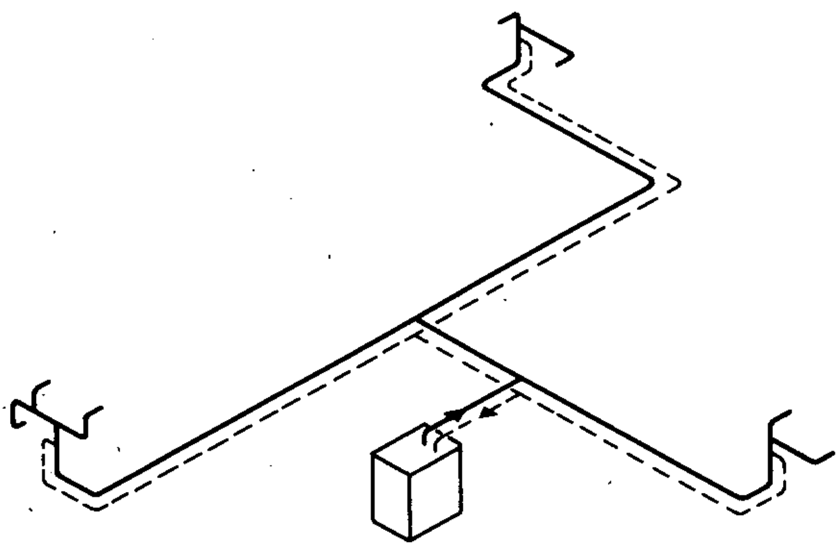

Fig. IV b-11 Hot tap water distribution system with circulation loop with return of unused water.

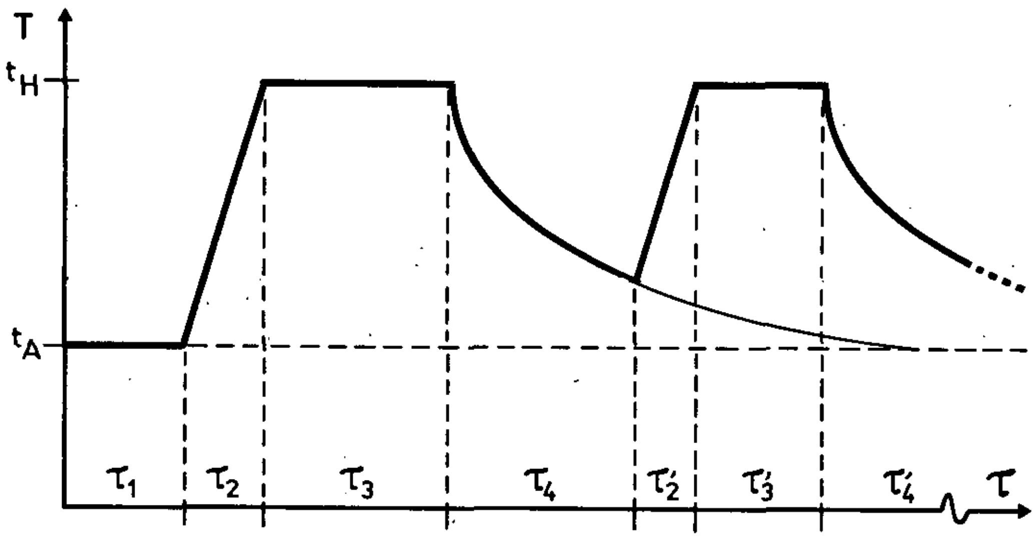

Fig. IV b-12 Utilization temperature of hot tap water. If there no draw-off, the temperature falls from the maximal water temperature at the tap point (t_H) to the room temperature (t_A).

τ_1 = period when water temperature has fallen to room temperature

τ_2 and τ_2' = water temperature just after draw-off

τ_3 τ_3' = period with maximal water temperature

τ_4 and τ_4' = period with falling water temperature

Assuming that, during this period, the cold water temperature is constant, one can assume that the water temperature rises linearly with time, from the temperature of the pipe and the water when the draw-off starts (t.), to the equilibrium water temperature during draw-off (t.). (Schellenberg 1967). The sum of the losses depends again on the type of draw-off:

. without accumulation

. with accumulation

2) In the case illustrated by fig. IV b-11, there are only two kinds of losses:

- stand-by losses during the draw-off and
- stand-by losses between the draw-off periods.

iii) measurements

For the measurements and monitoring of hot-water systems, different levels of complexity can be chosen and combined. The most elementary measurement to be made is the total energy input demanded by a system. Since most individual *production systems are based* on gas or electric energy, measurement devices provided by energy supply companies (gas or electricity meters) can be used. Sufficient accuracy is of course required.

The signal emitted by such a meter can be analysed by means of a pulse rate, proportional to the rate of consumption of the quantity monitored. *Note* also for some gas appliances the importance of recording the pilotlight consumption. Some of this energy is used to heat up the water content, the rest is converted into free heat in the room.

For the case of fuel-oil integrated hot water boilers, only measurements under summer conditions can give some indication of the energy consumption. Otherwise it is practically impossible to make a distinction between energy consumed for hot water and for space heating.

The pulse stream from the meter can be fed into a counter which produces an analogue signal, proportional to the number of pulses received in a time interval. These analogue signals can then be recorded by a data acquistion system. At the other end of the system, readings may be needed at each tap point. *From an energy balance* point of view, one needs data on the total water volume flow and on the temperatures as described in ii).

An indication of the utilisation temperature could be useful, but rather difficult to obtain. Generally, the measurement techniques for temperature are based on temperature differences between the water temperature at the tap point (t_H) and a fixed point, which could be, for instance, the temperature of the main water supply or a room temperature (t_A).

As indicated above, if the temperature of the main water supply is used, the balance is complicated by any time lag, occurring due to a storage system interposed between the main water supply and the tap point. This remark only applies to the energy balance on a short term analysis.

The measurement of the tap-point temperature can be made by using a thermocouple in the water distribution system itself, or by using a contact thermocouple (less accurate) on the external surface on the pipe supplying the tap point.

The recording of the heat loss could be of importance in unheated spaces such as cellars (affecting floating temperatures), or in heated spaces (affecting heat emission efficiencies of heating appliances).

The recording of the water volume used by each tap can be done in the same manner as the readings for gas or electricity consumption: a pulse stream converted to counter, and an analogue signal recorded at fixed time intervals. The basic water measurement can then be made using a diaphragm meter or other devices such as volumetric water meters. If a volumetric or turbine meter is used, one should make sure that every water hammering is sufficiently damped to avoid damage to the device, and avoid any errors due to reverse flow.

One can easily appreciate that due to the random character of hotwater use, readings based on a time-interval of 5 to 10 minutes is a minimum requirement for precise analysis. Otherwise daily or weekly averages can be sufficient. For the water meter an accuracy of 1 to 2% (water quantity) is a minimum requirement (for example 0.5 ltr). For the temperature readings, an accuracy of at least 1 K is required. It should be noted that calibration of the meters for pressure, temperature and water flow variations is generally necessary. Also a filter is generally required.

Instead of using separate measurements for water flow and temperature levels, converted by counters, and recorded as analogue signals at given time intervals by the same central data acquistion system, one can use integration devices for each tap point. In this case a micro-processor can be used to integrate the temperature difference and the waterflow for the tap period.

When the tap is opened, a flow switch can "open" the measurement devices and measurement could take place when, for example, the water temperature at the tap point exceeds the room temperature. The measurement would then take place on a rapid basis (very short intervals) using, for example, the above mentioned devices.

For x liters measured, n pulses are emitted and the number of pulses can be multiplied by a temperature difference to obtain an energy balance. The energy output can then be reconverted to pulses, which can be counted, reconverted into analogue signals and processed by the central data acquistion system as a single signal on its regular time interval scrutation (instead of two separate signals: temperature and water flow).

One should, however, note that the measurement interval used by the microprocessor should be as short as possibe to take into account the following difficulties:

- temperature is not always constant during tap use: mixing possibilities with hot and cold water, "cold" water stored in the pipework before heating up, but registered when the flow switch actuates measurement at the tap
- pressure differences arising when simultaneous tap use occurs in houses, and thus water flow differences.

On the basis of these data one can attempt to determine the energy balance and efficiencies of the water production and distribution system.

iv) Waste water

For this particular problem, the same measurement devices could be used as for hot-water systems (flowmeters and temperature measurements). But due to the two-phase flow this remains rather difficult. A solution could be found by incorporating a tap-seal.

- monitoring of domestic appliances

When studying the effect of a retrofit, the domestic energy consumption may be determined by the meter readings per month or per heating season. This may be combined with an inquiry determining the penetration and period of use of the various domestic appliances and the number of members of the family. When investigating the penetration, one also wants to know the capacities installed. In practice this is difficult, because many people do not know these data.

Additional supply meters will be necessary when domestic energy consumption is partly or entirely combined with the way in which the heating installation consumes energy.

This is so, when heating is done by electricity or if gas is used for cooking or for the provision of hot water. If one wants to determine the time pattern of use of the appliances, one may want data about the frequency and duration of use, the time of the day when the appliance is used and the unit-time consumption or load. This can be done in two ways:

1) by recording the time when appliances are used
2) by determination of the energy consumed by the appliance

In the first case the appliance may be connected to a clock. It is then possible to record the time when the appliance is used. The capacity of the appliance then has to be assumed known or be determined by other means.

In the second case the appliance may be connected to a watt hour meter. The energy consumption can then be measured continuously.

In both cases data can be stored with a chosen time-resolution. An alternative is to record only the total elapsed "on" time or the total energy consumption by the appliance. The consumption profile then has to be determined by other means. Survey techniques can be used. The co-operation with experts in this field is then necessary.

CHAPTER IV c

Occupancy and human behaviour

Contents

Key words

airing
blinds
caretaker
curtains
energy saving campaign
heating system
indoor temperature
maintenance of heating system
presence at home
psycho- physical experiments
radiator valves
set points
shielding of windows
thermostats
temperature difference, indoor- outdoor
time- pattern at home
ventilation

IV c Occupancy and human behaviour

- general introduction

In this chapter we will deal with operations and activities of the occupant that do not involve the use of energy consuming domestic appliances or tap water. The latter topics are treated in ch. IV b. Here we will discuss operations of the occupant that are relevant to the energy consumption of a residential building but are not easily quantified. The discussion will therefore be, to a large extent, a qualitative one. Many examples will be given. Some factors of importance for the monitoring of a residential building will also be pointed out.

It has already been pointed out (see ch. I e) that the occupant will always try to modify the indoor climate until he experiences it as being comfortable. This will affect the demand for heating of the dwelling. The occupant can influence the indoor climate by operating on:

- positions of manually operated radiator valves
- positions of thermostats (space thermostat,thermostatic radiator valves, boiler thermostat or installation thermostat, night and day set back)
- positions of doors, windows and ventilating grates
- indoor heat loads (lighting, hot water appliances, cooking appliances and other domestic electric appliances)
- shielding of windows (sunshades, curtains and blinds)
- use of open stove and auxiliary heating
- use of mechanical ventilation

Owing to differences in the behaviour and attitudes of the occupant, the demand for heating may vary largely from one dwelling or room to another. It is possible to monitor many of the above operations of the occupant. This is, however, often associated with great practical difficulties. One therefore often has to collect data by means other than direct measurements (see ch. III a and IV a). One should in any case try to ascertain wether the retrofit has changed any of the above habits of the occupant (see ch. II a). Often monitoring of the heat distribution (see ch. III f) becomes necessary if one wants to know the occupant's influence on the operation and control of the heating installation. This may be the case if, e.g.,

- part of the dwelling is insulated
- the pipes emit much heat
- the sun has a great influence on certain rooms
- the internal heat transport between rooms is large

This chapter starts by a section dealing with the presence at home by the occupant. This is followed by three sections dealing with the operations by the occupant where one cannot directly measure the consumption of energy associated with these operations. The headings of these sections are

- presence of the occupant at home
- operation of shutters, blinds and curtains
- control of ventilation and airing by occupant
- operation of set points and heating system

As the effect of the occupant's behaviour and attitudes on the variation of the energy consumption has already been dealt with in ch. I e, we refer to this chapter. The bibliography and references for ch. IV c are found in those common for Part IV.

