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ENERGY DEMAND AND SYSTEM SIZING

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GAS

Degree-days for heating calculations

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Building services engineers use degree-days for two main purposes; estimating the future fuel consumption for heating buildings and monitoring plant efficiency. There are other uses for degree-days[1, 2] but they are not discussed here.

This article attempts to provide a guide to the best application of degree-days. The accuracy of currently available degree-day data is also examined and compared with new figures calculated from hourly temperature records.

The two main applications use degree-days in different ways and are discussed in separate sections together with the appropriate degree-day data. But first degree-days are defined and the method currently used to estimate them is outlined. Sources of degree-day figures are also given.

A DEFINITION

What are degree-days? Strictly speaking they are units of measurement of accumulated temperature. Degree-hours would do just as well, much the same as measuring length in metres or millimetres, but it has become common practice to refer to accumulated temperature just as degree-days.

Accumulated temperature is defined as the integrated excess or deficiency of external air temperature with reference to a fixed datum, known as the base temperature, over a period of time. There are two types of degree-days, those above the base temperature and those below.

It is the degree-days below the base temperature (the shaded area in Figure 1) which are used in heating energy calculations and discussed in this article. They are a measure of the extent and length of time for which outside temperature falls below the base temperature.

Degree-days above the base temperature are not a useful index of energy consumption for airconditioning. Cooling loads are very dependent on humidity control, system design, solar and internal heat gains. Internal/external temperature differential is no longer the dominant factor.

In an airconditioned building the energy consumption for heating may not relate very well to degree-days below the base temperature because of the re-heat required by airconditioning processes for humidity control.

CALCULATING DEGREE-DAYS

Ideally we would determine degree-day figures from a continuous record of outside temperature. An empirical estimating method is used instead because continuous temperature records are not generally available.

The method which is used to prepare the degree-day data currently published by the Department of Energy[3] consists of a set of three equations (Figures 2a – 2c) which estimate degree-days from the daily maximum and minimum temperatures. It was developed by the Meteorological Office[4] from some original work by Lt. Gen. Sir Richard Strachey,[5] published in 1884. Degree-day totals for periods longer than a day must be obtained by summing the daily figures.

British Gas has recently developed a computer program which calculates more accurate values for degree-days from hourly temperature records. These hourly records are available for about fifty British weather stations. In this article published figures are compared with the degree-days produced by the new program.

PUBLISHED DATA

Degree-days for a base temperature of 15.5°C (known as standard degree-days) are published for seventeen regions by the Department of Energy. The figures are produced by the Meteorological Office using the empirical method. Prior to 1977 figures for fourteen areas were produced by British Gas.

Recently, at the instigation of the Department of Health and Social Security, degree-days for a base temperature of 18.5°C have been published in the journal "Health Service Estate". No other current data is published.

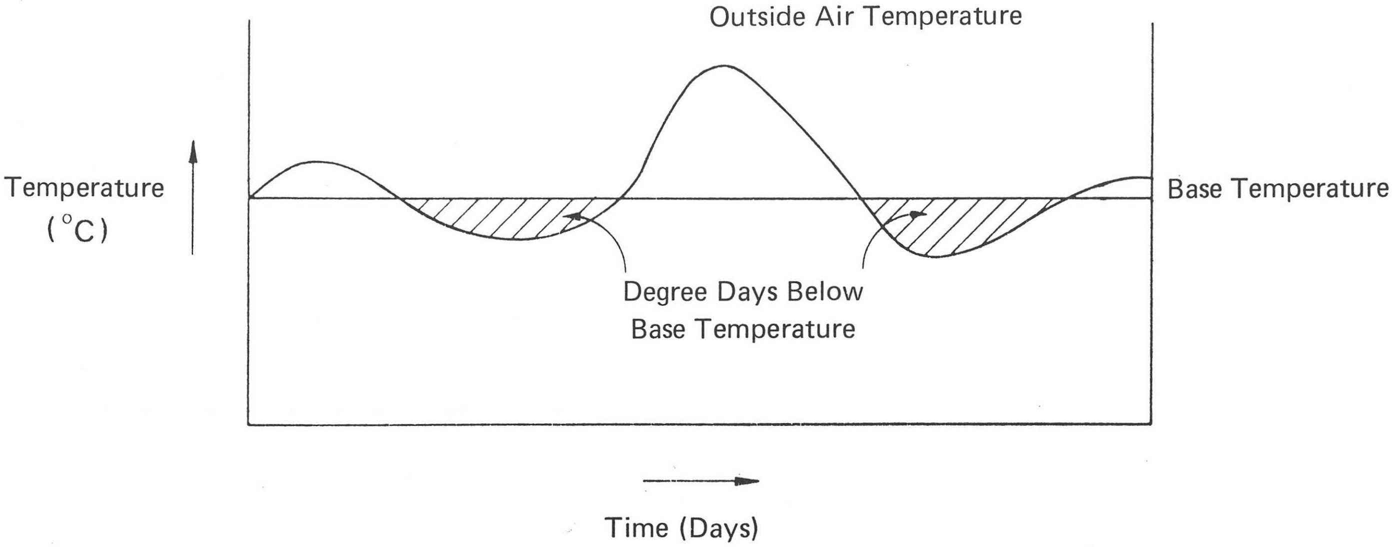


Figure 1

Graphical representation of degree days

Figure 2a

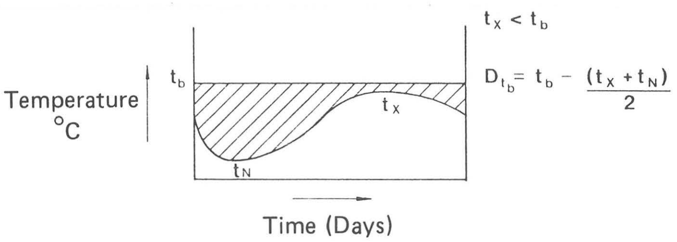


Figure 2b

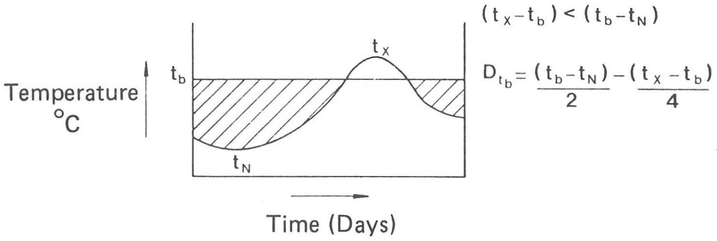
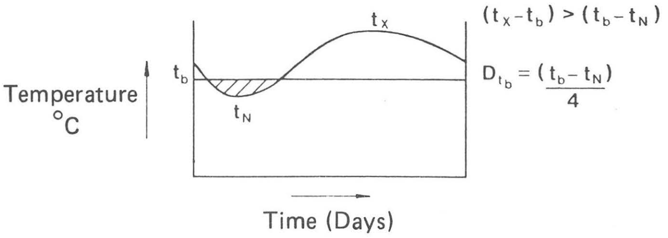


Figure 2c



Figures 2a — 2c

Estimation of degree-days from daily maximum and minimum outside temperature (empirical method)

ESTIMATING SPACE HEATING CONSUMPTION

One of the most detailed treatments of the subject was published in 1966 by Billington[6]. The method can be summarised by three equations for continuous heating.

$$t_b = t_i - \frac{G}{H} \quad (1)$$

$$E = \frac{24D_{t_b}}{\Delta t_d} \quad (2)$$

$$F = \frac{E\,Q_d}{N} \quad (3)$$

For key to symbols see Nomenclature.

Intermittent heating is more common than continuous heating in the U.K. To allow for this correction factors are applied to E, the equivalent hours of the full load operation, calculated for continuous heating. Tables of intermittency factors are published in Section B.18 of the 1970 I.H.V.E. Guide.

The degree-day method is not very accurate even for continuous heating as the equations are only a simplified representation of the heat transfer processes in a building[7]. Accuracy is further reduced by the use of intermittency factors which can only be approximate. Billington estimated that the errors in calculated fuel consumption could be as much as ± 25%.

It is worth emphasising a few points that are often overlooked in degree-day calculations:

1. The building heat loss per degree temperature difference (H in equation (1)) is calculated using an average fresh air infiltration rate and not the design value which is used to obtain Q_d.
2. An accurate estimate of the mean incidental gains (G in equation (1)) is a critical step in evaluating the base temperature.

Values of G/H should not be taken straight from a table such as B.18.11 in the 1970 I.H.V.E. Guide. Full consideration of the level of internal and solar gains and the level of insulation is necessary. Size and orientation of glazing, for example, has a significant effect on solar gains.

Sections A6 and A7 of the 1970 I.H.V.E. Guide contain some guidance on this subject.

3. In equation (1) t_i is not necessarily the inside design temperature nor is it the average inside temperature during the heating season. Properly defined t_i is the maintained inside temperature during periods when heating is required (but excluding any pre-heat). This excludes the effect of overheating due to incidental gains.

For buildings still on the drawing board t_i is normally taken as the inside design temperature. In existing buildings this may not be correct because of a change in use or poor control.

4. Evaluation of the seasonal plant efficiency, N, is difficult. It is not the full load efficiency usually quoted by manufacturers, but depends on the part-load efficiency, degree of oversizing and how the system is operated.

DEGREE-DAYS FOR ENERGY ESTIMATION

As yet outside temperature and hence degree-days cannot be predicted even in the short term. To estimate the energy consumption of space heating 20 year mean degree-days are used on the assumption that they will also represent future years.

Annual energy consumption is estimated using several degree-day totals. Annual totals are only used if a building is heated throughout the year. Two heating seasons are in common use, September—May and October—April. These are often fixed arbitarily by building operators. In applications such as domestic heating and season really fluctuates with the severity of the weather, but the longer season is usually used in calculations.

Figures published by the Department of Energy and in "Health Service Estate" include the 20 year means at a base temperatures of 15.5°C and 18.5°C respectively for each of the seventeen regional stations.

PROBLEMS

The use of regional figures introduces uncertainty into any analysis, but local degree-days are not usually available. At different times degree-days from both Kew and Heathrow have been used to represent the Thames Valley Region. A comparison of standard (15.5°C) seasonal* degree-day totals for these stations between 1957 and 1972 shows an average difference of 3% with individual seasons differing by as much as 12%.

Degree-days are particularly sensitive to altitude and proximity to the sea. Seasonal totals can increase with altitude, for example, by as much as 1% in ten metres[8]. There is no doubt that regional degree-day figures vary considerably from those applicable to many locations within the areas they represent.

If local records of daily maximum and minimum temperatures are available, degree-days can be estimated by the method of Figure 2. Comparison between this method and the more accurate British Gas program shows however that the accuracy of the empirical method drops at low base temperatures. It is not reliable for base temperatures below about 10°C.

Degree-days are only published for base temperatures of 15.5°C and 18.5°C, but modern levels of insulation have pushed the base temperature of most new buildings below these values. Some experimental low-energy buildings have base temperatures as low as 5°C or 7°C.

Section B.18 of the 1970 I.H.V.E. Guide contains a table of factors to convert standard seasonal degree-day totals to base temperatures between 10°C and 18°C. These correction factors imply that the outside temperature never drops below 7.3°C![7]

Figure 3 is a comparison of base temperature correction factors produced for Heathrow by the British Gas program and those in the I.H.V.E. Guide. At a base temperature of 10°C the I.H.V.E. figures are 21% below those for Heathrow. As the standard base temperature of 15.5°C is approached the correction factors tend towards unity and the error decreases becoming negligible between 14°C and 17°C (zero at 15.5°C) then increasing again.

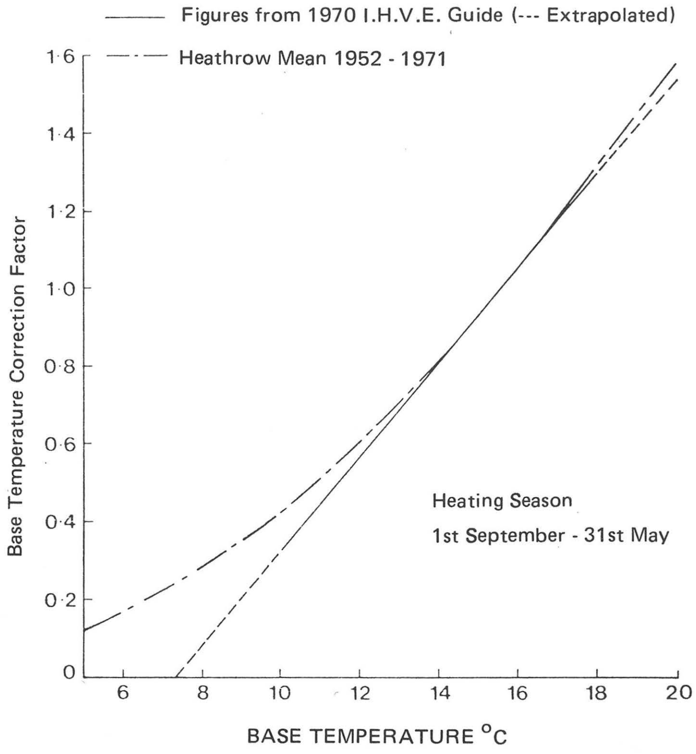


Figure 3

Seasonal base temperature correction factors

The variation of base temperature correction factors with location is illustrated in Figure 4. This shows, for Heathrow and Glasgow (regional station for West Scotland), the difference between mean seasonal correction factors for the period 1952–1971.

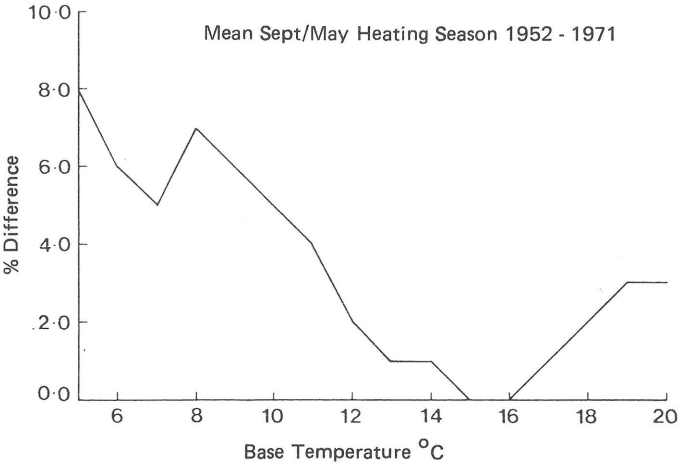


Figure 4

Change in base temperature correction factor between Heathrow and Glasgow.

Length of heating season is another parameter affecting the correction factors. Figure 5 compares the mean September/May and October/April seasonal factors for Heathrow 1952/1971.

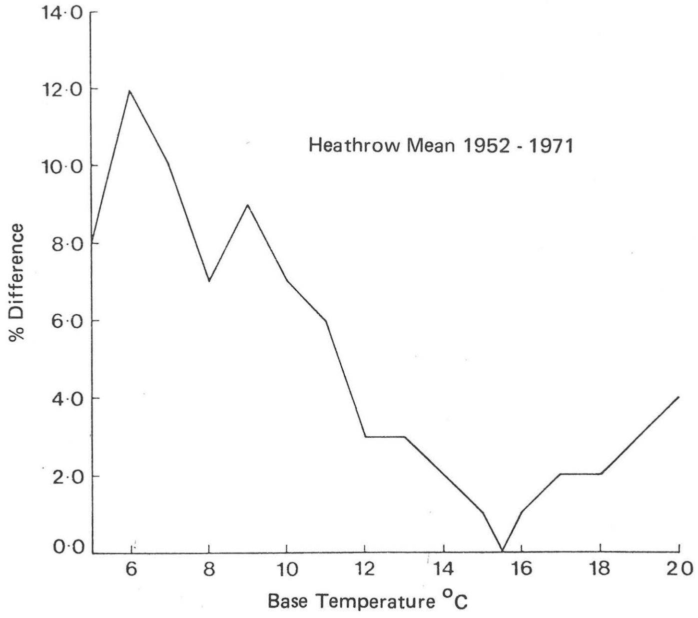


Figure 5

Change in base temperature correction factor between Sept/May and Oct/April heating season.

From the preceeding discussion it is apparent that there is insufficient published data to enable full use of the degree-day method in estimating energy consumption for space heating. There is a clear requirement for better information on non-standard degree-days. An increase in the number of sites for which degree-days are published and an agreed altitude correction method would also be useful.

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* 1st September — 31st May inclusive

WHAT TO USE NOW

Until more comprehensive degree-day information is published the best use must be made of what is available.

If local values of daily maximum and minimum temperature can be obtained standard degree-days (15.5°C base temperature) can be calculated using Figure 2. The correction factors for the Heathrow (Figure 3) can then be used to estimate figures for other base temperatures. Alternatively degree-days for base temperatures down to about 10°C can be calculated directly.

If local temperature data are not available the regional degree-day figures published by the Department of Energy can be used. They should be adjusted for local altitude (about 1% for each 10 metres). Again degree-days for other base temperatures can be estimated using Figure 3.

MONITORING PLANT EFFICIENCY

One of the first uses of degree-days in building services engineering was the correlation of fuel consumption with the weather as a means of checking the efficiency of heating plant.

The technique is straight-forward. Fuel consumption is plotted against degree-days, normally on a month to month basis. Ideally this would produce a straight line graph with the intercept on the vertical axis representing standing losses. Fuel consumption for purposes other than space heating, such as domestic hot water (d.h.w.) should be excluded from the analysis.

It is not always possible to extract space heating consumption from the total fuel consumption in a building. This is the case in many domestic applications for instance, where the d.h.w. load is met by the central heating boiler. In such circumstances total consumption can be used and the vertical intercept will increase to include a figure representing the consumption which is not weather dependent. It is important to exclude from the analysis all months when the heating is off and consumption is entirely due to other loads.

The convenient straight line relationship between degree-days and fuel consumption is usually distorted by inaccuracies in the method. This problem increases as the time between fuel consumption measurements gets shorter and it is inadvisable to use the method with intervals of less than a week between measurements. The analysis is also distorted by the inclusion of loads which are not air temperature dependent and may vary between measurements.

These problems can be overcome to some extent by fitting a linear regression to the data. The standard error from the regression is then used to plot confidence limits for the analysis (Figure 6). If, as in this case, the 95% confidence limits are used (2 standard errors from regression line) only one in twenty of the data points can be expected to fall outside their range. Plotting cumulative totals for degree-days and fuel consumption can also improve the accuracy.

Once the graph is plotted from previous records, new figures can be superimposed as they become available. If a point falls outside the confidence limits action is taken to locate possible malfunctions in the heating system. The graph should be re-plotted from time to time to reflect changes in the useage pattern of the building.

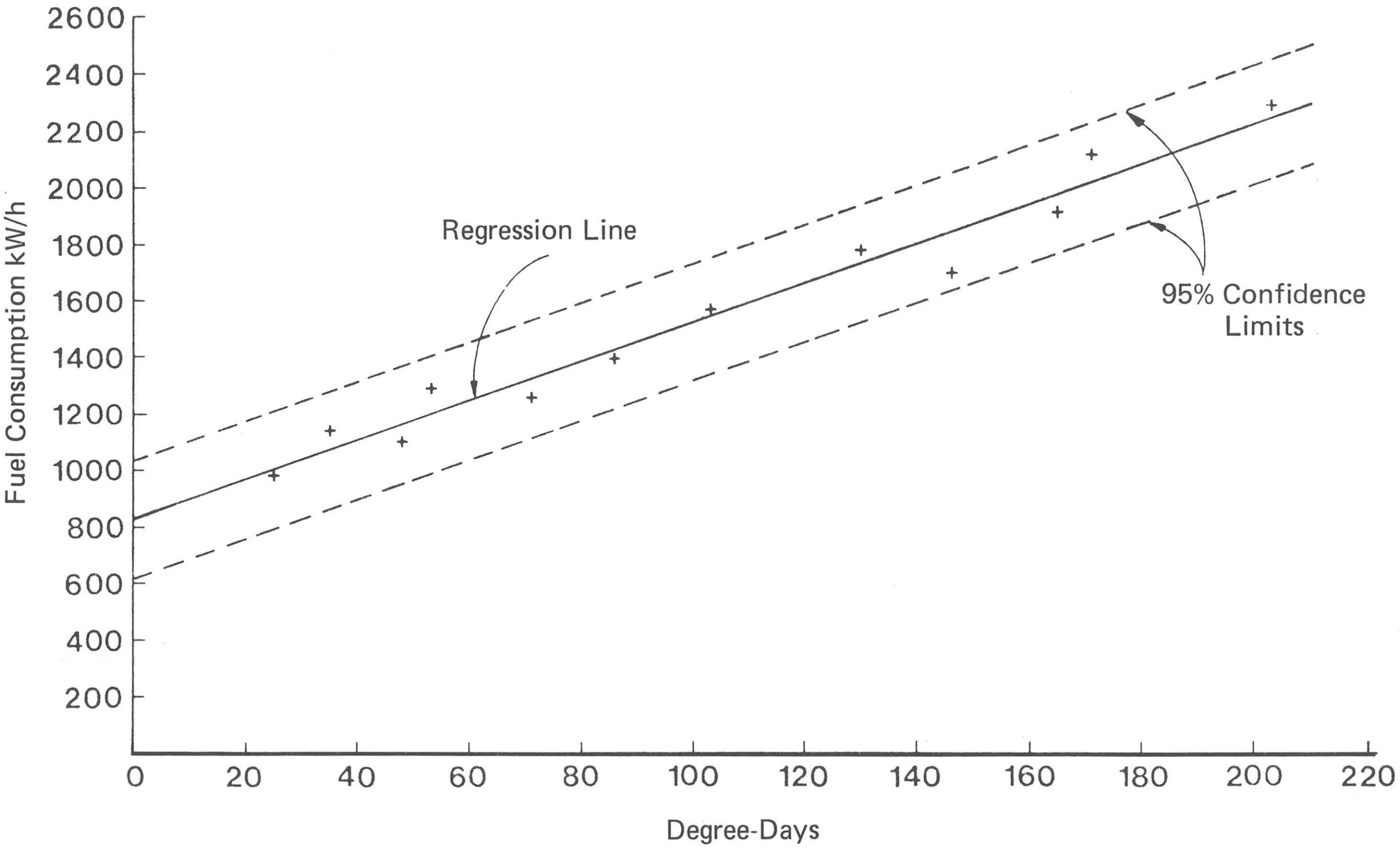

Figure 6

Typical graph for plant efficiency checks

Selection of the correct degree-day base temperature is just as critical in this application as it is when estimating energy consumption. This can be achieved by calculating the building heat loss and internal gains as before. An alternative approach is to produce regression lines over a whole range of base temperatures and to select the one which produces the smallest standard error.

Incidental gains and system efficiency vary from month to month, depending on the weather and changes in occupation or useage pattern. If sufficient historical data is available, regression lines can be found for each month of the heating season with the base temperature varying to suit the conditions, possibly month to month. Seasonal changes in system efficiency will then be reflected in the slope of the regressions.

DEGREE-DAYS FOR EFFICIENCY MONITORING

In this application monthly figures are normally used. The Department of Energy publishes monthly figures at the standard base temperature (15.5°C) for the seventeen regional stations and figures for an 18.5°C base temperature appear in "Health Service Estate". Both sets of data are estimated by the empirical method of Figure 2.

PROBLEMS

The effect of using degree-days which are not specific to the building site are more significant for monthly figures than 20 year mean seasonal values. Table 1 is a comparison of degree-days for the months September—May at Heathrow and Kew over the years 1957—1971. The differences are of obvious significance with a mean difference of 15% in the September figures for instance.

There is also a lack of published data for degree-days at the low base temperatures associated with modern buildings. If local records of daily maximum and minimum temperatures are available, degree-days may be estimated by the empirical method (Figure 2).

A comparison between standard (15.5°C) monthly degree-days for Heathrow estimated by this method and those produced by the British Gas computer program is given in Table 2. As in the case of the seasonal totals, the reliability of the empirical method drops at low base temperatures. Errors of 30% are possible at a base temperature of 10°C.

The base temperature correction factors in the 1970 I.H.V.E. Guide should not be used for efficiency monitoring. Average

TABLE 1

Comparison of Standard Monthly Degree-Day Totals for Kew and Heathrow 1957—1971

	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY
Maximum Difference. Percentage of Heathrow	43	29	8	9	7	6	7	8	23
Minimum Difference. Percentage of Heathrow	0	1	2	1	1	0	0	1	1
Mean Difference. Percentage of Heathrow	15	8	5	4	5	3	3	3	8

TABLE 2

Errors in Standard Monthly Degree-Day Totals Estimated by the Empirical Method. Heathrow 1957—71

	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY
Maximum Percentage Error	9	7	3	5	3	3	5	7	6
Minimum Percentage Error	0	0.5	0	0.5	0.5	0	0.5	0	0.5
Mean Percentage Error	5	3	1	2	2	1	2	3	3

correction factors for monthly degree-day totals at Heathrow (1951–1972) calculated by the British Gas computer program are shown in Figure 7. The I.H.V.E. factors, also shown in Figure 7 bear little resemblance to the true values.

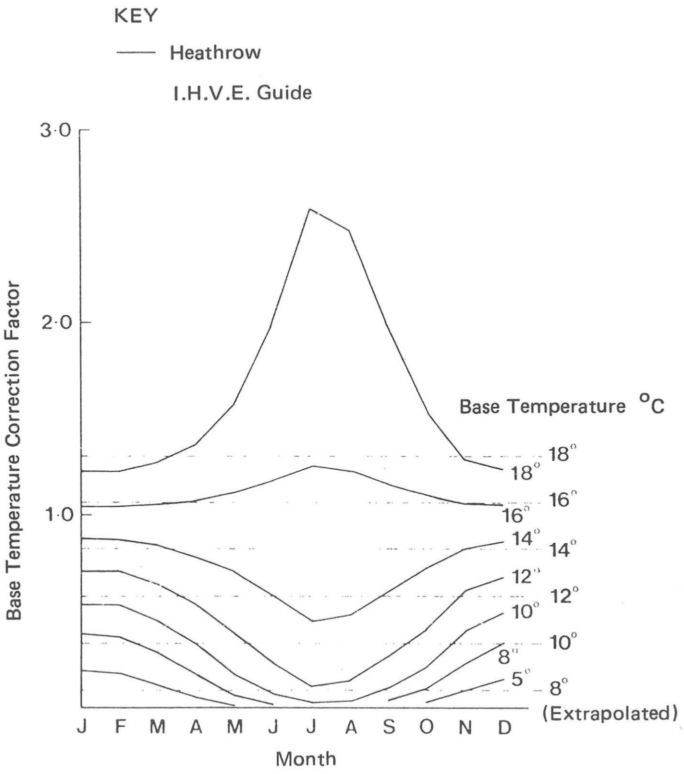

Figure 7

Comparison of mean monthly base temperature correction factors for Heathrow (1952-1971) with I.H.V.E. correction factors.

WHAT TO USE NOW

Ideally, all degree-day data used for plant efficiency monitoring would be calculated accurately from hourly temperature records, such as those used by the British Gas program. While it may be possible to publish this information for Met. Office Stations, few building operators can afford to monitor outside temperature on an hourly basis.