- presence of the occupant at home

Whether the occupant is at home or not during daytime will be of some importance for energy consumption. It has a direct effect via the heat produced by the human metabolism, the use of appliances for cooking, TV, etc. (for data collection see App. IV).

Energy consumption will also be affected by operations as window-opening, use of blinds and curtains, and the control of temperature set points.

Various information about occupant habits and behaviour in twelve countries has been collected by Szalai in the framework of a multinational comparative time-budget research project (Szalai, 1972). In fig. IV c-1 a-c we present the percentage of the population being at home at various times of the day for some Western European countries and the US. The occupants have been divided into

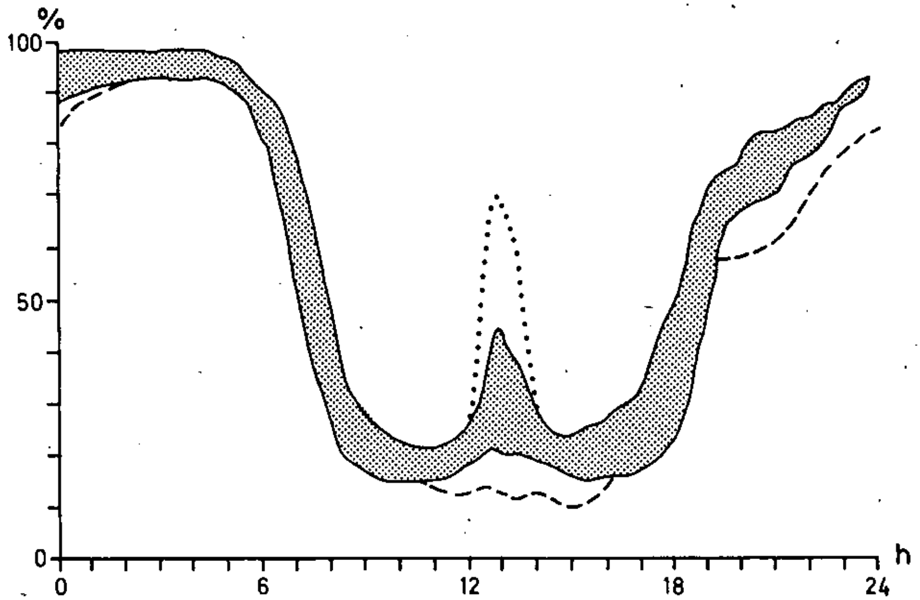

Fig IVc - 1a Percentage of occupants being at home. Employed men weekdays in Belgium, France, FRG, Sweden and and the US.
Dotted line: France. Hatched line: The US.
(After Szalai 1972 and Schulman 1977)

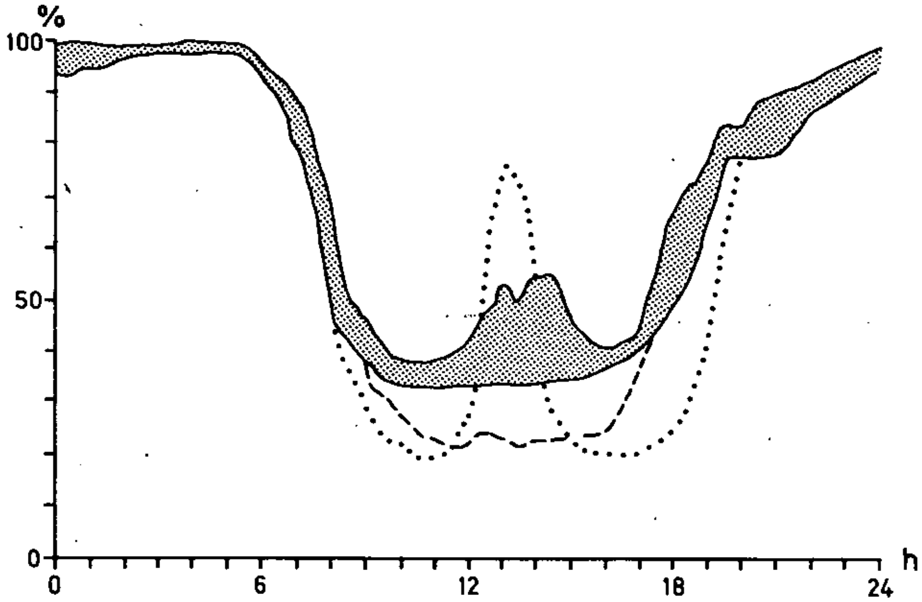

Fig IVc - 1b Percentage of occupants being at home. Employed women weekdays in Belgium, France, FRG, Sweden and the US.
Dotted line: France. Hatched line: The US.
(After Szalai 1972 and Schulman 1977)

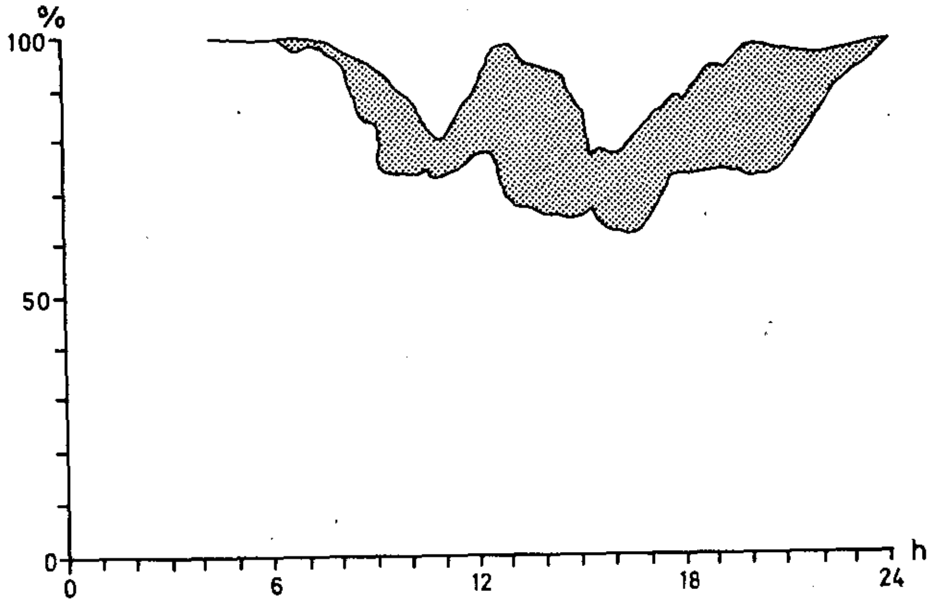

Fig IVc - 1c Percentage of occupants being at home. Housewives weekdays in Belgium, France, FRG, Sweden and the US. (After Szalai 1972 and Schulman 1977) three categories, employed men, employed women, and housewives. This division is practical as the fraction of housewives varies between the countries.

From these data it is possible to estimate the average fraction of women being at home during the day. This fraction differs from the percentage of housewives. In Table IV c-1 below, we have listed the proportions of women in the active labour force.

The percentage of employed women has probably increased in most countries since this investigation was performed. It is therefore interesting to note that even if the fraction of employed women is very large in the Soviet Union, more than 90%, still about 30% are at home at daytime due to part-time jobs, illness, and for other reasons. In countries where the fraction of housewives is large, many will not be at home because of shopping, social activities etc.

One would guess that in most Western European countries and the US today more than 40% of the women are at home in the daytime.

As one can see in fig. IV c-1, the time-pattern of a week is rather alike in different countries. The most note-worthy difference is that in some countries, especially in France, a high proportion of the inhabitants have their lunch at home.

There also exist investigations where a further subdivision of the occupants has been performed. As an example of the use of time by occupants of different ages, see fig IV c-2 (Walldén 1974 and Searle 1978).

To illustrate how some activities may vary between countries and change with time, we present in fig IV c-3 the results from two British investigations, the data of which were collected in 1961 and 1973 (BBC 1965 and Shapcott-Steadman 1978), and one Swedish investigation made in 1977 (Schulman 1977).

The percentage of occupants performing the activities of household duties, eating, and watching television at home at various times of the day are given. There are certainly differences among the results of these three studies, mostly due to the different participation of women in the labour force, but still the overall pattern is similar.

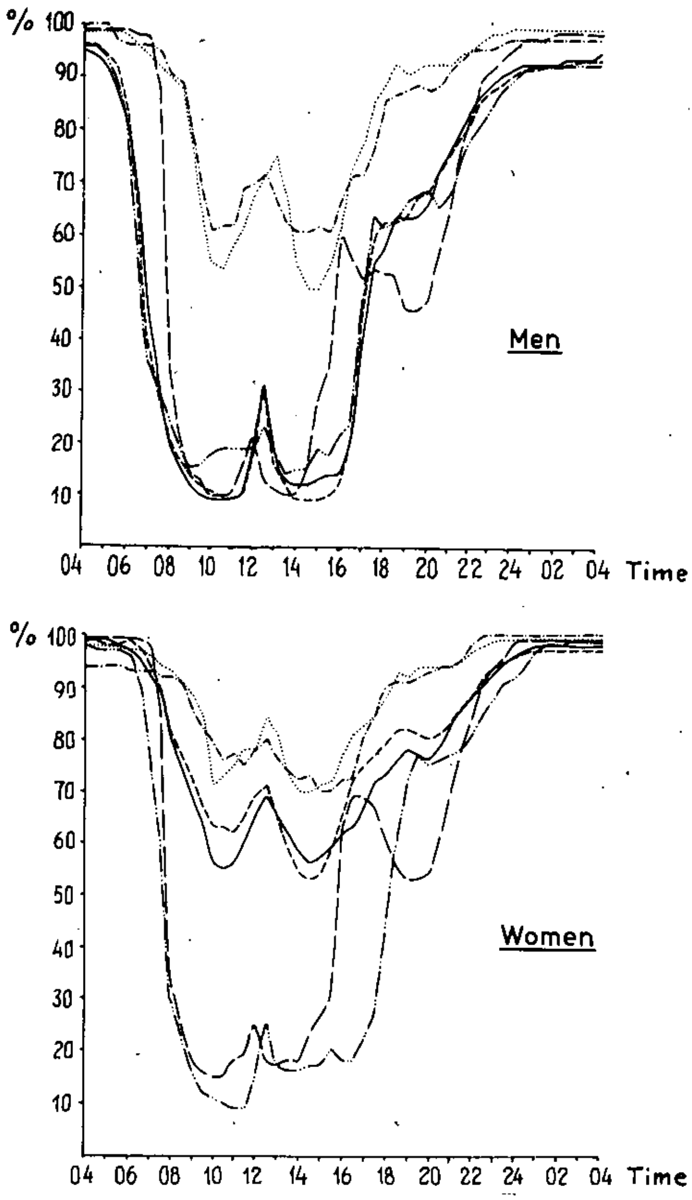

Fig IVc - 2 Percentage of occupants being at home at different times of day. (After Walldén 1975)