A possible compromise which should be explored is the use of regional base temperature correction factors with local standard degree-days estimated from daily maximum and minimum temperatures. This may be possible because although the correction factors do vary with location, they are much less variable than degree-days themselves. Correction factors for each month would have to be published every year because they vary with the weather. Until this information is available the correction factors in Figure 7 could be used.

A FINAL WORD

This article has been an attempt to clarify the methods involved in the two basic uses of degree-days and to indicate that the degree-day data currently published needs modification and expansion. It is interesting to note that the Irish Meteorological Service is ahead of its British counterpart in publishing degree-days for base temperature between 0°C and 23°C, although they are still estimated using the empirical method.

Finally, the author wishes to thank the British Gas Corporation for permission to publish this article. Thanks are also due to my colleagues at Watson House, particularly Barry Sutton, for their help in its preparation.

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NOMENCLATURE

D_{t_b}	Degree-days to base temperature t_b during heating season	
E	Equivalent hours of full-load plant operation	
F	Heating energy consumption kWh	
G	Mean rate of incidental heat gains kW	
H	Building heat load per degree, kW°C	
N	Plant efficiency	
Q_d	Calculated maximum design plant duty (no margins) for continuous heating, kW.	
t_b	Base temperature	°C
t_i	Maintained inside temperature	°C
t_n	Daily minimum outside temperature	°C
t_x	Daily maximum outside temperature	°C
t_d	Design temperature difference, used to calculate Q_d, °C.	

INTRODUCTION

The series of technical publications 'Energy Efficiency in Buildings' was introduced by British Gas during the International Energy Conservation Month, October 1979, as part of the Industry's support of Government energy initiatives. The publications consist of a compilation of technical studies mainly prepared by the staff of British Gas Watson House Research Station. The aim of 'Energy Efficiency in Buildings' is to contribute to the training and development of those concerned with building design and the efficient use of fuel. It is also aimed at assisting the Royal Institute of British Architects in its mid-career training programme for architects.

ENERGY DEMAND AND SYSTEM SIZING

This second number in the 'Energy Efficiency in Buildings' series covers the difficult area of energy demand calculation in buildings and includes 5 papers by the staff of Watson House Research Station selected to provide an understanding of the science behind the technology of designing heating systems. The papers range from a study of the practical problems of matching systems to buildings, especially for low energy housing, to what many might regard to as a "heavy" mathematical discussion of the science of energy demand estimates and the use of degree days.

Conservation Co-ordination
British Gas Corporation
March, 1980.

CONTENTS

Heat services for housing
The insulated house design requirements

by D.J. Nevrala, Ph.D, MCIBS, C.Eng, M.I.M.E.

SUMMARY

Semi-empirical methods of sizing heat services based on long experience have up to now proved sufficient. The application of high insulation levels disturbs a number of balances and therefore a new approach to the problem of designing heat services for future housing may be advantageous, especially as living patterns affected by socio-economic pressures may also change.

A comparison of the performance of a contemporary structure and realistic well insulated lightweight (timber frame) and a heavyweight (conventional) houses is presented. A computer simulation technique using real weather data was used. The most important conclusion of the study is that realistic well insulated structures tend to behave basically in a heavyweight manner. The relative advantages of heavyweight and lightweight construction are not clear cut, even for intermittent operation. The time required for both the lightweight and heavyweight structure to reach internal design temperatures is relatively long and systems of twice the design heat loss output would be required to guarantee a quick warm-up under design conditions. No additional capacity may be required to generate domestic hot water, but as with the fast response requirement, the extra capital cost involved has to be taken into account (larger hot water cylinder).

The heavyweight characteristic of the well insulated house should enable a redefinition of design specifications to be made and further more detailed studies are recommended. Weather data showing the implications of a change in design specification on the probable failure rate (i.e. percentage of time when the system would not attain design temperature) is presented. As the time to establish a consensus on a revised design philosophy is long, it is the purpose of this paper to initiate an early discussion on this topic.

1. INTRODUCTION

The results of a study of the thermal behaviour of future well insulated houses, set against a wider background of social and economic patterns, are presented in this paper with the purpose of initiating a discussion that would hopefully lead to a consensus on the basis for a design philosophy. The problems that are encountered when selecting heat services systems and the available design options and solutions will be the subject of the second part by Dr. M. B. Green.

To date the design of heat services for the great majority of dwellings has been based on long experience with heating and hot water systems. In traditional houses these have on the whole, provided a satisfactory service. As systems based on semi-empirical design criteria had provided acceptable customer satisfaction, the interaction between structure and system and the design and operation of domestic systems have not been studied to the same extent as in the commercial situation. At the same time, it had been felt that systems could be more efficient and in some cases the right answers had been fortuitous. The energy crisis and the resulting rise in fuel prices has led to a range of energy saving measures, the most prominent being the adoption of higher insulation levels for new housing. It is probable that the insulation levels of houses built in the future will continue to rise.

The application of high insulation levels disturbs a number of balances, e.g. fabric loss versus heat gains, and taken against a background of changing living patterns it becomes apparent that it is not possible simply to extrapolate past experience in the design of heating systems and heat services in general. The results of studies of some individual aspects of well insulated buildings have been published, but what has been lacking is an analysis of the performance of realistic future structures using real weather and living patterns. This paper on a 'first time round' basis is trying to fill the gap. The energy conservation potential does not depend solely on the structure and the heating system, but also whether desired levels of the indoor environment are attained for each individual living pattern.

The scope of this paper is limited to the most common situation as experienced when conventional heating systems are installed. Heat pumps, solar energy and other alternative energy resources have been covered sufficiently by other publications, and their inclusion would cloud the present issue.

The lead times for the development of new appliances and systems to meet the requirements of future houses is relatively well known, typically three to five years. What should also be appreciated is that if the new appliances and systems are to be utilised most efficiently, a design procedure based on a thorough knowledge of the inter-action of all the relevant parameters will have to be developed and become generally accepted.

2. BACKGROUND

The need to save energy had led, amongst other energy conservation measures, to the adoption of higher insulation standards. The minimum insulation level of new houses is governed by the 1976 Building Regulations. Houses built to this standard show a significant drop in the design heat loss compared to previously built houses, typically for an average semi-detached house from 11 to 7 kW. Some houses now being built have better insulation levels than the legally required minimum. The design heat loss of a semi-detached house could be as low as 4 kW without extreme measures being taken, and it is likely that the trend will extend in the future. There are two factors that could contribute towards better insulation levels. The relative rise in fuel prices would obviously make insulation more cost effective and more severe building regulations reflecting national needs could impose mandatory levels. What is of interest is that better than minimum legally required insulation levels are already seen as a good selling point in the private sector. Insulation will change the dominant position of the heating load from accounting for over threequarters of the heat energy requirement of the dwelling to just under a half.

It is also likely that the typical house of the future will be different in other ways than in the degree of insulation that is applied, the changes being brought about by various soci-economic factors. As an example the projected household size distribution in 1986, as shown in Fig. 1, differs from the 1971 distribution mainly in the growth of single and two person households at the expense of larger units. Another significant trend is the expected rise in the number of employed married women illustrated in Fig. 2. The impact of such changes can be manifold. Probably a greater percentage of smaller dwellings are going to be built accentuating the drop in energy requirements caused by energy conservation measures and at the same time the period during the day when the house is unoccupied will be extended. It is then a question of which system, e.g. whether designed for intermittent heating, set-back or continuous heating, etc., will be the one that will overall best satisfy the occupant and consume the minimum of energy;

the answer is probably different for various combinations of type of system and house construction.

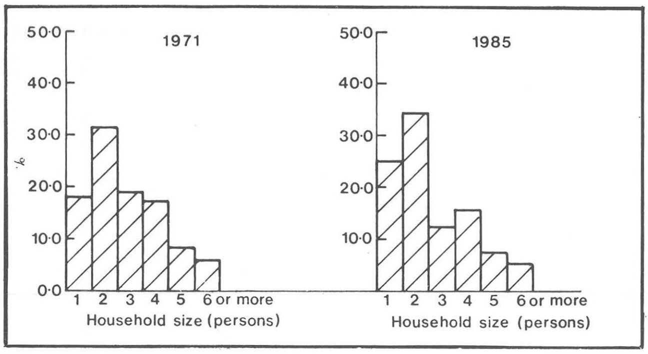

Figure 1

Projected change in size of households.

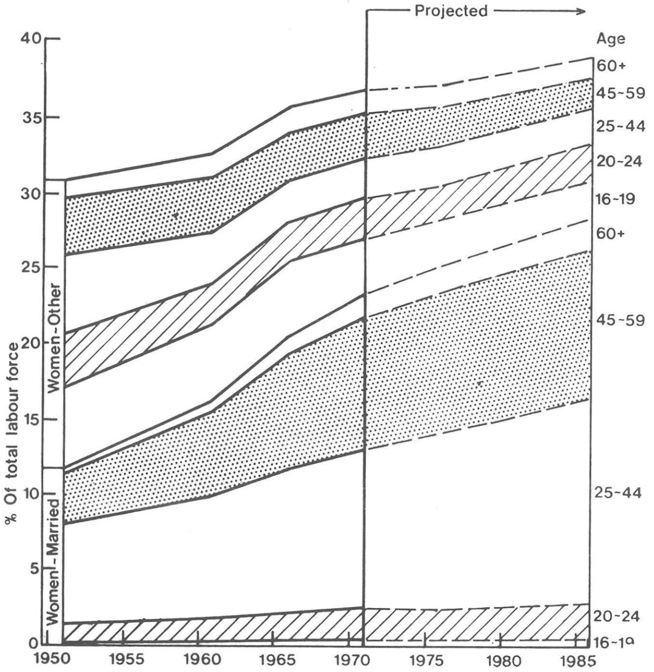

Figure 2

Distribution of economically active females by age and maritial status.

Only rarely can the heat services of a dwelling be designed for one particular living pattern, for normally during its lifetime the occupants would on the average have moved, or changes in the household, such as children growing up, would have occurred. As a result of projected demographic changes, houses for special categories will gain in importance. A change in the age structure of the population will require more suitable housing for the older age groups. Recent Medical Research Council findings[1] have shown that the older age groups are not sensitive to temperature changes of up to 3°C and therefore heating systems with special features may need to be designed to minimise the danger of hypothermia. The most likely approach would be to provide continuous heating and to use designs requiring a minimum of setting by the users.

Internal temperature, i.e. comfort levels of the house as a whole depend largely on the economic situation of the occupants who might be prepared to spend only a certain percentage of their income on fuel. This has been illustrated by the fact that when additional insulation is applied to houses a large part of the potential savings are used to raise the comfort levels. It can also be presumed that a high percentage of all occupants of new houses will have experienced central heating before, and as a consequence will be more discriminating. It is therefore probable that for all economic forecasts, except the extremely pessimistic, the comfort standard will either remain the same or possibly be higher.

The house that will be built in the future will reflect all the above mentioned trends and factors, but above all, will be influenced by monetary constraints both in the private and public sectors. In the near future, with the housing market depressed overall, the trend to concentrate on the smaller, usually terraced and deep plan, homes may continue, but with the expected upturn of our economic fortunes due to North Sea oil and gas becoming available in quantity (*circa* 1980), we may see a return to the building of more spacious accommodation ($80m^2$ plus) in greater numbers. The general consensus of the building industry is that no revolutionary changes in the methods of building houses are on the horizon, but the balance of construction methods may alter.

3. METHOD OF ANALYSIS

In order to analyse the performance of future well insulated housing, two probable construction methods were chosen — a conventional "heavyweight" and a timber framed "lightweight" construction and compared with a contemporary house. Subsequently for ease of identification the labels "heavyweight", "lightweight" and "contemporary" are used. The size, plan and glazed areas were a partial compromise with the contemporary house, as it is advantageous to have the same size and shape of the contemporary and future house in order to obtain a direct comparison of their performance. The insulation level of the contemporary house is based on current practice and conforms to the requirements of the Building Regulations[2]. The insulation levels of the two future houses are identical and are based on already available components.

The plan of the house and the details of the external wall construction are shown in Fig. 3, and the heat losses of the components and the overall heat loss as calculated according to the IHVE Guide Book A[3] are given in Table 1. The ventilation heat loss has been calculated with the help of a British Gas Corporation computer program[4] that takes into account the wind velocity, the stack effect, the configuration of the cracks and the background open areas.* During the daytime the internal doors were considered open and one window slightly open ($80cm^2$) to simulate observed living patters. Values of ventilation rates used in the thermodyanmic calculations include the air change caused by opening of windows and external doors during the day, and as design conditions are of primary interest, a wind direction giving the maximum air change rate was used. The air change rates provide a sufficient supply of fresh air[5] to satisfy ventilation requirements and the results of the study can therefore be applied to houses having a mechanical ventilation system. Lower ventilation rates, although from the energy conservation point of view are desirable, would in the majority of cases prove unacceptable to the occupants who would take action to restore tolerable levels.

As can be seen, in order to obtain some indication of how the structures are going to behave in a real-life situation, the emphasis in the choice of construction and insulation levels of the house has been on realism, for it is not the objective of this

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*Background open area is the open area of a room remaining after identifiable openings such as cracks around doors and windows and purpose provided openings have been sealed. The contribution of background open areas to the ventilation rate can be just as important as cracks around the doors and windows.

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*1955—1974 Heathrow

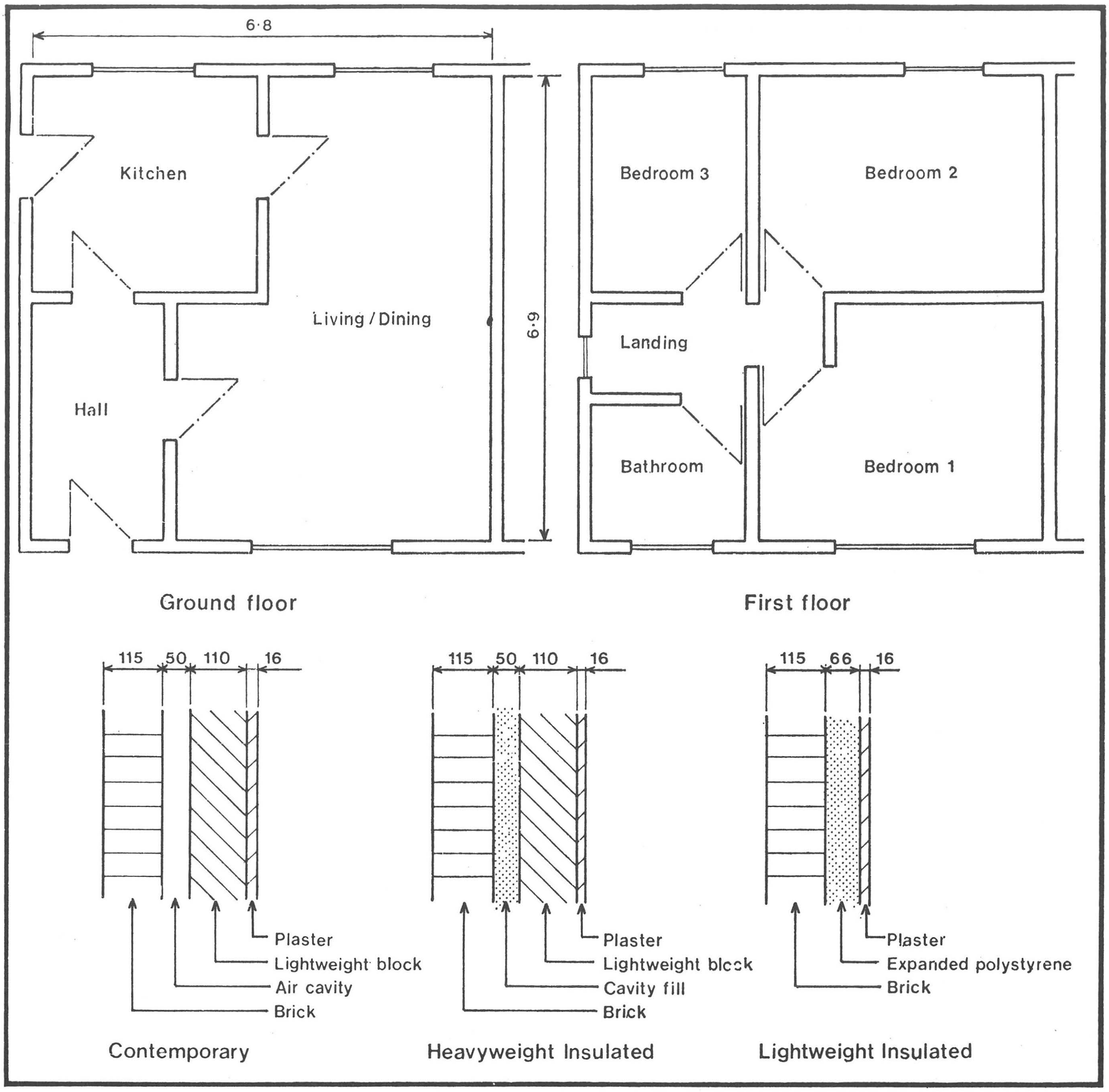

Figure 3

Plan and wall construction details of structures used in the computer study.

paper to explore the potential of extreme situations, for instance, a theoretical lightweight building or the ultra insulated structure having 200mm or more of insulation. In the real life approach one factor cannot be omitted — real weather. Although heating systems are designed on the basis of a steady state design heat loss, the external design temperature usually being $-1^{\circ}C$, such steady conditions in real life do not exist. It was therefore found necessary to postulate a 'design-day'. For this purpose all days over a 20 year period having a mean temperature of -0.5 to $-1.5^{\circ}C$ were analysed.* The parameters that were considered important were the temperature swing, hours of sunshine and wind velocity. As an example of how these variables interact a graph of hours of sunshine against temperature swing is shown in Fig. 4. As a result of the analysis, two typical design days — a cloudy and a clear day — were formulated and used in the computer analysis.

The computer program that has been used for the analysis had been developed on the basis of Rouvel's[6] work. The behaviour of all three structures:—

(a) contemporary house for reference,

(b) lightweight house of the future (timber frame),

(c) heavyweight house of the future (conventional),

are studied under various conditions. Days having a mean temperature of $-2^{\circ}C$, $-1^{\circ}C$, $+1^{\circ}C$, $+4.5^{\circ}C$, $+6.5^{\circ}C$, $+8.5^{\circ}C$ were analysed. A day having a mean temperature of $-1^{\circ}C$ represents a 'design day' and a day having a mean temperature of $+6.5^{\circ}C$ represents a 'typical' winter day. Both cloudy and clear days were used in conjunction with the above temperatures. Other parameters that were varied were continuous and intermittent heating modes and the available plant size ratio. Some investigations were carried out into the influence a change in the ventilation rate would have on the minimum temperature to which the house would cool when heated intermittently and its influence on the warm-up time. The basic assumptions in the computations are summarised in Table 2. The assumptions made about the internal heat gains presented a problem. On the one hand it is generally predicted that the trend will be to have more labour-saving and leisure equipment in the home and it is sometimes presumed that they, on their own, will release enough heat to cover the heat loss of the house, but on the other hand some of these appliances are becoming more efficient. For example, it is commonly assumed that a colour television set releases up to 500–600W and statements are made that when it is switched on, a colour television set in the lounge covers one half of the heat losses, but the more recent models require only *circa* 90W input, the least efficient only 135W.

Over the past years energy consumed in the domestic sector has remained constant[7] even though standards and saturation levels of appliances have obviously risen. High efficiencies of domestic appliances have contributed to this trend and will probably continue to do so in the future. A significant reduction in the level of internal heat gains would result from a similar rise in the efficiency of domestic lighting to that experienced in the public and industrial field.

TABLE 1

HEAT LOSS OF CONTEMPORARY AND WELL INSULATED HOUSE

(House Plan Fig. 3)

		Contemporary		Insulated	
Element	Area (m^2)	'U' ($W/m^2 {}^\circ C$)	'UA' ($W/{}^\circ C$)	'U' ($W/m^2 {}^\circ C$)	'UA' ($W/{}^\circ C$)
Roof	46.6	0.50	23.3	0.30	14.0
Wall	83.8	0.89	74.6	0.40	33.5
Floor	46.6	0.69	32.2	0.45	21.0
Window	14.1	5.60	79.0	2.50	35.3
TOTAL			209.1		103.8
Fabric heat loss Qf		209.1 x 21 = 4391 W		103.8 x 21 = 2180 W	
Ventilation heat loss Qv					
Mean tai – tei =		2°C		1°C	
Mean ventilation allowance		0.33W/$m^2 {}^\circ C$		0.27W/$m^2 {}^\circ C$	
200 x 23 x 0.33 =		1518 W			
205 x 22 x 0.27 =				1217 W	
Total heat loss Q Qf + Qv =		5909 W		3397 W	

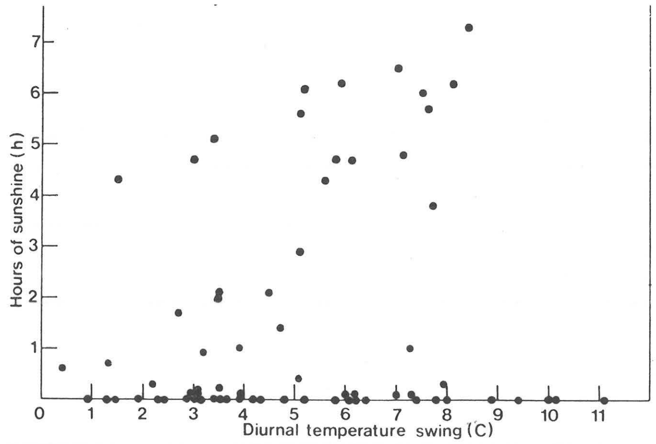

Figure 4

Diurnal temperature swing and hours of sunshine on design January days ($T_{mean} = -1^\circ C$).

TABLE 2

DETAILS OF HOUSE CONSTRUCTION AND SYSTEM OPERATION

(a) House Construction

Building Component	Contemporary (mm)	Insulated Heavyweight (mm)	Insulated Lightweight (mm)
Internal Wall:			
Plaster/Plasterboard	16	16	16
Lightweight Block	110	110	–
Air Gap	–	–	50
Plaster/Plasterboard	16	16	16
Internal Floors/ Ceiling:			
Plasterboard	10	10	10
Air Gap	50	50	50
Timber	20	20	20
Ground Floor:			
Carpet	10	10	10
Timber	–	20	20
Glass Fibre	–	25	25
Concrete	1000	1000	1000
Roof:			
Plasterboard	10	10	10
Glass Fibre	50	100	100
Tiles	10	10	10
External Wall:			
Plasterboard	16	16	16
Lightweight Block	110	110	–
Air Gap	50	–	–
Polystyrene	–	50	66
Brick	115	115	115

(b) System Operation

Occupancy: (i.e. time period when internal design temperatures should be maintained)	8.00–23.00 h
Internal design temperature:	20°C
Lights:	300 W
a.m. on	8.00 h
off	1 h after sunrise
p.m. on	1 h before sunset
off	23.00 h
Other heat gains: A weighted average of gains from people, domestic appliances, DHW, etc.	
Day	600 W
Night (All occupants presumed in house, 2 adults, 2 children)	667 W
Intermittent operation:	
Heating system on	6.00 h
off	23.00 h

Therefore the *total diurnal useful miscellaneous heat gains* are

3.6×10^{-3} (300 x 8) + (600 x 15) + (667 x 9) =	63 MJ/day
consisting of:	
DHW (170 1/day, 45°C rise, 0.6 of heat content as useful heat into house)	19 MJ/day
Occupants (2 adults, 2 children, average living pattern)	12 MJ/day
Cooking (22 MJ/day, 0.6 considered as useful)	14 MJ/day
Electricity (lighting, television, appliances)	18 MJ/day

The level of internal heat gains as given in Table 2 is based on current data[8] and therefore presumes that any wider use of appliances and equipment will be balanced by their higher efficiency. It is likely that the average useful miscellaneous heat gains (solar not included) of a future insulated house will be less that 750W, approximately half the value used in some publications[9, 10]. The largest discrepancy occurs in the estimate of the electricity used for lighting and other appliances. Preliminary results of Watson House field studies, where electricity consumption was measured during the heating season indicate a weekly usage of 35-70 kWh (126-252MJ). Although there is an overall scatter of two to one, the usage of individual households varies only slightly week to week. The upper value has also been quoted by Smith[11]. This paper is concerned with the performance of structures in design and typical winter conditions, and therefore the use of a value nearer the lower limit was considered necessary. In contrast a mean value would be appropriate for the estimate of annual energy requirements.

Although annual energy consumption figures can be sensitive to the magnitude of internal heat gains, our studies have shown that for design consideration they do not play an important part. A substantial increase of steady internal heat gains, e.g. from 250 W to 750 W will effect the plant sizing for intermittent heating of a well insulated house by only 10 per cent although the annual energy consumption will reduce by as much as 30 per cent.

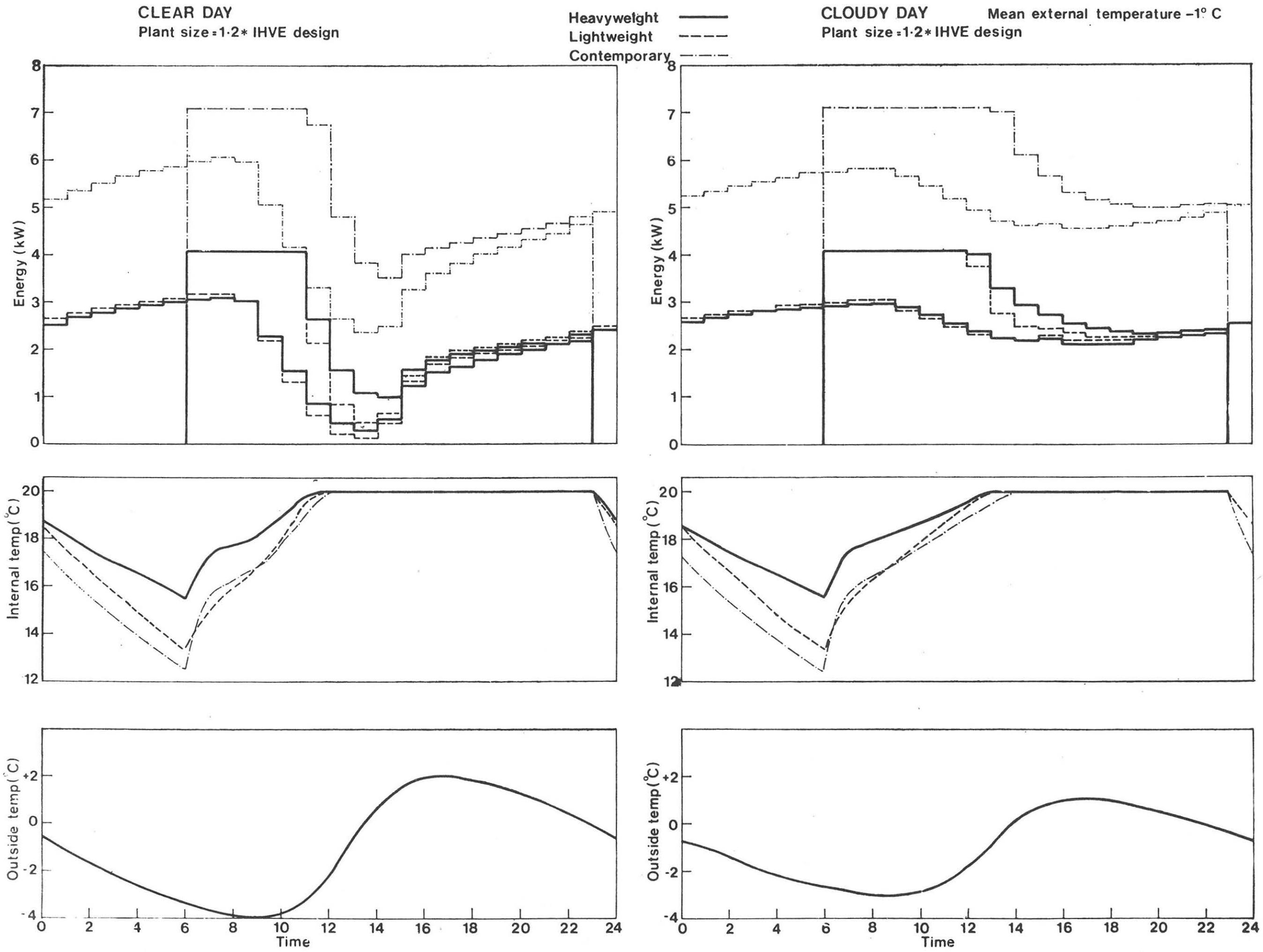

Figure 5

Energy consumptions and internal temperatures on clear and cloudy design days ($T_{mean} = -1^{\circ}C$).