			Average time (min)	
			Men	Women
— —— — —	Youth	age 14-15	868.0	915.9
- - - - - - -	Couples, husbands	" 22-31	791.7	1177.8
————	" "	" 35-44	788.9	1161.8
—— · · ——	Single	" 35-44	793.8	849.2
—·—·— ·	Single	" 67-75	1238.6	1280.4
···········	Couple, husbands	" 67-75	1218.5	1297.4

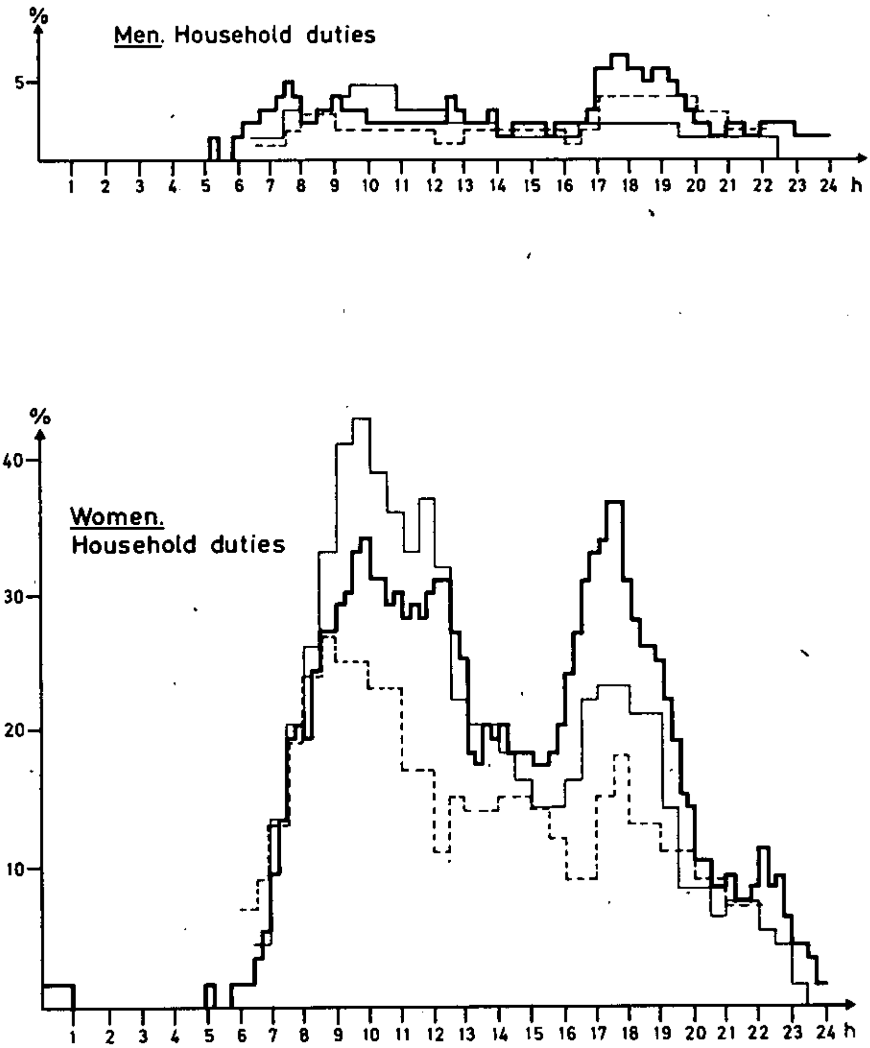

Fig IVc - 3a Percentage of occupants performing different activities at home.

-------- United Kingdom 1961 (After BBC 1965)

-------- " 1973 (" Shapcott- Steadman)

-------- Sweden 1977 (After Schulman 1977)

House hold duties

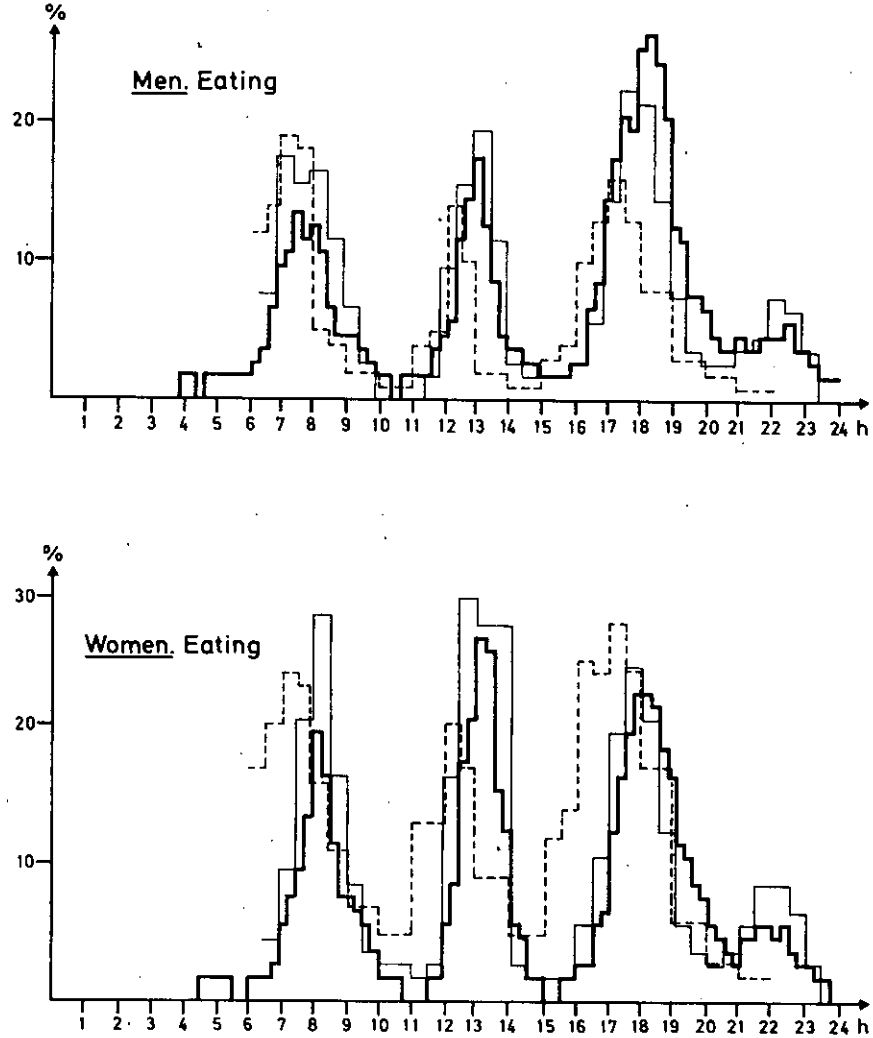

Fig IVc - 3b Legend as in fig IVc - 3a. Eating.

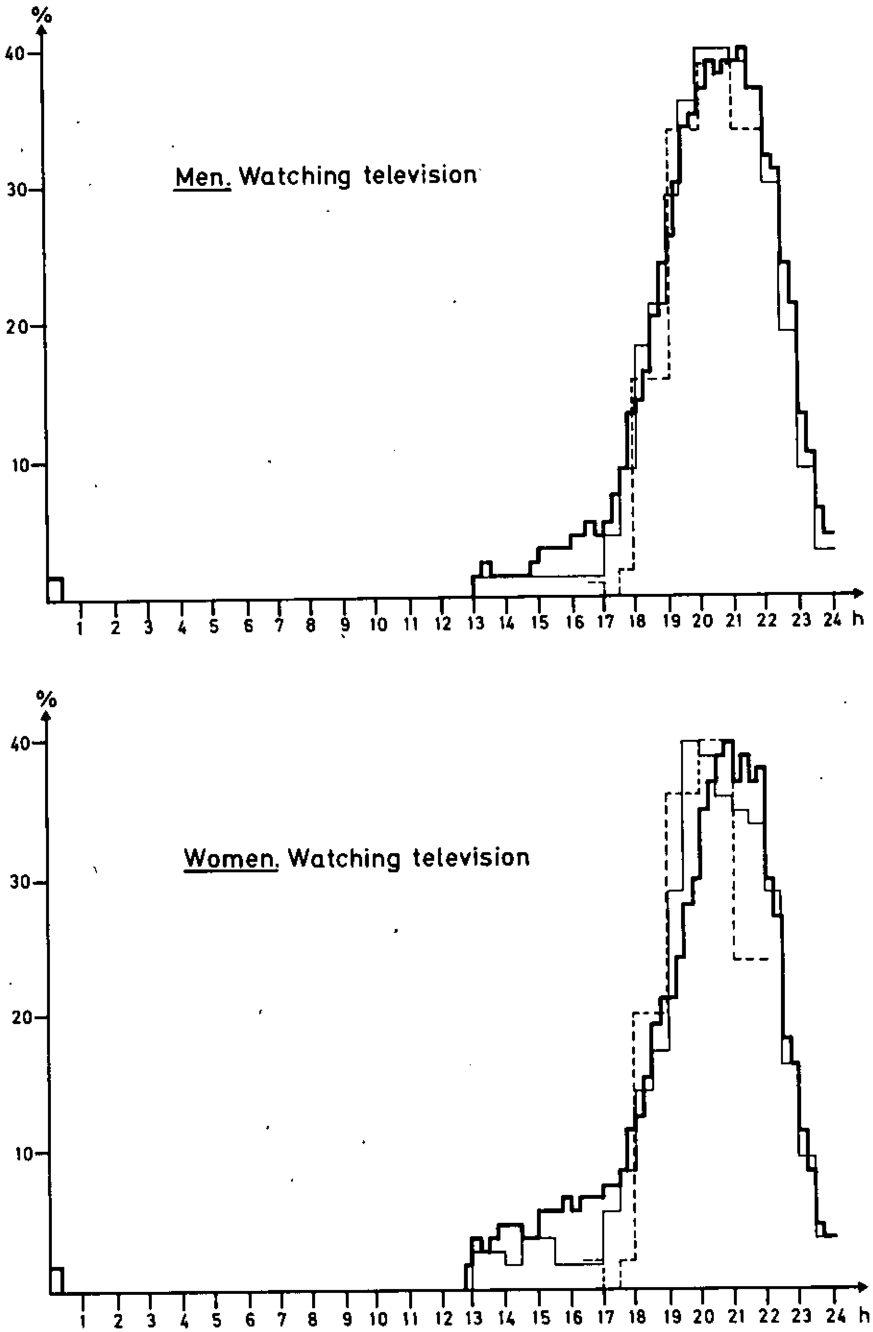

Fig IVc - 3c Legend as in fig IVc - 3a. Watching television

From investigations of this kind it is possible to draw conclusions about when certain energy consuming activities take place.

There also exist investigations about where in the dwelling the occupants spend their time when performing different activities. As examples of such studies we refer to Holm (1956), Meyers-Ehlers (1968), Bachtold (1964), Cornuau and Retel (1966), Hole and Attenburrow (1966), Boalt (1965) and Searle (1978).

For a more detailed review of domestic habits we refer to Grandjean (1973) and Szalai (1972). Data on number of residents per dwelling and the size of dwellings can be found in publications from the ECE (1979) and the UN (1974).

TABLE IV c-1

Percent of women being in the active labour force of the persons questioned in the cited investigation (Szalai, 1972) and being at home during day-time on weekdays (estimate).

	Employed	At home at daytime
USSR (Pskov)	92	29
USA	49	49
France (six cities)	48	52
FRG (Osnabruck)	44	57
Belgium	41	63
FRG (National)	36	66
Sweden (1973)	55	42

- operation of shutters, blinds and curtains

Shutters, blinds, and curtains serve several purposes. Closing shutters and opening windows will increase the ventilation but still prevent solar radiation from heating the interior of the building and, to some extent, damp noise from the outside. Venetian blinds can be used to modify illumination and indoor overheating by solar radiation. Curtains can be used in the same way but they can also serve an aesthetical purpose.