4. DISCUSSION

4.1 Design Day

An extensive analysis has been carried out and the most relevant data selected. Fig. 5 shows the energy consumptions and the internal temperatures on a clear and cloudy design day for the three structures and two modes of operation – continuous and intermittent. The plant size ratio has been arrived at by adding 20 per cent to the calculated heat loss as recommended in the IHVE Guide Book A, Section A2, and in general is typical of the contemporary sizing procedure, and as further discussion shows, for the well insulated house, an alternative approach may be necessary.

The energy consumption for the design day is summarised in Table 3. Firstly, we can see that the total energy consumption has been halved by the application of extra insulation (446MJ down to 220MJ) (Col. 1) and secondly, the difference in percentage terms between the energy consumption on cloudy and clear days has nearly doubled from 100/88 (Col. 2/Col. 3) for the contemporary to 100/80 for the more insulated house, lightweight and heavyweight alike. The greater impact of solar gains reinforces the importance of orientation of houses as an energy saving measure, but the same phenomenon viewed from another angle could create control problems.

Maximum and minimum energy demands are summarised in Table 4. It is evident that when a house is better insulated, the minimum demand as a ratio of the maximum, i.e. the output of a correctly sized boiler, has diminished moderately for continuous operation on cloudy days (0.78 down to 0.73) (Col. 3/Col. 2) but severely on clear days (0.38 down to 0.05). The results for intermittent operation are somewhat less sensitive. The above values are for the average whole house, the problem will, however be more severe for individual rooms, as illustrated in Fig. 6, where overheating occurs in a south facing room of a well insulated house even on a clear January day. In practice, the case for individual room control or at least North – South zoning will be greatly strengthened and a system capable of transporting heat from one room to another should show an annual running cost advantage and increased comfort for the occupants.

TABLE 3

Total Absolute and Relative Energy Requirement of Well Insulated and Contemporary Structures on Clear and Cloudy Design Days ($T_{\text{mean}} = -1^{\circ}C$) Heated Continuously and Intermittently

(Plant Size Ratio 1:2)

Type of Structure	Consumption (MJ)	Continuous (per cent)		Intermittent (per cent)	
		Cloud	Clear	Cloud	Clear
Column	1	2	3	4	5
Contemporary	446 (= 100 per cent)	100	88.3	84.5	73.0
Lightweight Insulated	220 (= 100 per cent)	100	80.4	85.2	66.0
Heavyweight Insulated	220 (= 100 per cent)	99.5	80.5	88.6	69.5

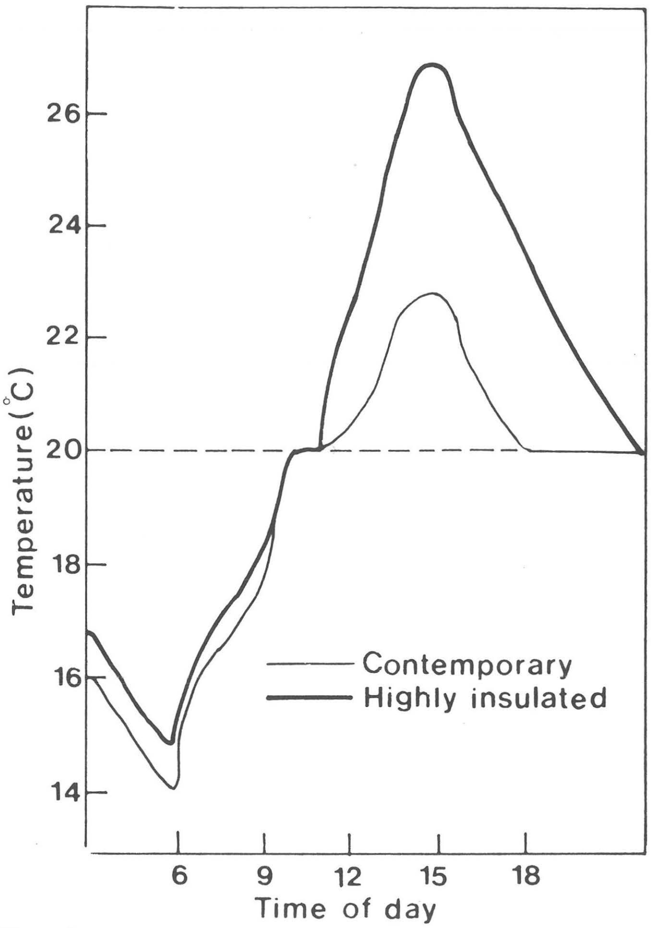

Figure 6

Temperature in a south facing room on a clear January day.

Table 3 also shows that there is very little difference between the energy requirements of lightweight and heavyweight insulated structures, the greatest difference being for the clear design days and intermittent operation. There is a significant difference between the energy requirements of the two modes of operation, continuous and intermittent, but it is not possible to interpret these results qualitatively. Graphs in Fig. 5 indicate that for intermittent heating, the design temperature has not been reached at the beginning of the occupied period (08.00h) and therefore if a true comparison were to be made the pre-heat period would have to start earlier resulting in a higher energy requirement.

From the design point of view the most important question is whether the heating system, sized in accordance with the currently accepted design philosophy (heat loss plus 20 per cent), performs adequately on a design day. For continuous heating (Fig. 5) the design internal temperature during the specified period is achieved. Performance of continuously operated systems on colder than design days was also investigated. Results for a day having a mean temperature of $-2^{\circ}C$ show that the design internal temperature is maintained and even colder days would probably present no problems. When operated intermittently and exposed to outside design conditions, all three structures require approximately 6h of pre-heat to reach design temperature. Results of computer calculations using other plant size ratios are plotted in Fig. 7.

TABLE 4

Absolute and Relative Maximum and Minimum Energy Demands of Well Insulated and Contemporary Structures on Clear and Cloudy Design Days ($T_{\text{mean}} = -1^{\circ}C$) Heated Continuously and Intermittently.

Plant Size Ratio 1:2

Type of Structure	Design Heat Loss x 1.2 (W)	Continuous (per cent)				Intermittent (per cent)			
		Cloudy		Clear		Cloudy		Clear	
		Max	Min	Max	Min	Max	Min	Max	Min
Column	1	2	3	4	5	6	7	8	9
Contemporary	7116 (= 100 per cent)	82.2	64.1	85	33	100	70.2	100	49.1
Lightweight Insulated	4100 (= 100 per cent)	73.6	53.2	76.8	3.7	100	53.5	100	11.2
Heavyweight Insulated	4100 (= 100 per cent)	73.2	53.7	76.3	7.6	100	57.2	100	25.9

It is clear that to achieve short warm-up times on a design day plant size ratios of 2 or even 3 would be required. The cost of a wet central heating system designed on the basis of these plant size ratios would be in the order of 10-40 per cent higher than those sized to heat loss plus 20 per cent. In monetary terms at current prices this could put up to £200 on to the initial cost of a wet central heating system. Annual running costs could be adversely affected by high plant size ratios if unsuitable boilers or appliances were used. Boilers and appliances having low part load efficiencies would suffer the most, as they have to operate predominantly in this region, and therefore should not be recommended when a high degree of intermittent operation and high plant size ratios is required.

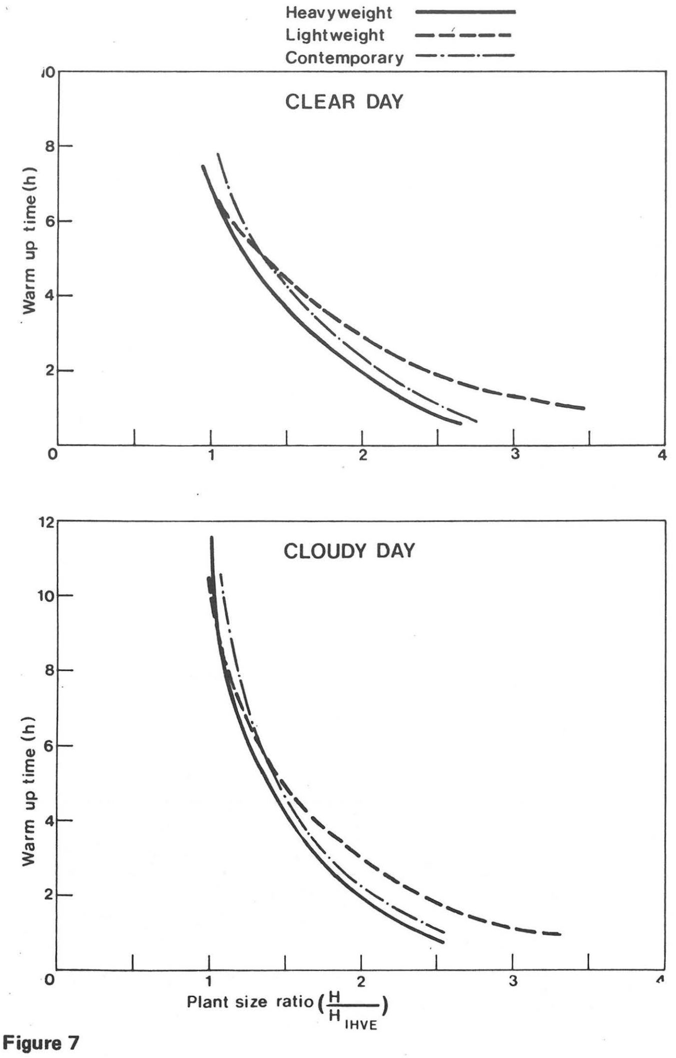

Figure 7

Change of warm-up time with plant size ratio on clear and cloudy design days.

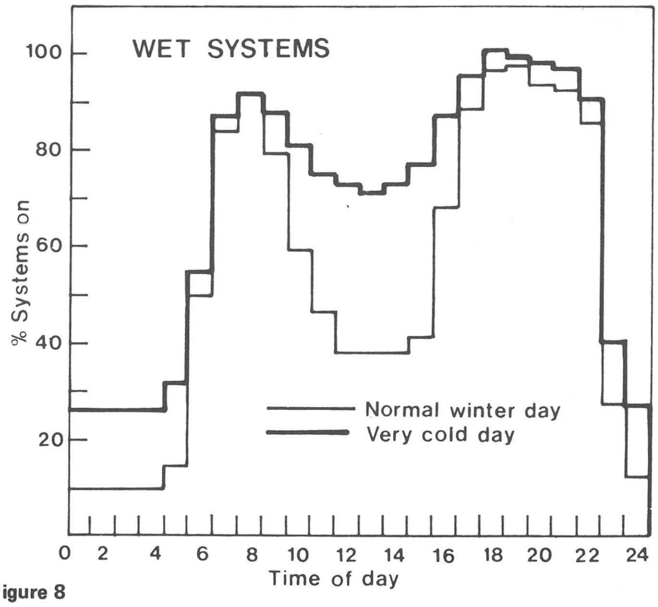

Figure 8

Use of wet central heating systems.

Predictably, the lightweight structure cools down overnight more than the heavyweight version and it is a question whether the minimum internal temperatures achieved at the end of the overnight cooling period of the lightweight structure are acceptable. It can be argued that in the morning lower temperatures can be tolerated because of the higher activity levels of the occupants (housewife) and there are indications that many systems tend to be used in this way (see Fig. 8), even on cold winter days.

It is of interest that the lightweight insulated structure has

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$$*\text{Thermal weight} \approx \frac{\text{Thermal admittance}}{\text{Thermal transmittance}} \approx \frac{\Sigma AY + Cv}{\Sigma AU + Cv} = \frac{1}{Po}$$

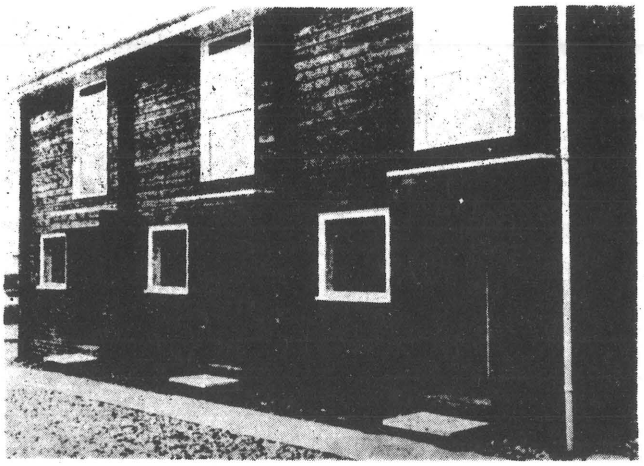

Figure 9

BGC test houses.

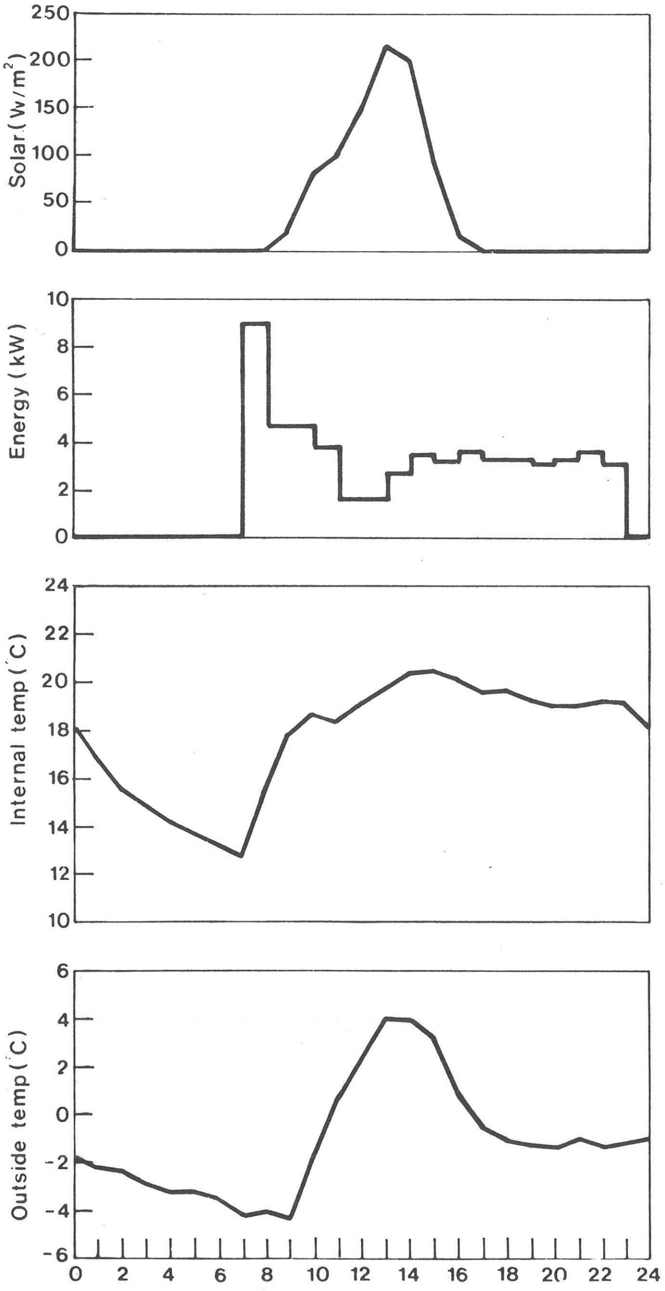

Figure 10

Energy consumption and internal temperature on a cold winter day in BGC test house.

approximately the same cooling characteristics as the rather heavyweight contemporary structure, the heavyweight insulated structure cooling down far less.

The sequence of cooling curves in Fig. 5 is in agreement with the 'thermal weight'[12] (or 1/Po[13]) values* of these structures. The values of thermal weight are 5.2 for the contemporary structure, 6.2 for the lightweight and 8.7 for the heavyweight insulated structures. These values also indicate that when the insulation level is increased the structure will behave in a more heavyweight manner. Thermal weight effects may offer a partial explanation of the sequence of curves in Fig. 7 showing that it is the lightweight insulated structure that required a longer pre-heat period for a given plant size ratio than the heavyweight structure, which is contrary to what would be generally expected. To explain this phenomenon in detail would require a modified computer program, capable of giving wall temperature profiles at much shorter intervals than the present one hour. One possible explanation would be, as the internal room temperature has a radiant temperature component, that the rather heavier inside partitions have retained a relatively high core temperature and therefore need a shorter time to reach acceptable surface temperatures, the whole wall heating up to equilibrium during the day as the higher daytime energy consumption would indicate.

An alternative to large plant size ratios would be the use of a setback. The cooling and heating curves indicate that for a warm-up period of *circa* two hours a set-back of 2°C would be required. The use of a setback will be included in the next phase of our research programme at Watson House.

4.2 EXPERIMENTAL RESULTS

To obtain experimental data on the performance of heat services in small well insulated dwellings, a row of three unoccupied test houses have been built by the British Gas Corporation in London (Fig. 9). Construction of the houses is almost identical to that of the heavyweight version of the future house used in the computer simulations except that the windows are only single glazed. The fabric design heat loss of the middle terrace house is 102 W/°C and the end of terrace 147 W/°C. First experimental results have been collected in this heating season but for a full set of data sufficient for a full set of data sufficient for a statistical analysis, a further heating season will be required.

To illustrate the results that are being obtained, a cold sunny day has been selected and the hourly energy demand, internal and external temperature and solar radiation on the horizontal surface plotted in Fig. 10. An end of terrace house has been chosen to enable a comparison with the computer program results to be made. The house is heated by a wet central heating system controlled by a room thermostat in the south facing lounge and radiators in other rooms are equipped with thermostatic radiator valves.

As had been mentioned, more data is required before a thorough analysis can be made. Nevertheless some deductions from the results gathered so far can be made. Probably all but the most sophisticated heating systems installed in test houses will show deviations in performance from computer simulation predictions. The mean internal temperature for the test shown in Fig. 10 is not steady throughout the day but fluctuates by ± 1°C. The warm-up time indicated by the temperature and energy requirement curves is approximately three hours. Computer simulation curves in Fig. 7 for the heavyweight structure show that to achieve a 3-hour warm-up time a plant size ratio of 1:6 is required. This is in good agreement with a plant size ratio based on a 3-hour mean energy input of p = 1.54 for the test house result, even though in the first hour the effective plant size ratio is as high as p = 2.3. The apparently increased plant size ratio is in all probability due to the ability of the radiators, operating in conjunction with an oversized boiler, to dissipate more heat at start-up from cold.

TABLE 5

Available Energy for Heating of Domestic Hot Water on a Cloudy Design Day ($T_{\text{mean}} = -1^\circ$C) and Continuous Heating

Type of Structure	Plant Size Ratio	24 Hour Capacity (MJ)	24 Hour Structure Energy Requirement (MJ)	Energy Available For DHW (MJ) Col (2) – Col. 3
Column	1	2	3	4
Contem-porary	1 1.2	511 613	446 446	65 167
Light-weight Insulated	1 1.2	294 613	220 446	74 167
Heavy-weight Insulated	1 1.2	294 352	219 219	75 133

In conclusion, experience so far shows that test house measurements of actual systems are necessary, although more sophisticated computer simulation techniques taking into account systems behaviour could reduce the range of tests significantly.

4.3 ENERGY FOR DOMESTIC HOT WATER

Due to internal and solar heat gains, the plant capacity is not fully utilised on a design day even where the system is operated continuously and no additions are made to the calculated heat requirement, i.e. the plant size ratio is p = 1. Table 5 in the last column gives the surplus heat available over a 24-hour period on a cloudy design day that could be utilised to heat domestic hot water. Billington[14] has suggested that there is no need to add extra plant capacity for the heating of domestic hot water and the figures in Table 5 give some support to this thesis. The figures indicate that in the insulated house the available energy is sufficient to generate enough hot water for *circa* 5 to 9 persons depending on the plant size ratio. This statement is based on an average consumption of 45 1 per person per day and an overall efficiency for winter operation in the region of 70 per cent. Although the capacity is there, to utilise it would possibly require a larger hot water cylinder than is standard practice. Some severe draw-off patterns require short recovery times and the available spare capacity of only 1.5kW in the afternoon and evening on a cloudy day (see Fig. 5) coupled with a small cylinder would probably not be equal to the task. For intermittent heating and the same plant size ratio of 1:2., the afternoon and evening situation is somewhat worse but there is an advantage of having more than enough

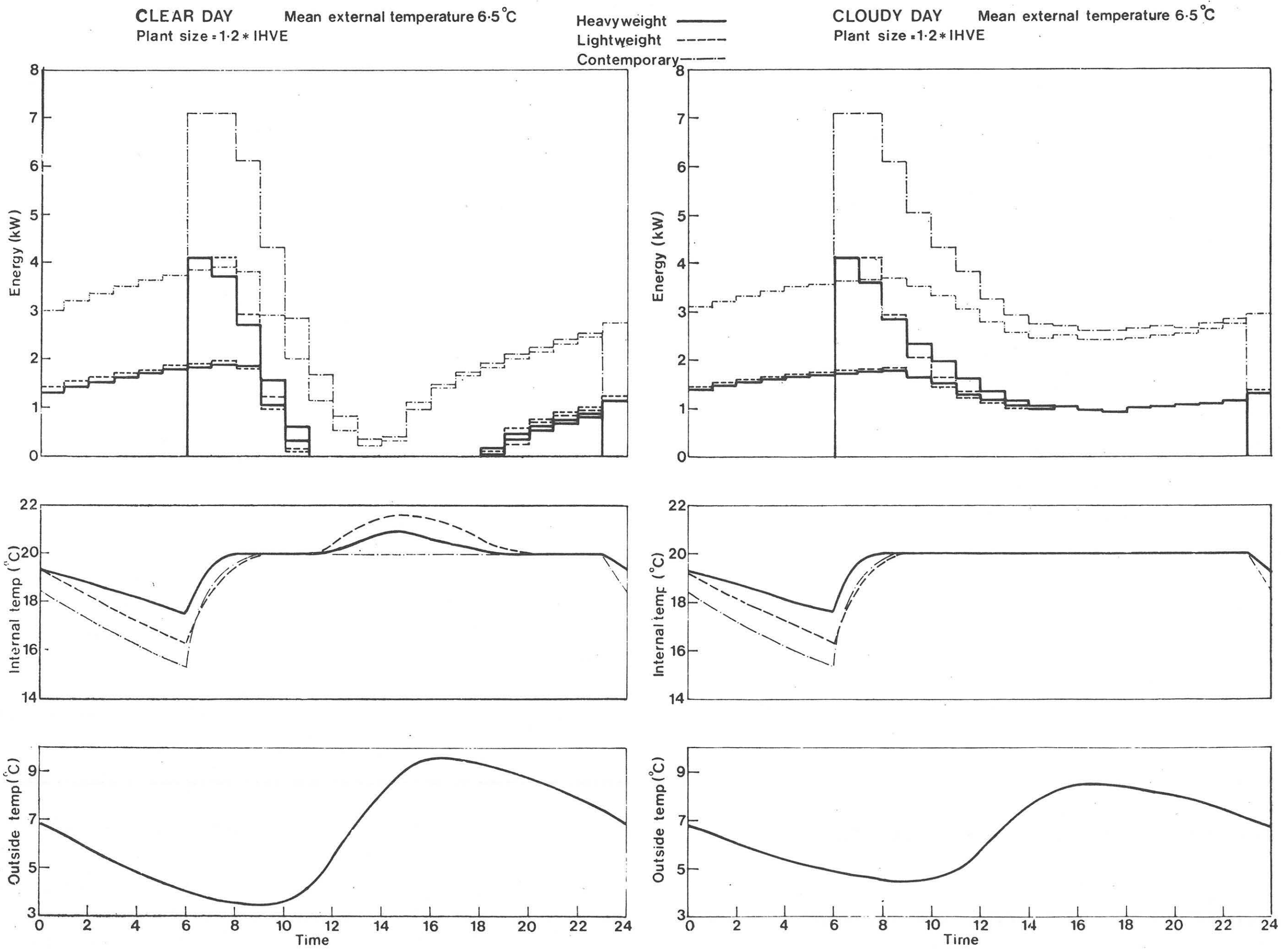

Figure 11

Energy consumption and internal temperatures on a clear and cloudy typical winter day ($T_{\text{mean}} = -1^\circ$C).

spare capacity during the night. (The boiler could be brought on say 1 hour before heating is required). Whether the above approach could be better than current practice will depend on the detailed costing of the cylinder, controls and the boiler and its efficiency characteristic.

4.4 TYPICAL WINTER DAY

Although the heat services are designed to meet requirements for a specified extreme condition, i.e. a design day, for most of the time they will be operating in much milder climatic conditions. The heating requirements on a typical winter day, having a mean external temperature of +6.5°C are shown in Fig. 11.

TABLE 6

Energy Requirements on a Typical Winter Day (+ 6.5°C) as a Percentage of Design Day Requirements. Intermittent Mode of Operation. Plant Size Ratio 1.2

Type of Structure	Day	Per cent
Traditional	Clear	52
	Cloudy	60
Lightweight Insulated	Clear	40
	Cloudy	53
Heavyweight Insulated	Clear	38
	Cloudy	53

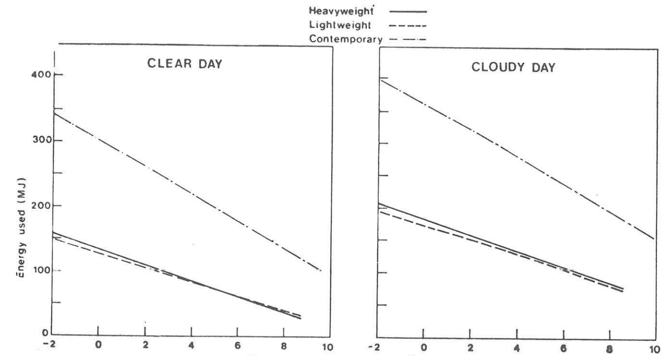

Figure 12

Effect of external temperature on energy consumption. Intermittent Operation. Plant Size Ratio p = 1.2.