At night these devices can be used to increase the thermal insulation of the building in winter and damp outside light in summer. Finally they help the occupant to keep his privacy.

It has been noted that the habit of window-covering can differ even between countries that in other respects are often considered to have much in common. It is, e.g., often stated that in the Netherlands, where large windows are common, shutters are seldom used while in Belgium, where large windows are not so common, shutters are used very frequently at night.

From an energy point of view this habit is important for two reasons:

1) The habit of shielding windows at night decreases the U-value of the window. Laboratory measurements indicate that the magnitude of this effect depends on what heating system is used in the building (Caluwaerts-Verougstraete 1978)

2) Shielding of windows as a protection against solar radiation reduces the heat gains from insolation, as compared to when no shielding is performed.

In a Swedish investigation (Lyberg 1983) two thousand dwellings were observed at night in the heating season to study the use of blinds and curtains. Excluding the cases where the need for privacy played an important role, between 30 and 40% of the window area was covered at day and between 40 and 50% at night. It was noted that the covered window area of Southern facades was greater than the average on sunny days in the spring, but the increment was only about 5 % . From this, one could conclude that the first of the factors listed above was relatively unimportant for the heat balance of the residential building. However, shielding of windows could reduce the heat gains by short wave solar and sky radiation through windows by up to one third compared to an unshielded window.

- control of ventilation and airing by the occupant

To the occupant the control of ventilation may serve many purposes. Primarily, it obviously serves to control the rate of air change, but it may also serve to control the indoor temperature if the ventilation system is such that this can easily be done. In an investigation forming part of the Twin Rivers project (Seligman, Darley and Becker 1978) an attempt was made to determine the impact of the attitudes of single-family house occupants on the consumption of electric energy during the summer.

It was found that the only attitude consistently predictive of actual energy consumption was the concern for comfort and health. This attitude was, especially for women, strongly linked to air conditioning usage. Thus, the more a household perceived energy conservation as leading to discomfort and ill-health, the more energy the household consumed.

For many reasons it is important that the occupant does not have the possibility of shutting off the ventilation system completely so the air change rate becomes too small (see ch. I c).

From an energy point of view, it is evident that the rate of air change is of great importance for the heat balance of a building. In buildings equipped with a mechanical system for ventilation, the rate of air change due to the operation of this system can be measured directly. This topic is dealt with in ch. III f .The measurement of the thermally driven or wind- driven infiltration is discussed in ch. III e . Here we will treat in more detail the air exchange due to airing.One then requires information about

1) the occurrence of airing
2) the rate of air change when airing is performed

There exist many results from observations of airing during the day, mainly from Sweden and the U.K. (Dick- Thomas 1951, Holm- Pleijel- Ronge 1964, Brundrett 1979, Lyberg 1983 and Hartmann- Pfiffner- Bargetzi 1978). Also survey techniques have been used (Dick- Thomas 1951, Holm- Pleijel- Ronge 1964, Newman- Day 1975, Edén- Persson 1978 and CNR 1979). Of special interest are the observations where the occurrence of airing during the day as well as at night has been studied (Dick- Thomas 1951,Holm- Pleijel- Ronge 1964 and Edén- Persson 1978). It turns out that in these studies the degree of airing at night was about as frequent as at day. However, in a study of a multifamily residential building in Switzerland where magnetic switches were used to record the frequency of open windows, it was found that airing was more frequent at night than during the day (Favre-Trachsel 1982).

A strong correlation between the degree of airing and the external air temperature is found in most investigations. A correlation between airing and wind speed has also been noted. Even the outdoor humidity may be relevant (Brundrett 1979). However, from an energy point of view the important relation is the one between airing and the internal- external air temperature difference. One way of expressing this relation in a quantitative manner is to relate the fraction of rooms having a window open, n , to the internal- external air temperature difference, ΔT (Lyberg 1983). It then turns out that the product $n^* \Delta T$ takes a constant value for ΔT greater than 5 K, the constant value being roughly between 2 and 2.5 K in all the measurements discussed above. This result seems to be independent of the heating system and the external and internal air temperature. These results have been summarized in Table IV c-2.

Studies of variations in the occupants' habits of airing have been performed (Conan 1982). It was found that the variation between households in terms of their total daily window opening was greater than that within households. Their were indications that occupants adopt consistent airing patterns.

Even if it is possible to determine the degree of airing, one still has to determine the resulting air exchange if one wants an estimate of the energy losses due to airing. The air flow through a window open or ajar has then to be determined. This air flow will depend on wind speed, difference between interior and exterior temperature of the building, wind direction, geometric properties of the building facade, position of the window on the facade, and to what extent the window is open.

Some attempts to determine the air flow through a window, open or ajar, have been made in model scale (see e.g. Cockroft-Robinson 1976 or Etheridge-Nolan 1979). Also test boxes have been used for this purpose. Case studies of the rate of infiltration when one or more windows are open have been performed. It is,however, uncertain whether the results of these measurements can be generalized to give a prediction other buildings. At present it is therefore rather futile to try to estimate the contribution of open windows to the ventilation of a residential building in this way.

Another way of approaching this problem is to use simple models of air infiltration (Lyberg 1983). Then input data from a few infiltration measurements on the residential building in question are needed. Some of these measurements must be performed with all windows closed, and some with one or more windows open. By model calculations of the kind mentioned above it has been estimated that up to 5 % of the total energy consumption of a residential building may be ascribed to airing.

Another approach to this problem is to use information from psychophysical experiments under controlled laboratory conditions. The limits of the temperature interval where an occupant wearing a given clothing ensemble feels comfortable is rather well known. Assume that the air temperature of a room reaches the upper limit of this interval. An occupant present in this room will then try to adjust the temperature to probably below this interval, e.g., by opening a window. The temperature difference is known. Assuming that the exchange of air is instantaneous, it is possible to calculate the required energy.This approach will not give the actual energy loss when opening a window, but rather a lower limit of this value.

We will end this section with some observations that have been made in studies of airing and energy saving. Some studies have investigated the occurrence of airing in buildings equipped with a system for mechanical ventilation (Berg 1979, Jonson 1980 and Eden- Persson 1978). It has then been observed that airing was still rather frequent also in this kind of residential buildings.

In an investigation of energy saving in two blocks of flats in Sweden, the indoor temperature in one block was lowered by 3 K and the flow rate of the supply air was reduced by one half (Adamson et al 1975). The occupants were subjected to a general energy saving campaign. This led to an immediate energy saving of 20%. When asked why they opened windows less, about 75% of the occupants gave the reason that it was too cold in the flats for window-opening. The rest of the occupants aired less frequently in order to save energy. In another block the thermostats of electric radiators were preset, resulting in a much smaller lowering of the indoor temperature than in the previous case. Here the rate of ventilation was not altered. In this case almost nine out of ten inhabitants stated that they opened windows less in order to save electric energy. The investigations cited above indicate that the exterior and interior air temperature are of great importance for the actual window-opening habits (see above).

TABLE IV c- 2

Experimental studies of airing habits

reference	building type and length of investigation	heating system	average temp indoor (^{o}C)	range ΔT (K)	n*ΔT
Dick and Thomas UK 1951	8 detached 2-storey houses. Sheltered site One heating season	central heating water-heated ceiling panels	14	6-12	2.6
"	15 2-storey rowhouses. Exposed site. One heating season	various	14	5-11	1.9
Brundrett UK 1979	25 2-storey highly insulated houses. One winter. v< 5 m/s	electric	16	3-20	2.2
Holm-Ronge and Pleijel Sweden 1961	10-storey MFD.200 flats. One year	water-heated radiators	22	1-24	2.6
" pilot study	3-storey MFD. 200 flats. One week	"	22	10-14	1.9
Lyberg Sweden 1983	3-5 storey MFD 1000 flats. 3 months	district heating	22	5-45	2.3
"	2-storey row-houses 1000 houses. 3 months	district heating	22	5-45	2.4
Favre and Trachsel Switzerland 1982	16 flats of 4-storey residential building	water-heated radiators	20	9-23	1.8

n=fraction of rooms having a window open or ajar   v=wind speed

Δ T=outdoor- indoor temperature difference

A number of unexpected habits in connection with window- opening have been found in studies of energy saving. In one case the occupants had the habit of sitting next to a warm radiator in the kitchen. After the installation of thermostat radiator valves, the radiator was not always warm. But as the radiator was situated below a window the occupants soon found out that by opening the window for a while they could ensure that their radiator again became warm and cosy.

The heating system of the residential building and the properties of the wall insulation may also influence the window-opening habits of the occupant. In dwellings where the indoor temperature can rise quickly after closing of the window, the occupant will find that window-opening does not lead to lower indoor-temperatures and he will therefore have no compunction in opening the windows.

- operation of set points and heating system

The way the occupant operates temperature set points on radiators seems highly dependent upon his expectations of how the heating system of the residential building is functioning. In one investigation, using the test-reference design (Lange-Lundgren 1979), the test buildings were equipped with thermostat radiator valves with a preset max value for the indoor temperature. The reference buildings had adjustable radiator valves. It was found that in the test buildings almost all thermostat radiator valves were set on their maximum value while in the reference buildings this was the case for only a small proportion of the radiator valves.

In another investigation (Edén-Persson 1978), many occupants, interviewed, requested that their dwellings were equipped with devices for automatic control of room temperatures. It was also found that the manually controlled radiator valves were either off or set on a value that was seldom changed, often the maximum value. For quick adjustments of the room temperature window-opening was the preferred operation.

The settings of radiator valves and thermostats chosen by the occupant are not determined by the required indoor air temperature alone. Indoor surface temperatures and the occurence of draught are important.

In one survey it was found that about one third of the occupants adjusted their thermostats more than once a day while one quarter did this only once a year (Berg 1979).

Heating systems, with individual thermostats or radiator valves on the radiators, may sometimes be too complicated for the occupant to handle. This may partly explain why radiator valves are often set on their max value and quick adjustments of the indoor temperature is achieved by other means than a change in the set-point. It is therefore important to inform the occupant about how such systems should be operated in an efficient way in order to save energy. With a design of the control system for heating, suitable to be handled by the occupants, and an improved insulation, it may be possible to achieve an energy saving better than the one theoretically predicted (O'Sullivan- McGeevor 1982).

Sometimes it is not the occupant that is to be blamed for a room temperature control system which is not working properly. In many cases it has been found that thermostat radiator valves have not been accurately calibrated, or have been wrongly assembled, or fixed to the wall in a faulty way, or that the whole heating system is badly adjusted.

The caretaker plays an important role in energy-saving programmes. He has often a difficult position between the landlord and the occupants. He will receive all the complaints from the occupants if the indoor temperature of the residential building is lowered, complaints which are often caused by the occupant's lack of knowledge about the properties of the heating system and how it is working. It may be tempting for him to eliminate the complaints by taking actions to increase the indoor temperature. On the contrary the caretaker should have sufficient time at his disposal to investigate whether the complaints are justified, measure the indoor temperature of the dwelling in question and, if it is too low, look for the cause of this. Often the cause is that the occupants thermometer is not functioning properly.

In research programmes it is also important that the caretaker is properly informed about what is going to be measured and why. In many such programmes, where the indoor temperature was lowered as part of the investigation, after a while it has been found that the care-taker has received complaints, and as a consequence he has taken action to increase the indoor temperature in the middle of the measurement period.

The caretaker should also receive proper information also concerning more general energy-saving programmes. It is not sufficient just to tell him what to do, but not why he has to do it.