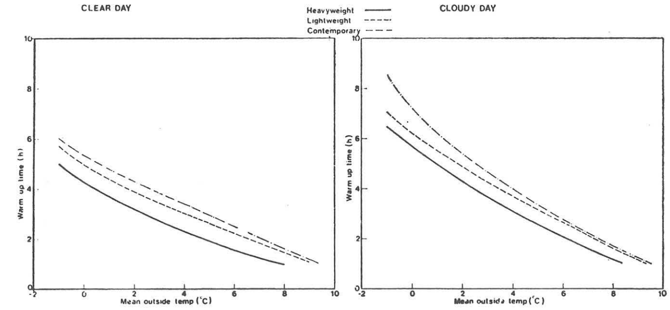

Figure 13

Effect of external temperature on warm-up time. (Plant Size Ratio p = 1.2.)

What is notable is that on a typical clear winter day the better insulated structures do not require any heat input for a significant period and the internal temperature of the house as a whole rises above design. Some confirmation of this has been obtained from experimental test house studies. The rise is higher for the lightweight structure (2°C) than for the more heavyweight version (1°C), which probably explains the results in Table 6 where energy requirements of all three types of structure as a percentage of the design day requirements for intermittent heating are given. As expected the insulated structures show a smaller percentage requirement than the traditional structure. What is of interest is that the heavyweight structure is more efficient on clear days than the lightweight version (38 against 40 per cent). This trend is confirmed by the graph in Fig. 12 where results of computer calculations for other temperatures have been plotted. From the energy conservation point of view, this result is of importance as it illustrates that the more heavyweight building, even when the heating system is operated intermittently, can use less energy under its most frequent operational conditions.

How the pre-heating period or warm-up time varies with mean diurnal temperature is shown in Fig. 13. The trend for the heavyweight house to reach design temperature more quickly is present over the whole temperature range, although for the higher external temperatures the difference is not so pronounced. The graph in Fig. 13 is useful in determining the mean external temperature at which the warm-up period will be equal to or less than specified. If, for example, we would require the house to warm-up in two hours time, it would be possible to switch to intermittent operation at a mean diurnal temperature of approximately + 7°C for systems oversized by 20 per cent.

4.5 DESIGN CRITERIA

All the previous analysis has shown that a realistic well insulated dwelling, whether heavyweight or lightweight, behaves basically in a heavyweight manner and that systems sized according to present practice, when continuous heating is employed, are capable of maintaining design temperatures at sub-design conditions. Even when operated intermittently, even the heavyweight structure would probably maintain acceptable conditions. The lightweight structure would require preferably a night set-back instead of a complete shut down of the heating system. Based on this conclusion after an extensive study of the behaviour of insulated structures over a succession of cold days, it should be possible to re-define the external design temperature.

The heavyweight characteristic, and its resultant thermal flywheel effect, may enable the insulated house to perform successfully on the first or possibly even the second and third day of a sub-design cold spell. It might therefore be possible either to raise the design day temperature while keeping the same annual failure rate, or to lower the failure rate (i.e. percentage of time when the system would not attain design temperature). Such decisions would have to be based on what is acceptable to the customer. To illustrate the possibilities, Table 7 contains a frequency distribution of days having a lower mean diurnal temperature than −1°C and +1°C over a period of 20 years. The 20 year period contains the cold winter of 1963 when most of the very long spells occurred. The consequence of raising the external design temperature from −1°C to +1°C is to treble the number of colder than design days from 112 to 334 for the 20 year period (or from 5.6 to 16.7 days per annum). For the failure rate to remain the same (5.6 per annum) the structure would have to cope with a 6-day cold spell. If a degree of failure on 10 days per annum (4.5 per cent of days in a heating season on average) were acceptable, the structure would have to attenuate a 3-day

TABLE 7

Frequency of Distribution of Days Having a Lower Mean Diurnal Temperature than –1°C and +1°C Over a Period of 20 Years (1955 – 1974 at Heathrow)

Length of run of days having a mean temperature less than specified	Frequency of occurrance of length of run of days having a mean temperature less than		Number of days involved	
	–1°C	+1°C	–1°C	+1°C
1	20	36	20	36
2	10	25	20	50
3	9	13	27	39
4	2	13	8	52
5	4	5	20	25
6	0	5	0	30
7	1	4	7	28
8	0	1	0	8
9	0	2	0	18
10	1	0	10	0
11	0	0	0	0
12	0	0	0	0
13	0	1	0	13
14	0	1	0	14
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
19	0	0	0	0
20	0	0	0	0
21	0	1	0	21
TOTAL			112	334

cold spell. Continuous heating and the probability of solar gains on at least some days of a cold spell may enable even a better performance to be achieved. Continuous heating is recommended[12] for structures where the thermal weight ratio exceeds 10 and the heavyweight version of the insulated house approaches this value (8:7).

Any revision of the design philosophy would have to be based on a detailed study of the thermodynamic characteristics of structures and at the same time a consensus would have to emerge on the acceptable failure rate. The degree of failure, which in many cases may be marginal, must be balanced against savings in installation and running costs.

5. CONCLUSIONS

The general conclusions of this paper are that it is important to use realistic structures and real weather in the study of the behaviour of well insulated future houses as the answers could differ from the results of theoretical studies usually focussed on the optimisation of one parameter. Living patterns affected by socio-economic factors could be equally important as the structure and climatic conditions in the sizing of heat services. Miscellaneous internal heat gains may not be as high as linear extrapolation would predict because of the trend towards more efficient domestic equipment and possibly lighting.

The specific conslusions of this computer analysis are that realistic well insulated structures in real weather conditions tend on the whole to behave in a heavyweight manner, are sensitive to solar radiation (possible control problems) and not very sensitive to internal heat gains. When the mode of operations of the heating system is intermittent, the preheat period to reach specified internal temperatures at external design conditions is rather long, typically six hours. A shortening of the warm-up time would require large plant size ratios resulting in higher capital costs. An alternative could be the acceptance of low comfort levels in the pre-heat period. The relative advantages of realistic heavyweight versus lightweight structures are not clearly defined even for intermittent operation, the heavyweight structure surprisingly performing better in milder weather and having a shorter warm-up time.

Even on cloudy design days a conventionally designed system would have, over a 24-hour period sufficient spare capacity to heat the domestic hot water without any additional extra capacity being added for this purpose, but it is questionable whether such a system would be cost effective (extra cost of a larger hot water cylinder).

Due to the heavyweight characteristics of the insulated house it should be possible to re-define design specifications, but further studies using more sophisticated techniques are required. Further research is also required into the impact of various living patterns and modes of operation on the sizing and performance of systems and structures.

ACKNOWLEDGEMENTS

The author would like to record his appreciation of the contribution made by colleagues at Watson House to the progress of the work described in this paper, namely Mr. S. L. Pimbert, Mr. E. R. Hitchin, Mr. P. Phillips and Mr. R. Foster, and to thank the British Gas Corporation for permission to publish it.

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An "Example Year" for the calculation of energy demand in buildings

by M.J. Holmes, BSc, ACGI, and E.R. Hitchin, BSc, C.Eng., MCIBS, M.I.Gas E.

1 INTRODUCTION

The current concern with energy consumption of existing and proposed buildings is generating a family of design and investigatory methods often supported by computer programmes, that take account of the reaction of the building and its heating and cooling systems to outdoor conditions as they vary with time.

This makes it desirable to have some agreed sample of weather to allow contrast and comparison between various methods for predicting building and system behaviour, and between individual design cases to be on a common basis.

The proposals below although evolved from work in the authors' establishments have been discussed more widely and they have the support of the Electricity Council, National Coal Board, British Gas Corporation and Building Services Research and Information Association. The proposals are published to make them available more widely and thus fulfill their objective of eliminating one of the obstacles to easy comparison of information from diverse sources.

2 RECOMMENDATION

It is recommended that the year October 1964 – *September* 1965 *is selected as an example year for comparitive energy demand calculations.*
If a calendar year is essential, it should be 1967.

These recommendations are for weather at Kew, hourly data for which is readily available from the Meteorological office. No recommendation is made for other sites.

The example year is not intended to be used for peak load sizing but to be an arbitary but not too abnormal benchmark by which energy demands can be compared.

3 PRINCIPLE OF SELECTION

It seems self-evident that the proper unit of time for the present purpose is one year – weather conditions occur on an annual cycle and this is also the normal unit of time for accounting purposes. It may, of course, be possible sometimes to ignore part of the year – for example, when considering heating demands the summer months are usually unimportant. On the other hand, no single year can include all variations in climate and to establish mean consumptions it is necessary to use a number of years. Computing costs mean that this approach will be rarely used and so the requirement is for an *example year* of readily available meteorological data. The first decision is whether to choose an actual year's data, or to synthesise a "reference year" from individual days, weeks or months. The latter approach should, in theory, be able to produce a better statistical representation of the past, but is very difficult to realise[1]. With an historical year, selection becomes a matter of choosing the least abnormal year from those for which data are available.

The use of an actual year from the past preserves the inter-relationships between climatic elements and permits retrospective inspection of secondary elements such as rainfall, if this should prove desirable.

No example year can accurately predict the future and agreement by different workers to use the same year is probably more important than the fine detail of the year selected. Clearly the year selected should not include extremes which may unreasonably favour one type of plant, building or fuel supply.

While a 12 month period is logical, it is not obvious that this should begin in January. An October–September year for example will not have a discontinuity in the middle of the heating season.

An initial unpublished survey by Holmes based on eliminating years containing extremes of dry bulb temperature, solar radiation and rainfall etc., covering the years 1937–1973 suggested that the calendar years 1970 to 1971 could be satisfactory. Further analysis by Hitchin suggested that 1971 was the more suitable of the two. The data employed were however rather restricted and it was decided to base the selection on monthly averages rather than annual maxima and minima and averages. It is, however, interesting to note that if the ASHRAE[2] selection method, based on temperature alone, is employed then 1971 appears to be a suitable calendar year.

The variables considered in the final method adopted were monthly averages of: dry bulb temperature, solar radiation and windspeed. Data for Kew alone were studied, as the Meteorological Office has produced a magnetic tape containing ten years of hourly recordings for this site, copies of which were already owned by several computer-program owners (similar tapes exist for other sites, but these are remote from centres of population).

Selection involved studying the years 1956–1975 and first eliminating the years which contained any monthly mean which varied more than two standard deviations from the long term mean for this month. (This is almost the same as carrying out Students 't' test on the monthly means and rejecting those with less than 5 per cent probability of being random variations). For this exercise wind speed and temperature were combined to produce an infiltration variable, equal to wind speed x (18°C – mean monthly temperature). (Analogous to Jackman's[3] "wind-temp number".) This reduced the number of years to three in the case of the calendar year and six for the October–September year. Similar examination of monthly means of diffuse radiation, and degree days and excluding any years outside the period 1959–68 i.e. years not contained on the ten year tape, suggested the following example years:

Calendar year	1962 or 1967
October–September year	1964/65 or 1966/67

The main difference between 1964/65 and 1966/67 is that the winter temperatures (and therefore degree-days) of the former are a considerably better fit to the long-term averages and so 1964–65 is proposed as the example non-calendar year. Of the calendar years, 1967 has the smaller deviation in temperature from the long-term means and is preferred to 1962.

The data used for the analyses are from Meteorological Office Annual Weather Summaries for Kew, except for degree-days which are from Gas Council monthly degree-day reports for "Thames Valley".

4 THE YEARS

Table 1 shows the principle monthly mean values and their standard deviations for 1956–75. Table 2 lists the corresponding monthly means for 1964/65 and 1967. Figs. 1–4 show how the monthly mean values of dry bulb temperatures and total solar radiation compare with the long term means and standard deviations.

TABLE 1

Summary of Monthly Mean Values, 1956–75

	Windspeed m/s		Air Temperature °C		Total Solar Radiation (Horiz) W/m²		Diffuse Solar Radiation (Horiz) W/m²		Degree-days (base 15.6°C) °C day	
	mean	sd.	mean	sd.	mean	sd.	mean	sd.	mean	sd.
Jan.	4.22	0.77	4.9	1.8	24.5	2.4	17.9	3.5	339	53
Feb.	4.27	0.67	5.0	2.1	45.8	6.7	29.9	3.0	309	60
Mar.	4.32	0.57	6.8	1.6	90.2	15.0	51.3	5.8	281	51
Apr.	4.27	0.41	9.1	0.9	131.4	13.8	77.0	5.5	201	29
May	3.96	0.51	12.5	1.1	183.8	14.7	101.7	6.2	117	26
June	3.66	0.36	15.7	1.2	206.8	24.9	107.4	6.5	48	16
July	3.40	0.62	17.4	1.0	183.9	18.8	108.1	8.0	26	9
Aug.	3.35	0.57	17.0	1.1	156.5	15.3	89.5	5.4	30	9
Sept.	3.29	0.57	14.8	1.0	116.9	14.4	64.3	3.4	61	23
Oct.	3.29	0.51	11.6	1.3	68.9	7.1	38.7	3.0	135	37
Nov.	3.81	0.62	7.4	1.0	33.7	4.9	21.3	3.1	253	30
Dec.	4.17	0.82	5.5	1.5	19.7	3.1	13.9	1.8	321	46

N.B. — Standard deviations are for variations of monthly mean values between years.