Assume that a water-based heating system is subjected to a balancing procedure consisting of e.g. presetting of all values to calculated levels, establishing the flow in main distribution pipes by direct measurement, checking of the water distribution to heaters by measurement of pressure differences and post adjustment in rooms where the resulting temperature deviates too much from the desired value. In this case it is vital that the man who has to survey and maintain the system in future years has an understanding of how the system works.

In the past, maintenance of a heating system has in practice often meant that its performance has been checked every ten years. If this must be changed, the caretaker will have to play a more active role in the maintenance of the heating system, e.g., by performing more regular checks of its performance as it varies with time. The caretaker should be instructed to report at once gaps in the insulation, untight windows etc.

If the caretaker is instructed to try to reduce energy consumption through a more efficient operation of the heat plant, it is important that he receives a feed-back in the form of the result of his efforts. If he can observe a lower energy consumption, this will encourage him to try even harder. In the long run, this may well lead to a permanent reduction of the energy consumption for heating.

Even if the caretaker is properly instructed and given the basic knowledge of how to run the heating system of the building,this is not sufficient. If not in constant use, this knowledge is quickly forgotten in everyday practice.

Even if the measures desribed above may make the caretaker more observant on the importance of saving energy, it should not be forgotten that the caretaker will not be judged by the landlord or the tenants according to how much energy he can save, but according to how well he can keep things running in the residential building.

CHAPTER IV d

Implementation of simulated occupancy

Contents

IV d Implementation of simulated occupancy

- factors influencing occupational patterns related to energy demand

The essential background for the implementation of simulated occupancy, in experiments on building retrofits, is the knowledge of the general principles on which such experiments are based (see Ch. II e), and the energy- related activities by occupants (see ch. IVb, IVc, and App. IV). Activities aiming at the control of indoor climate can be motivated by a great number of factors in the environment of the occupant, such as:

1) indoor climate influences the occupant, but it can also beinfluenced by him: the most representative parameter for the definition of indoor climate is generally assumed to be the air temperature.
2) the climatic and geographic zone can be synthetically defined by the local degreedays.
3) the age of the building can be important whenever some particular event (new building regulations et.) has caused a change in building construction techniques.
4) the insulation of the building can be evaluated by, e.g., the mean overall heat transfer coefficient in relation to the local climate.
5) the size of the building, e.g. single family or multi-family
6) the location of the building e.g. countryside, suburban or urban
7) the location of the heating system or the type of metering, e.g., central or individual
8) the form of control system, e.g. central, room local, or others
9) the socioeconomic status of the occupants can have a great impact on their behaviour, but the relations with energy consumption are not well known

The most influential of these factors on energy related human behaviour are 1), 2), 7), 8), and 9). From now on, only these factors will be considered. When performing a simulated occupancy experiment, these factors and the object of investigation are given beforehand, except the factors 1) and 9) which can, to a certain extent, be chosen by the experimenter. The choice of typical factors in a region or country will lead to the establishment of typical occupancy patterns (standard occupancies).

- influence of simulated activities on energy demand

Only some of the activities performed by people in their homes actually influence the energy required for heating the building. Obviously, only these activities have to be taken into account in experiments with simulated occupancy. They include:

a) use of light
b) use of electric appliances
c) cooking
d) use of cold and hot tap water
e) operation of the control system set points
f) presence at home of occupants
g) opening of windows
h) operation of blinds, shutters, etc.

TABLE IV d-1.

Relations among energy-related activities and environmental factors.

Activities	a	b	c	d	e	f	g	h
Factors								
1	X						X	X
2	X	X	X	X	X	X	X	X
7	X						X	X
8	X						X	X
9	X	X	X	X	X	X		

The qualitative relations among these activities of the occupant and the *environmental factors mentioned above* are given in Table IV d-1. The geo-climatic zone and the socio-economic status of the occupants appear as the most influential factors, while the operation of set points and window systems appears as the activity which can be influenced more. These activities have a different impact on the energy consumption. Some of them are usually not modified by retrofits and exert a "neutral" influence on the energy consumption of the building, whether it is retrofitted or not (e.g. the use of lights, cooking, the presence at home of occupants). Others will be modified after the retrofit, due to a change in environmental factors influencing them (e.g. the operation of set-points, the use of appliances, etc.). Others will not only be modified by the retrofit, but may have a different impact on energy consumption (e.g. the operations on windows and blinds in before- after experiments).

The experimenter will therefore have to consider carefully the problem of choosing the energy related activities to be simulated, and he might in some cases consider the possibility of establishing different occupancy patterns in retrofitted and non retrofitted buildings.

- assessment of daily schedules related to occupants' activities

Every activity can be represented as a daily schedule, characterized by a constant, periodic, or random pattern. It is the task of the experimenter to assess these schedules, making use of information derived from statistical investigations, observations, interviews, and direct measurements. The quality of this information is rather uneven, and the data collected are often contradictory. Moreover, the information has been collected for purposes other than that of establishing energy related patterns, and therefore require further elaboration.

It should be pointed out that the experimenter is generally interested in reproducing the energy effect of these activities, not in the activity itself. However, when the effect is uncertain, as for operations on windows, the real activity should be simulated. The experimenter will proceed as follows:

- collect all available information on energy-related activities
- choose the general features of the occupancy
- establish the schedules for the energy-related activities
- decide how to simulate and record these schedules

When collecting data on energy-related activities, the experimenter should be aiming at:

- when and where the activity is performed
- for how long the activity is performed

- what the energy effect of the activity is

Available data, however, seldom refer to the questions above, rather providing the total daily amount of time devoted to the activity, or the average thermal power released when using a certain equipment, or the global yearly energy consumption of the equipment. The second task will be that of choosing the general features of the occupancy of the building to be investigated, that is:

- *number, composition, age of occupants etc.*
- main activities of the occupants: sleeping, eating, and working time
- socio-economic data on occupants

Usually, one will refer to the "average-family" in the area where the experiment is to be performed. For example, an average Italian family could be identified as characterized by:

- 3-4 persons (man 30-40 years, woman 30-40 years, children 5-12 years)

- sleeping time for parents:	23 to 7
- sleeping time for the children:	21 to 7.30
- *eating time for the man:*	7.30, 20
- eating time for the woman:	7.30, 13, 20
- eating time for the children:	7.45, 13, 20
- working time for man (including travels):	8 to 17
- working time outside the home for woman:	none (housewife)
- school time for the children:	none (age 0 to 3)
	8 to 15 (age 4 to 5)
	8 to 13 (age 6 to 18)

- average socio-economic status

When establishing the schedules of the activities, the following distinctions must be taken into account:

1) activities not performed to modify the indoor temperature
2) activities performed to modify the indoor temperature

Activities belonging to the first category are (Hauglustaine 1981):

- presence of occupants at home
- cooking
- use of hot and cold tap water
- use of electrical appliances

- use of light
- opening of windows for hygiencial purposes
- operating of blinds for keeping privacy or modifying natural illumination

For "presence at home of occupants" use fig. IV c-1a for employed men, fig. IV c-1b for employed women and fig IV c-1c for housewives. In the case of children not at school, one could consider their presence at home to coincide with that of the housewife.

The amount of heat from people performing different activities can be found in the literature. An average value of 180 W, 150 W, and 130 W could be used, respectively, for men, women and children. The occupants' use of space, that is the rooms where they use to spend their time at home, should also be decided.

For "cooking", Tables App. IV -4 and 5 give respectively the daily amount of time spent on, and the estimated net energy consumed in a year for cooking, in different countries. Cooking will, in general, occur just before meals (see Fig. IV c-3b).

For "hot water", Table App. IV-3 provides the net (or useful) energy used in the building. To decide at what time of the day this energy is used, one can use Table App. IV-2 to estimate the amount of water for each end-use, and one can then choose a schedule for each end use. For example, place personal hygiene after waking up and/or before going to bed, place dish-washing just after eating, and distribute the remaining activities randomly over the day.

Cold water is mainly used to flush WC and its volume can be deduced from Table App. IV-2. Assuming a certain cistern capacity, one can estimate the number of flushings and schedule them during the day using common sense.

There exist data of the most common "domestic electric appliances", data are available for the most common ones such as refrigerators, clothes-washers, clothes-dryers, and dish-washers. The yearly average net energy consumed by these appliances, along with their penetration, is given in Tables App. IV-7, 8, 10, 11, and 12. The penetration index can be used to choose what appliances should be considered according to the socio-economic status of the simulated occupants. For instance, an average occupancy will not include those appliances having a penetration index smaller than 50%.

A different approach is that of considering the penetration as a "percentual ownership". In this case, of course, only the effect of the appliance could be simulated. These two approaches will in general yield very close results. A more difficult task is to decide when these appliances are used.

For TV-sets one can use Fig. IV c-3c, but children watching TV should also be considered. For refrigerators a flat schedule can be adopted. For clothes-washers and driers information can be drawn from fig. IV c-3a. The dish-washer will generally be operated after the main meal. In all cases the use of common sense will be necessary.

For "lighting", the data on yearly energy consumption are usually determined as a difference between the total electricity consumption and the electricity consumption of the main electric appliances mentioned above. In this case these data are not separated from those referred to as "other electrical appliances", the importance of which varies between countries (see Table App. IV-12). The first task is to split the data in some reliable way, assuming that the schedule of "other appliances" is similar to that of "presence at home of occupants". The use of lights shows a seasonal dependance particularly relevant at high latitudes. It could be useful to adjust the lighting schedule during the heating season.

"Opening of windows" is the operation through which indoor air quality is usually regulated in many countries. As a hygienically motivated action it will depend on the activities performed in the dwelling and on the sources of pollution. Some information on when and for how long are windows opened, as well as empirical relations between window opening and indoor-outdoor air temperature difference can be found in ch. IV c.

"Operations of shutters, blinds, etc." are performed for regulating the indoor climate as well as natural illumination, and for ensuring the occupants' privacy. See ch. IV c for further information on this topic.

Activities performed to modify the indoor climate are:

- operation of thermal system control set-points
- opening of windows
- operation of blinds, etc.

The simulation of these activities requires a very detailed analysis. Statistics are not of great help in this case, because of the small amount of available data, and because these data do not afford generalizations. Therefore, it would probably be correct to assume that these activities receive a feed-back from some kind of thermal comfort index, e.g., temperature measured by a globe thermometer.

The difficulty of predicting what actions will be undertaken by the occupant when he does not feel comfortable with the indoor climate has already been pointed out in ch. IV c. Given this fact, the experimenter will be free to make a priority list. As an example, the succession of actions, performed by a person when solar radiation produces an overheating, is the following:

1) shielding of the window
2) taking off clothes
3) opening the window
4) operating the radiator valves or the room thermostat

Points 1, 3, and 4 can be simulated, while point 2 cannot. When choosing this sequence, one should notice that the actions above produce their effect with different promptness, and that the higher the discomfort, the more prompt the effect should be. These actions will in general continue even after the thermal comfort conditions have been reached, until nearly discomfort conditions are approached.

- simulation of energy related activities

Once the activities of the occupants have been expressed in terms of daily schedules, the experimenter will choose a practical way of simulating such schedules. An underlying assumption is that the simulated activities can be easily adjusted and monitored. A microprocessor sequence controller will be particularly suitable for the purpose. Following the same order as in the previous section, we first find the simulation of occupants themselves. For energy purposes, just very simple devices could be used, such as a lamp or any other electrical resistance. If, however, their influence on the indoor climate has to be taken into account in a more realistic way, the heat gain from the occupants can be simulated by means of heaters that, when switched on, have a surface temperature of about $30^{\circ}C$ and deliver about 50 g of water vapour per hour to the air. There should be, in each room, a number of heaters equal to the maximal number of people who can contemporarily be in the room. These heaters, electrically fed, can be easily switched on and off by the sequence controller. Only the final effect caused by the occupants' activities to the energy budget should, whenever possible, be reproduced by means of electric resistances. We will also give some information on more sophisticated simulation techniques below.

Cooking can be simulated by an electric cooker: vapour can be produced by a simmering pot whose water level is restored by means of a solenoid valve.

Hot water from taps should be simulated at the kitchen sink and at the bathroom basin and bath. Fisk and Morrison (1979) suggest the following procedure: "... flow to each is controlled by a solenoid valve which is opened at preset times by the sequencer. A thermocouple in the flow pipe then integrates the amount of heat passing and closes the valve when this reaches a preset level. The warm water is allowed to drain slowly away, so that additional heat gain is transferred to the house."

As for electrical appliances, one could, as stated above, either use real ones, or simulate them. Whenever the operation of the appliance is technically hard to simulate, but its energy effect is well known, as for a refrigerator, the second approach should be preferred. In the other cases real appliances can be used. Lighting will be simulated by using real lamps. In this case, photoelectric cells detecting the need for artificial light can be used, along with information on occupants' activities and presence at home.

The mechanical equipment for window opening should be assessed according to the window opening system. In many cases a simple commercial drive can be used. Similar devices can be used for curtains and blinds.

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APPENDIX IV

Data on energy consumption by tap water and appliances

Contents

App. IV Data on energy consumption by tap water and appliances

- hot and cold tap water

Methods for collecting data on the occupants' use of tap water has already been treated in ch. IV a and IV b. Here only a few comments will be made on the data contained in the tables. How these data have been used in ch. I e, for the estimate of the contribution to the heating of a dwelling will also be commented upon.

In Table App 4- 1 we give some numbers for the estimated average household water consumption for a few cities in some countries and for different types of dwellings. The temperature of the inlet water is important for an estimate of the energy losses caused by the use of water. This temperature will be influenced by the temperature of the ground. In Table App 4-1 we have included an estimate of the temperature difference between the inlet water and the building interior, during the heating season, for some cities. In general, cold water will not take the indoor temperature before discharge (the time constant of a 10 ltr water closet is e.g. 7-8 hours). A good approximation is to assume that the water takes the average of feed temperature and the indoor environment before discharge.

In Table App IV- 2 data on the end use of tap water are given. One can note the relatively uniform fraction ,about one third, used for bathing and showers.

In Table App IV- 3 the estimated use of net energy is given for the consumption of hot tap water. In a few cases the figure presented refers to useful energy.

For an estimate of the hot water consumption for clothes- washing and dish-washing see these sections below.

The estimates of the amount of the net energy for water heating that is lost to the building by heat losses from the hot water storage and the plumbing (before the tap) during the heating season varies from 15 to 30% (Over 1974, Ebersbach 1977, Heap 1977, Wilson 1978, Mutch 1974, Lee 1976 and Elkis 1977).

The heat gains to the building after the water is drawn from the tap should not be very large if most of the water goes directly to the drain. Hauglustaine (1980) has estimated that about 20 % of the heat content relative to the indoor temperature of the water of a shower is lost to the interior of the building.

The amount of water required for a hot bath has been estimated to 100-150 l, and the water temperarure to 35-40°C (Askensten 1977, Todd 1970, Nørgård 1979 and Hauglustaine 1980). Thus the required energy for taking a hot bath can be estimated to range from 5 to 20 MJ. There seems to be agreement between different sources that the water temperature when taking a shower is 35-40 °C, but the amount of water used can vary greatly. American sources give estimates from 45 to 75 litres (Hastings- Clark 1977, Maadah- Maddox 1976 and Hopp- Darby 1980). The amount of energy for taking a shower has been estimated to vary from 4 to 36 MJ (Askensten 1977).

If the water temperature of a 150 ltr hot bath is originally between 35 and 40 °C, this temperature will under normal indoor conditions drop only about 2 K in 15 minutes and about 4 K in an hour. Therefore only a small amount of the energy spent for bathing will contribute to the heating of the building, unless the water is deliberately allowed to cold before discharge. This energy-saving procedure is not likely to be widely adopted as it leaves the tub rather dirty.

Most sources do not consider this possible heat gain from the hot tap water at all. Those who do, give a number of about 10 to 25% of the net energy used for water heating (Ebersbach 1977, Seymour-Walker 1978, Socolow 1978 and Hauglustaine 1980).

In ch. I e it has been assumed that 25 % of the net energy used for hot water generation contributes to the heating of a dwelling by losses from the hot water storage and the plumbing. It has also been assumed that another 20 % of the thermal energy of the hot water relative to the indoor temperature is lost before being discharged.

- cooking

The source of energy used for the operation of cookers and ovens in Western Europe and North America is mostly electricity and gas.

The electric energy used for cooking can probably be well estimated by the utility in countries where the penetration of electric cookers and ovens is between 20 and 80%. If the penetration is large one can expect the estimate to be influenced by the use of other domestic electric appliances. The actual penetration ranges from about 1% in Italy to almost 100% in Norway.

The electric effect of a hot plate of an electric cooker is between 1500 and 2000 W. The fact that about 50% of women are at home during the day in many countries may indicate that lunch is prepared at home in about half of all households. Assuming that the preparation of a meal requires the use of two hot-plates half an hour each will mean that the energy consumption for cooking on an electric cooker is between 8 and 12 MJ per day or between 3 and 4 GJ per year. It has, however, been shown that the energy used for preparation of the same meal may differ by a factor of five (Smith 1978).

In Western Europe the efficiency of electric cookers is probably rather uniform as 85% of all hot plates come from one manufacurer. The efficiency of a gas cooker has been estimated to 40- 60 % (Over 1974, IHVE 1972, SW 1980, Smith 1978, Maadah- Maddox 1976). In ch. 1 e it has been assumed that the efficiency of a gas cooker and oven is 50 % when connected to a flue.

If, as in Italy, a non-negligible percentage of the households use more than one source of energy for cooking, it can be difficult to estimate the amount of energy used for cooking. But in general the estimate will be close to that obtained for households using only electricity.

In Table App IV- 5 we give the estimated amount of useful energy used for cooking in some countries. The average value for the per capita use is 1.25 +- 0.25 GJ/year. Due to the errors in the different estimates one could take the per capita use to be approximately the same in all countries.

A related similarity can be deduced from data on the time spent in cooking. The average time spent in cooking by inhabitants in four countries is given in Table App IV- 4. In Western European countries and the USA employed women spend about one hour and unemployed women about two hours in cooking every day.

For electric cooking it would theoretically suffice to use only 15% of the energy that is actually used (Nørgård 1979). Therefore most of the energy used would contribute to the heating of a dwelling. However, due to the large amount of heat released by cooking and due to odours it is common in many households to operate electric fans or open windows when cooking. It is, therefore, clear that to estimate the contribution from cooking to the heat balance of a building, one must take into account also the ventilation of the kitchen. If the rate of air change is measured, and appears in the heat balance equation of the building, the energy used for cooking should be added to the heat balance of the building. If the ventilation of the kitchen during cooking is not known, it is common to assume that only a certain fraction of the energy used for cooking contributes to the heat balance of the building. In ch. I e it has been assumed that 75 % of the net energy for cooking will contribute to the heating of a dwelling.

- use of television

The amount of energy used by TV sets cannot be estimated from utility data as the penetration in most countries is 100% or more. This will therefore have to be estimated from data on the time people spend in watching it and the capacity of a television set. Also the electric demand of a colour TV often exceeds that of a black-white by 50% . The energy use will therefore depend on the penetration of colour TV.

The time spent in watching television in Western Europe and the USA was 1-1.5 hours/cap. a day about ten years ago (Szalai, 1972). The time the television is used in a household consisting of more than two persons can be assumed to be at least twice as much now. The electric demand of an average modern television set is 50-150 W. The energy used by a TV-set would then vary from 0.4 to 2.5 MJ a day or between 0.1 and 0.6 GJ a year. An old television set may well more than double this energy consumption.

In Table App IV- 6 we give some estimates from different countries on the energy usage by TV-sets. The smallest estimate is for countries with the smallest penetration of colour TV. The major part of this energy will be spent in the late afternoon and in the evening (see ch. IV c).

In ch. I e it has been assumed that all the energy consumed by a television set is converted into heat inside the dwelling.

- use of refrigerator and deep freeze

In most households the refrigerator or freezer will be used all the year round. The energy used will therefore depend only on the electric demand of the appliance which for a modern European refrigerator is 60-90 W and for a deep freeze it is about twice as much value. The demand for electricity does not depend very much on the size of the appliance because a small unit is often less insulated. For a combined deepfreezer and refrigerator the demand is about the same as for a deepfreezer.

The average capacity of refrigerators sold in Europe is generally 100-300 litres compared to 300-600 in the US. The latter are often equipped with a top freezer and the energy consumption is larger than for a European one of the same size and often increases with the capacity (Hoskins, Hirst and Johnsson 1978). The energy consumption of a modern European deep freeze and refrigerator will be respectively 5-7.5 MJ and 3.5-5 MJ a day. For households with older equipment the energy consumption may be twice the above.

In Table App IV- 7 we give some estimates of the energy consumption for refrigerators and freezers. The total energy consumption in different countries largely depends on the penetration of freezers.

Energy consumption will be constant throughout the day and the night and most of the electric energy will be converted to heat inside the dwelling.

- clothes-washing and clothes-drying

An estimate of the amount of energy used for clothes-washing and clothes-drying can be obtained in two ways. One is to use data on the electricity consumption from the utilities, as discussed above in ch. IV a. This method will be reliable if water is electrically heated inside the washer. The second method is to use test data for a certain load. The average load and the frequency of use then has to be estimated by other means. Washers have been tested using test procedures close to those suggested by various organizations.

In a Swedish investigation (KOV 1979) of 19 washers sold in Western European countries the average energy consumption was found to be .8+- .1 MJ/kg dry laundry when washing white laundry at 90°C and 1.0 +- .3 MJ/kg dry laundry when washing synthetic fibres at 60°C. The cold-feed temperature was 10°C. Similar results have been obtained elsewhere (SH 1971-76, SIFO 1979).

Washers common in the US are generally connected to the hot water tap. As the electric energy used by the motor and the automatic control will only amount to 10-15% of the energy needed for water heating (Nørgård 1979, Arri-D'Emilio 1974), it can be neglected.

When the above mentioned tests have been used to estimate the energy consumed by washers, an amount of laundry per capita and year of 150 kg dry-weight laundry and a certain load for different kinds of washing cycles has been assumed. These estimates are partially based on interviews (KOV 1976) but they must be regarded as rather uncertain.

Other investigations on the frequency of washing give only the time used for washing. Some data are given in Table App IV- 8. Time varies between 3 and 5 hours/week and the number of times a week varies between 2 and 3.5 for the countries in the list. The number of persons in an average household in these countries varied from 3.3 to 3.6 when this investigation was performed. This means that each washing cycle will consist of the weekly laundry for one or two persons.

In Table App IV- 9 we present some estimates of the net energy used for washing. Different methods have been used to arrive at these estimates. The amount of this energy that contributes to the heating of the dwelling has been estimated to 20-40% (Nørgård 1979). In ch. I e it has been assumed that 20% of the net energy used by washers is converted to heat that stays inside the dwelling.

The energy required for drying the laundry is often greater than the energy required by a washer (Smith- Marwich 1980). In the above mentioned Swedish investigation it was found that if the laundry is spin-dried in the washer it will contain .8 +- 0.15 litres of water per kg dry-weight laundry and about half this value if a more efficient separate spin-drier is used. In this investigation it was also found that manual laundry is more energy-consuming than when a washer is used.

Drying the laundry will theoretically require an energy of 2.3 MJ/litre of water. If a drier is not used this energy will be supplied by the heating system of the building during the heating season if the drying takes place inside a residential building. If a drier is used more energy will be needed. The efficiency of European tumble-driers and drying cupboards has been given to 30- 60% (KOV 1976) and that of driers in American homes to 50% (Smith 1977).

In Table App IV-10 we present some estimates of the yearly energy consumption of a drier. Assuming an efficiency of 50% the energy needed for drying the laundry when a drier is not used can be assumed to be half the values given in Table App IV- 10.

When a drying cupboard which circulates hot air is used, the temperature of the air in the room where the drying cupboard is situated will rise. To determine the contribution of the released energy to the heat balance of the building, one must take into account the amount of air exhausted from the room by the ventilation system. The comments made at the end of the section about cooking then apply also here.

- washing up dishes

The energy required by a dish-washer will depend on whether it is connected to the cold or the hot water tap. Here the custom varies from country to country. In a Swedish test (KOV 1980) of 14 dish-washers sold in Western Europe it was found that the required energy/place setting was 1.1 MJ for connection to the cold water tap and 1.9 to the hot one if including and .3 if excluding the energy required for heating the water before it gets to the dish-washer. The average number of place-settings in this test was 10. Similar results have been obtained in Denmark, Norway and Finland.

The energy required for manual dishwashing will vary much depending on how it is done. The conclusion of a Swedish estimate (KOV 1976) ,partially based on interviews, is that a dish-washer is by far more energy efficient than manual dish-washing unless the occupant is really trying to save energy when washing up dishes.

In Table App IV- 11 we present estimates of the energy consumed by dish-washers. In most households this energy will probably be consumed in the evening.

Part of the energy consumed by a dish-washer (including the energy used for heating the water) will be lost to the interior of the dwelling. A number of 20-40% has been given (Nørgård 1979). In ch. I e 20% has been assumed..

- illumination and "other appliances"

It is difficult to estimate the energy consumed by illumination. If data from utilities on electric consumption is used as described above in ch. IV a, the energy consumed by lighting can not be distinguished from that used by TV and refrigerators which also have a penetration of about 100%.

Most utilities therefore do not try to estimate the energy consumption by illumination but they instead give a figure for the energy consumption by "other appliances" including lighting. Most estimates are based on the assumption that a certain number of electrical lights are switched on for a certain number of hours. A better estimate will probably be obtained if it is based on the sales and the expected life-time of bulbs (SOU 1974).

The daylight in dwellings is probably in general sufficient for most normal activities from one hour after sunrise to one hour before sunset. This is based on the assumption that the daylight factor is 1% and the outdoor illuminance between 5000 and 15000 lux when the sun is 10 above horizon. During winter months at high latitudes there is never sufficient daylight for normal household work indoors and electric light must be used during the whole day.

All of the electricity for lighting contributes to the heating of the dwelling. When the outdoor temperature is higher the direct solar radiation can create unpleasantly high temperatures indoors. Shutters, blinds or curtains are then often used to reduce heat penetration. The exclusion of solar radiation often reduces the indoor illuminances. As a first approximation it can be assumed that enough daylight still penetrates the sunshading device to allow most normal activities to be performed without the use of extra electric lighting indoors.

In Table App IV-12 we present some estimates of the energy consumed by lighting and by "other appliances" (including lighting). For countries where both estimates are available the fraction of energy consumed by illumination varies from 25 to 75%. This great varation can be expected because of the uncertainty in the estimate of the energy consumed by lighting or by "other appliances". These entities are often estimated by subtracting from the total consumption of electric energy by a household the electric energy consumed by all other appliances

In ch. I e it has been assumed that all of the electric energy consumed by "other appliances" is converted to heat inside the dwelling.

TABLE App IV- 1

Use of household water (m^3/cap., year) and estimated temperature difference between inlet water and room temperature during the heating season (ΔT)

		(m^3/cap,year)	ΔT(K)
BELGIUM:	(Schmidt 1974)	28	
	(Antwerpen, Coe 1978)	46	10-15
	(Bruxelles, Coe 1978)	33	
DENMARK:	(National, Olsson et al 1980)	64	
	(Copenhagen, Coe 1978)	55	10-15
FINLAND:	(Helsinki, Coe 1978)	79	10-15
	(Lahti, Coe 1978)	55	
FRANCE:	(National, Olsson et al 1980)	37	
	(National, Coe 1978)	42	
	(Paris, Coe 1978)	56	8-12
FRG:	(1977)	49	
	(Battelle 1969)	43	
	(Ebersbach 1977)	46	
	(Dortmund, Coe 1978)	65	
	(Dusseldorf, Coe 1978)	65	
	(Hamburg, Coe 1978)	43	10-15
	(Munich, Coe 1978)	44	10-15
ITALY:	(National, Olsson et al 1980)	82	
	(Rome, Coe 1978)	80	5-10
	(Torino, Coe 1978)	100	8-12
JAPAN:	(National, Olsson et al 1980)	80	
NETHERLANDS:	(National. Olsson et al 1980)	50	
	(Amsterdam, Coe 1978)	44	10-15
	(Rotterdam, Coe 1978)	51	10-15
NORWAY:	(Oslo, Coe 1978)	66	10-15
	(Baerum, Coe 1978)	100	
SWEDEN:	(National, Olsson et al 1980)	72	10-15
	(Nilsson 1976)	65 a	
	(Klebert 1974)	100 a	
	(Svensson-Larsson 1978)	78	
	(Lundström 1980)	60 b	
SWITZERLAND:	(National, Olsson et al 1980)	93	
	(Basel, Coe 1978)	80	
	(Zürich, Coe 1978)	77	10-15
UK:	(National, Olsson et al 1980)	74	
	(Webster 1972)	50 a	
	(Sharp 1969)	48	
	(London)		5-10
US:	(Hopp-Darby 1980)	88	
	(New York)		10-15
	(Washington D.C.)		8-12

Notes to Table App IV- 1

a) MFD b) SFD

TABLE App IV- 2

End use of water (m^3/cap.,year)

	Bath Shower	WC	Clothes washing	Dish washing	others	Total
FRG:						
(Battelle 1969)	14	13	7	2	7	43
	(32%)	(30%)	(17%)	(5%)	(15%)	
(Ebersbach 1976)	11	20	4	5	5	46
	(23%)	(43%)	(10%)	(12%)	(12%)	
SWEDEN:						
(Larsson-Svensson 1979)	25	15	11	15	13	78
	(33%)	(19%)	(14%)	(19%)	(10%)	
UK:						
(Sharp 1967)	17	18	5	4	3	48
	(35%)	(38%)	(10%)	(8%)	(7%)	
US:						
(Hopp-Darby 1980)	28	35	12	5	9	88
	(32%)	(39%)	(14%)	(6%)	(10%)	

TABLE App IV- 3
Net (or useful) energy for hot tap water (GJ/year)

		per dwelling	per capita	penetration of electric hot water(%)
BELGIUM:	(Potiau 1979)	5.0		23
DENMARK:	(Potiau 1979)	9.0 a		8
	(Nørgård 1979)	11.3 b,p		
FINLAND:	(Potiau 1979)	7.1 a		9
	(Ettestøl-Lund 1980)	11		
FRANCE:	(CSTB 1977)	5.8		
	(Potiau 1979)	6.1 a		27
FRG:	(Läge 1980)		2.6	
	(Ebersbach 1977)		3.3 c	
	(VDEW 1977)	6.0 a		45
IRELAND:	(Minogue 1973)	12.8 a		
	(Knott 1976)	8.6 a		
	(Potiau 1979)	6.8 a		39
ITALY:	(ENEL and ENI 1978)	5.8		
	(Potiau 1979)	3.9 d		41
NETHERLANDS:	(Over 1974)	8.7 e		
NEW ZEALAND:	(Trethowen 1980)	19 a		
NORWAY:	(Hagen 1975)	14 f		
		9 g		
SWEDEN:	(SOU 1975)		5.9 h	
	(" ")		5.0 i	
	(Jonson et al 1980)		3.2 i	
SWITZERLAND:	(Potiau 1979)	8.1 a		
UK:	(Webster 1972)		3.3 k,p	
	(ECR 1972)		3.0 p	
	(Courtney-Jackman 1976)		3.8 l,p	
	(Brundrett 1980)		3.3 m,p	
	(Potiau 1979)	5.7 d		66
US:	(Smith 1976)	14		
	(Maadah-Maddox 1980)	17		
	(Mutch 1975)	16		
	(Lee 1976)	24		
	(Hastings-Clark 1977)	22-23 i		
	(" ")	16 n		
	(" ")	10 o		

Notes to Table App IV- 3

a) dwellings with electric heating of hot tap water. b) use of 60 l hot water/cap. and day heated 45K. c) including use of washer and dish-washer . d) including dwelling with additional possibilitiesof water heating apart from electric. e) water heating by fuel. f) electrically heated SFD. g) electrically heated MFD. h) MFO with electric heating or district heating. i) SFD. k) local authority flats. l) district heating, collectively charged. m) electrically heated SFD. n) low-rise apartment unit. o) high-rise apartment unit. p) useful energy

TABLE App IV- 4

Time in hours per day spent on cooking by inhabitants. Data from Szalai (1972)

	Employed women	House wives	Women	Men
BELGIUM	0.9	2.0	1.5	0.1
FRANCE (six cities)	0.9	1.7	1.3	0.2
FRG (100 election distr)	1.1	2.0	1.7	0.1
USA (44 cities)	0.8	1.6	1.2	0.1

TABLE App IV- 5

Net Energy Consumption for cooking (GJ/year)

		per dwelling	per capita
BELGIUM:	(Potiau 1979)	3.0	1.1
CANADA:	(Schipper-Ketoff 1978)	3.5	1.2
DENMARK:	(Potiau 1979)	2.3 a	0.9
	(Nørgård 1979)	3.4 b	1.4
FINLAND:	(Potiau 1979)	2.2 a	0.8
FRANCE:	(CSTB 1977)	2.7	0.9
FRG:	(VDEW 1977)	2.2 a	0.9
INDIA:	(Gupta, Rau and Vasudevaraju 1978)		1.1-1.4 i
IRELAND:	(Potiau 1979)	5.6 a	1.4
	(Knott 1976)	6.3 c	1.6
ITALY:	(ENEL and ENI 1978)	2.7 h	0.9
NETHERLANDS:	(Ferguson 1974)	4.7 a	1.4
	(van Bremen 1974)	3.2 d	1.0
NORWAY:	(EFI 1979)	3.6 a	1.3
SWEDEN:	(Potiau 1979)	3.0 a	1.3
SWITZERLAND:	(Potiau 1979)	4.6 a	1.5
UK:	(Potiau 1979)	3.5 a	1.3
	(Heap 1977)	4.9 e	1.8
US:	(Smith 1976)	4.3 a	1.1
	(Maadah-Maddox 1976)	5.8 f	1.4
	(" ")	5.7 g	1.4

Notes to Table App IV- 5

a) electric cooker and oven . b) electric cooker and oven used 1 hr/day . c) electric cooker and oven 5.5 GJ/year and electric kettle 0.8 GJ/year . d) gas cooker and oven excluding pilot light. e) electric cooker and oven 4.1 GJ/year amd electric kettle 0.8 GJ/year. f) electric range with self-cleaning oven. Family of four. g) energy consumption in a mostly gas home. Family of four. h) including electric energy consumption in dwellings with mixed gas and electric appliances. i) the smaller number refers to semi-urban areas, the higher number to rural areas. Primary energy in order of importance in form of firewood, cow-dung, and kerosene.

TABLE App IV- 6

Net Energy Consumption for TV (GJ/year)

		Black-White	Colour	Total	Penetration (%) B-W/C*
BELGIUM:	(Potiau 1979)			.6	59/40
DENMARK:	(Nørgård 1974)	.6	1.0		
	(Potiau 1979)			.75	63/47
FINLAND:	(Potiau 1979)			.4	85/25
FRANCE:	(Potiau 1979)			.9	
IRELAND:	(Knott 1976)			1.1	
	(Potiau 1979)			.9	51/26
ITALY:	(Potiau 1979)			.4	87/6
JAPAN:	(Potiau 1979)			.9	34/120
NETHERLANDS:	(KEMA 1975)	.6	1.4		
NORWAY:	(EFI 1978)	.7	1.1	1.3	
SWEDEN:	(Potiau 1979)			1.0	45/60
SWITZERLAND:	(Potiau 1979)			1.2	44/44
UK:	(Heap 1977)			.9	
	(O'Callaghan 1978)			.7	
	(Potiau 1979)			1.3	38/60
US:	(Smith 1978)		1.6		
	(Basile 1976)		1.5		
	(Newman-Day 1975)				64/53

* B-W/C - Black-White/Colour

TABLE App IV- 7

Net Energy consumption for refrigerators and freezers (GJ/year)

		R*	F*	R+F*	Penetration of R+F (%)
BELGIUM:	(Potiau 1979)			1.5 a	130
DENMARK:	(Nørgård 1976)	2.0 c	2.9 c		
	(Naver 1976)	1.7 c	2.7 c		
FINLAND:	(Potiau 1979)			2.3 a	140
FRANCE:	(CSTB 1977)	.9 c			
	(Potiau 1979)			1.5 a	116
FRG:	(VDEW 1979)	1.4 c	2.7 c	2.4 a	140
IRELAND:	(Knott 1976)	1.5 c	2.6 c	1.6 a	90
ITALY:	(Potiau 1979)			.8 a	97
JAPAN:	(Potiau 1979)			2.0 a	105
NETHERLANDS:	(Ferguson 1974)	1.6 c	2.9 c		
NORWAY:	(EFI 1979)	2.2 c	2.7 c		
	(Poleszynski 1978)			3.6 a	180
SWEDEN:	(SOU 1974)	2.1 b	2.7 c		
	(Potiau 1979)			2.4 a	160
SWITZERLAND:	(Potiau 1979)			1.4 a	127
UK:	(CA 1979)	1.6 c			
	(O'Callaghan 1978)	1.3 c	3.3 c		
	(Potiau 1979)			1.6 a	115
US:	(Maadah-Maddox 1976)			7.6 d	
	(Hoskins-Hirst-Johnsson)			3.2-4.7 f	
	(" " ")			6.0 e	
	(Smith 1976)			5.7	
	(Newman-Day 1975)				134

* R - refrigerator, F - freezer

Notes to Table App IV- 7

a) with given penetration. b) refrigerator volume 250 l. c) volume unknown. d) total energy consumption for refrigeration in a typical american home. e) refrigerator with top-freezer volume 450 l. f) refrigerator with freezer volume 340 - 570 l with improved insulation.

TABLE App IV- 8

The time in hours/week and number of times/week spent by women on laundry. Data from Szalai (1972).

	Hours/week	Times/week
BELGIUM	3.3	2.0
FRANCE (six cities)	4.2	3.5
FRG (100 election districts)	3.9	2.2
USA (44 cities)	4.8	3.4

TABLE App IV- 9

Net (or Useful) Energy Consumption of clothes washer (GJ/Year)

		per dwelling	per capita	penetration (%)
BELGIUM:	(Potiau 1979)	0.95a	.4	91
DENMARK:	(Naver 1976)	2.0	.8	
	(Nørgard 1979)	2.5 b	1.0	
	(Potiau 1979)	2.3 a	.9	61
FINLAND:	(Potiau 1979)	1.2 a	.4	66
FRANCE:	(Potiau 1979)	1.1 a	.4	72
FRG:	(Ebersbach 1979)	1.8 c	.5	88
IRELAND:	(Knott 1976)	1.2	.3	
	(Potiau 1979)	1.1 a	.3	64
ITALY:	(Potiau 1979)	2.0 a	.6	75
NETHERLANDS:	(Ferguson 1974)	1.6	.5	
NORWAY:	(EFI 1978)	1.5 d	.6	90
SWEDEN:	(Potiau 1979)	1.5 a	.6	50
	(KOV 1976)	1.5 e	.6	50
SWITZERLAND:	(Potiau 1979)	2.8 a	1.2	50
UK:	(CA 1978)	1.5	.5	
	(O'Callaghan 1978)	1.1	.4	
	(Potiau 1979)	0.7 a	.3	76
US:	(Smith 1976)	5.3 f	1.3	
	(Maadah-Maddox 1976)	3.7-5.6 g	.9-1.4	
	(Wilson 1978)	3.2 h	.8	
	(Hopp-Darby 1980)	3.7 i	.9	
	(Newman-Day 1975)			78

Notes to Table App IV- 9

a) net energy. b) 8.8 MJ event, 4.5 events/week. c) 7 events/week using 47 l of hot water heated from 23 to 55°C, i.e. 4.9 MJ/event. d) 3.6 MJ/event, 2 kg dry laundry per event, 150 kg dry laundry per capita washed every year e) assuming 40% hot wash (85°C, 3.3 MJ/kg dry laundry) 30% warm wash (60°C, 4.1 KJ/kg dry laundry) and 30% luke-warm wash (40°C, 3.3 MJ/kg dry laundry), 150 kg dry laundry/capita and year and an average load of 80% at hot wash and 40% else. f) 7 events/week using 100 l of hot water heated from 15 to 60 °C, i.e. 14.6 MJ/event. g) 4.5 events/week, all warm rinse. h) 6 events/week, half hot cycle and half warm cycle, hot cycle using 90 l and warm cycle 40 l of hot water heated from 15 to 63°C. i) 5 events/week, 190 l/event of hot water on the average heated from 15 to 35°C assuming 30% hot loads (54°C), 50% warm (38°C) and 20% cold (20°C).

TABLE App IV- 10

Net Energy consumption of clothes drier (GJ/year)

		per dwelling	penetration (%)
BELGIUM:	(Potiau 1979)	.4 h	7
DENMARK:	(Nørgård 1979)	2.2 a	
	(Potiau 1979)	2.2 h	6
IRELAND:	(Knott 1976)	1.4 h	
	(Potiau 1979)	1.3 h	13
NETHERLANDS:	(Ferguson 1974)	2.5	
NORWAY:	(EFI 1978)	2.2 b	30
	(Solem and Songe-Møller 1974)	4.0 c	
SWEDEN	(KOV 1976)	2.3 d	
	(" ")	1.9 e	
	(Potiau 1979)	2.5 i	
SWITZERLAND:	(Potiau 1979)	2.1 h	9
UK:	(O'Callaghan 1978)	1.1 f	
US:	(Smith 1976)	3.0 g	
	(Maadah-Maddox 1976)	3.6	
	(Newman-Day 1975)		54

Notes to Table App IV- 10

a) tumble dryer. 3 kg dry-weight laundry containing 1 kg of water per kg dry-weight laundry to be dried/event. Assumed efficiency of appliance 63%, i.e. 11 MJ/event. 4 events/week. b) tumble dryer. For a 4-person household 600 kg of dry laundry/year. Energy required 3.6 MJ/kg dry-weight laundry. c) drying cupboard. Amount of laundry as in b but 6.5 MJ/kg dry-weight laundry required. d) drying cupboard. Per 3-person household 450 kg of dry-weight laundry/year containing 0.8 kg of water per kg dry-weight laundry. Energy consumption 5 MJ/kg dry laundry. e) tumble dryer. Amount of laundry as in d) but assuming 4.3 MJ/kg dry laundry. f) tumble dryer. g) 50% efficiency. h) unknown distribution of tumble driers and drying cupboard. i) mostly drying cupboard

TABLE App IV- 11

Net Energy consumption of dish-washers (GJ/year)

		per dwelling	penetration (%)
BELGIUM:	(Potiau 1979)	3.2	11
DENMARK:	(Nørgård 1979)	2.3 a	
	(Potiau 1979)	2.4	17
FINLAND:	(Potiau 1979)	2.0	6
FRANCE:	(Potiau 1979)	2.3	12
FRG:	(Ebersbach 1978)	2.6 b	
	(VDEW 1977)	3.2	15
IRELAND:	(Knott 1976)	3.6	
	(Potiau 1979)	2.2	4
ITALY:	(Potiau 1979)	4.3	10
NETHERLANDS:	(Ferguson 1974)	3.2	
NORWAY:	(EFI 1978)	1.4 c	10
SWEDEN:	(KOV 1979)	2.9+-.5 d	
	(KOV 1979)	5.2+-.7 e	
	(Potiau 1979)	1.3	17
SWITZERLAND:	(Potiau 1979)	1.2	20
UK:	(O'Callaghan 1978)	1.4	
	(Potiau 1979)	1.7	
	(CA 1978)	2.6	3
US:	(Smith 1976)	1.3 f	
	(Hopp-Darby 1980)	2.5 g	
	(Wilson 1977)	3.2 h	
	(Newman-Day 1975)		25

Notes to Table App IV- 11

a) 24 l of water heated from 10 to 65°C (connected to cold tap water). 5 events/ week, total energy consumption 9 MJ/event (average of 13 different models). Connected to cold tap water. b) hot water only. c) not including hot water. Assuming 3.6 MJ/ event and 7 events/week. d) average of tested models manufactured in Sweden, Germany,Italy, Finland and Spain. 7 events/ week. Connected to cold tap water. e) average of tested models manufactured in Sweden, Germany,Italy, Finland and Spain. 7 events/ week. Connected to hot tap water. f) not including hot water. g) hot water energy only. 47 l of water heated from 15°C to 60°C, i.e. 6.9 MJ/ event, 7 events/ week. h) hot water energy only. 57 l of hot water heated from 15°C to 63°C, i.e. 8.9 MJ/ event, 7 events/ week.

TABLE App IV- 12

Net Energy consumption for lighting and energy consumption for "other appliances" (including lighting) (GJ/year)

		lighting	other appliances
BELGIUM:	(Potiau 1979)		2.6
DENMARK:	(Naver 1975)	2.9	
	(Potiau 1979)		3.4
FINLAND:	(Potiau 1979)		2.5
FRANCE:	(CSTB 1977)	.9	
	(Potiau 1979)		1.6
IRELAND:	(Knott 1976)	1.2	
	(Potiau 1979)		3.6
ITALY:	(Potiau 1979)		1.5
NETHERLANDS:	(van Bremen 1976)	2.5	
NEW ZEALAND:	(Trethoven 1980)	3.0	
NORWAY:	(EFI)	4.5	6.D
SWEDEN:	(FERA 1969)	2.0 a	
	(EPU 1973)	1.4	
	(Potiau 1979)		2.7
SWITZERLAND:	(Potiau 1979)		2.5
UK:	(Heap 1977)	.9 b	
	(O'Callaghan 1978)	2.0	
	(Potiau 1979)		3.7
US:	(Smith 1976)	7.2	
	(Maadah-Maddox 1976)	3.4	10
	(Robinson-Yeung 1977)		10

Notes to Table App IV- 12

a) based on sale and expected lifetime of bulbs
b) consumption during the heating season

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