TABLE 2

Summary of Proposed Example Years

	Windspeed m/s		Air Temperature °C		Total Solar Radiation (Horiz) W/m²		Diffuse Solar Radiation (Horiz) W/m²		Degree-days (base 15.6°C) °C day	
	1964/5	1967	1964/5	1967	1964/5	1967	1964/5	1967	1964/5	1967
Jan.	5.30	3.81	4.6	5.3	27.4	28.7	18.5	19.3	348	320
Feb.	4.27	4.94	4.0	6.6	39.4	52.7	33.0	33.2	326	257
Mar.	4.58	5.30	6.7	8.2	99.5	110.6	49.7	58.4	279	228
Apr.	4.22	4.63	9.4	8.6	141.6	132.3	78.7	77.8	185	212
May	4.27	4.58	13.1	11.9	192.4	169.0	104.1	99.0	97	124
June	3.86	3.55	15.5	15.5	206.7	202.6	110.7	109.7	42	48
July	4.02	3.40	15.8	18.9	159.6	214.0	109.6	112.5	34	13
Aug.	3.45	2.88	16.6	17.3	162.9	166.0	92.5	91.6	29	22
Sept.	3.45	3.35	13.3	14.9	112.7	102.3	63.3	64.0	83	46
Oct.	2.99	4.58	9.6	12.1	75.6	74.4	40.2	37.5	191	113
Nov.	3.91	2.93	8.9	6.5	29.6	21.8	20.8	23.3	295	276
Dec.	5.20	3.29	4.9	5.0	19.8	23.3	13.5	15.9	339	331

Table 3 compares the deviations of the two years from the long-term means. The non-calendar year seems to be slightly preferable unless annual windrun is considered of great importance. More importantly 1964/65 is clearly better for solar radiation and for annual degree-days and only slightly worse for dry bulb temperature. The table also shows deviations for the Danish reference year[4]. This is constructed of months taken from different historical years. It can be seen that the deviations of annual and monthly means are of a similar order to those of the proposed example years.

Hourly values of meteorological data for Kew for these years are available as part of a ten year (1959–68) record obtainable on magnetic tape from the Meteorological Office.

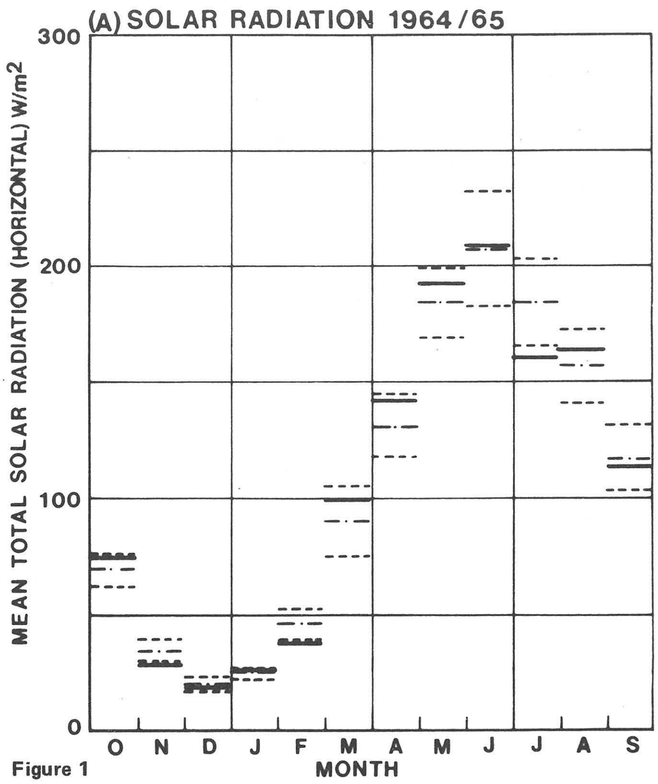

Figure 1

Temperature and solar radiation in proposed years — solar radiation 1964/5.

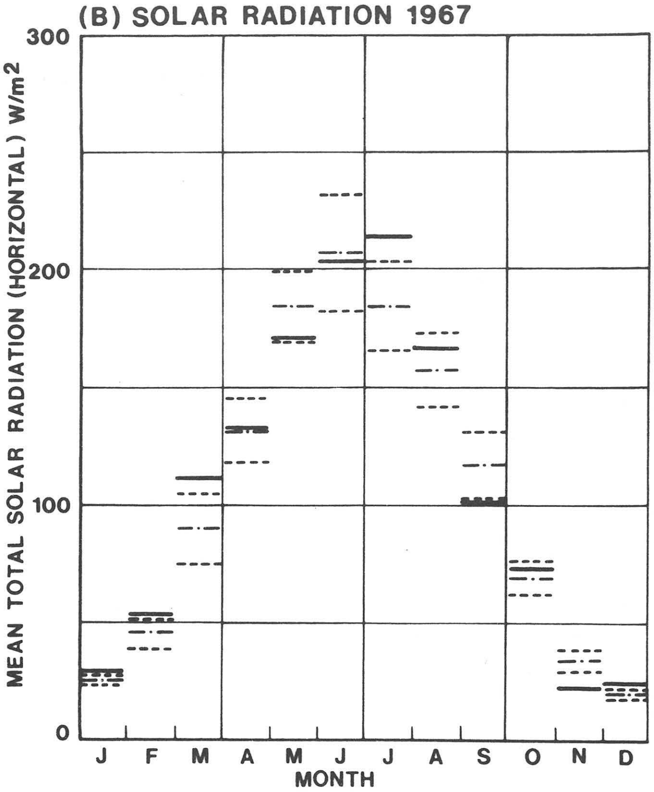

Figure 2

Solar radiation 1967.

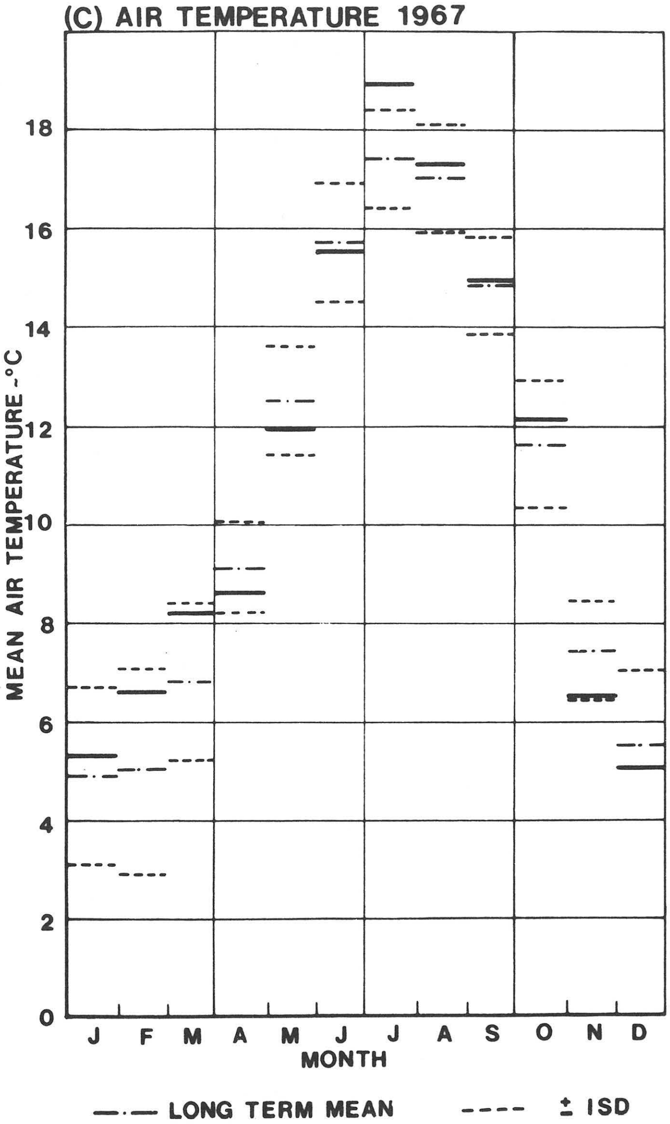

Figure 3

Air temperature 1967.

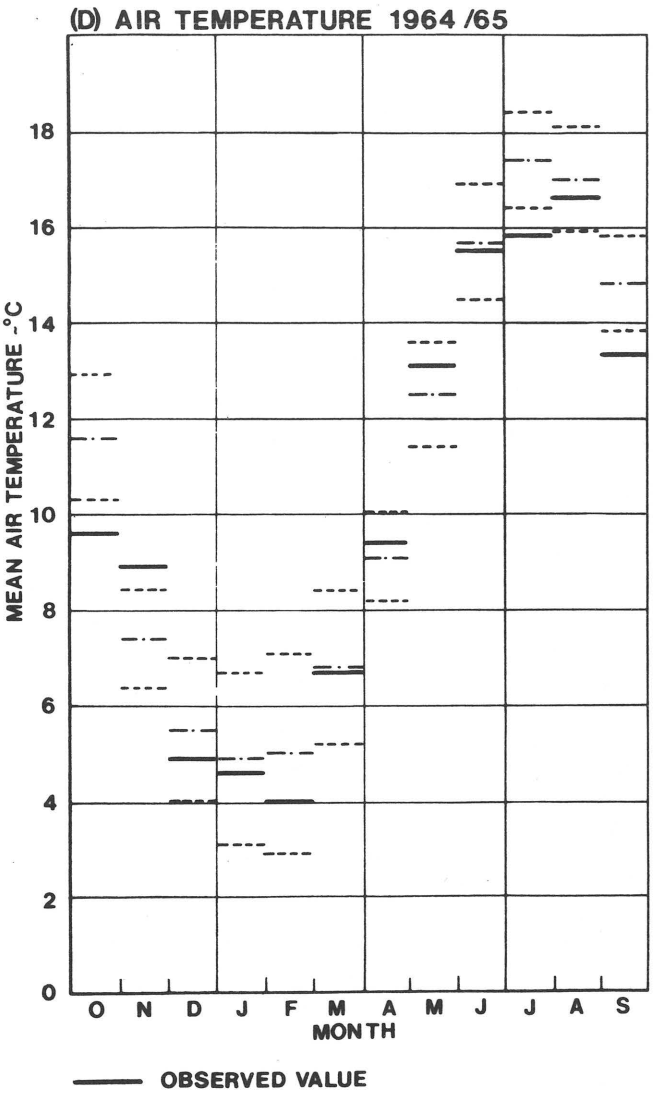

Figure 4

Air temperature 1964/5.

TABLE 3

Deviations from long-term means

Deviation	Oct 1964–Sept 1965	1967	Danish Reference Year
TEMPERATURE °C			
Annual mean deviation	0.4	0.3	0.1
Mean monthly deviation	0.8	0.7	0.6
Worst month	2.0	1.6	2.6
TOTAL SOLAR W/m^2			
Annual mean deviation	0.4	3.7	0.8
Mean monthly deviation	7.0	9.3	7.9
Worst month	24.3	30.2	14.4
DIFFUSE SOLAR W/m^2			
Annual mean deviation	1.1	1.5	–
Mean monthly deviation	1.7	2.2	–
Worst month	3.3	7.1	–
WIND SPEED m/s			
Annual mean deviation	0.3	0.1	–
Mean monthly deviation	0.4	0.6	–
Worst month	1.1	1.3	–
DEGREE-DAYS °C days			
Annual mean deviation	163	331	–
Mean monthly deviation	19	19	–
Worst month	56	53	–

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The sizing of heating systems for well-insulated houses

by E.R. Hitchin B.Sc., C.Eng., M.C.I.B.S., M.I.Gas E.

SUMMARY

Because the balance between factors influencing the sizing of heating systems is altered in well-insulated houses, it may be necessary to move away from conventional sizing procedures. The cost-effectiveness (in the UK) of modes of operation other than traditional intermittent operation is explored. A possible new form of sizing procedure is put forward.

INTRODUCTION

The recently increased concern with energy conservation has led to a greater use of insulation in both new and existing houses. Although well-insulated houses do not incur in principle any fundamentally new sizing problems for heating system design, the balance between the various influencing factors is altered, and it may be necessary to move away from conventional methods of sizing to reflect this change. In particular, more attention than has previously been usual may need to be paid to the implications of intermittent heating, if an adequate heat service is to be provided under all circumstances.

This paper outlines the sizing problem for intermittent heating and discusses the effects of three factors influencing it: building structure, patterns of use and incidental heat gains. A discussion then follows of the cost-effectiveness of modes of operation other than traditional intermittent operation. Finally, a possible new form of sizing procedure is suggested.

The work described in the paper develops and applies the theory described by Harrington-Lynn[1,2] and Billington[3] and presents a broad view of the effects of the main factors affecting sizing. The theoretical basis is described in Appendix 1 and probably represents the limit to which the admittance procedure can be reasonably developed for this type of problem. For this reason it is intended to investigate some aspects of the problem in future using more sophisticated computer simulation techniques.

Except where it is otherwise stated, examples quoted are for a heating system operated intermittently, with 16 hours of use per day. The term 'Plant Size Ratio' is used to denote the ratio of the maximum heat output of which the heating system is capable to the steady-state design heat loss of the house.

THE SIZING PROBLEM

The correct sizing of a heating system is not merely a matter of ensuring that the required temperatures can be achieved — the system should also be economical and efficient in operation, and compatible with the thermal behaviour of the building and pattern of use of the occupants. It should also provide, at the same time, an adequate supply of hot water.

Traditionally, domestic central heating systems have been sized on the basis of steady-state continuous operation, plus an arbitrary allowance to permit intermittent use. In practice, most domestic central heating systems in the UK are operated intermittently and so sizing ought, logically, to be based on this mode of operation.

The operation of an intermittently operated heating system on a 'design day' may be divided into three phases (Fig. 1):

(a) *Preheat period.* Immediately following switch-on, the system operates at maximum output, and the internal temperature rises.

(b) *Controlled period.* When the design internal temperature is reached, the system output reduces to maintain this temperature (as closely as control operation permits).

(c) *Off period.* The night-time off period during which the internal temperature falls.

For a clock-controlled system, the ideal would be for the preheat period to end (and design temperatures to be reached) at the moment when the occupants rise (or return to the house in the case of an afternoon switch-on). When the heating system is controlled manually, the objective is to achieve an acceptable temperature in a reasonable time. Very little work has been done to determine what constitutes an acceptable performance for this situation.

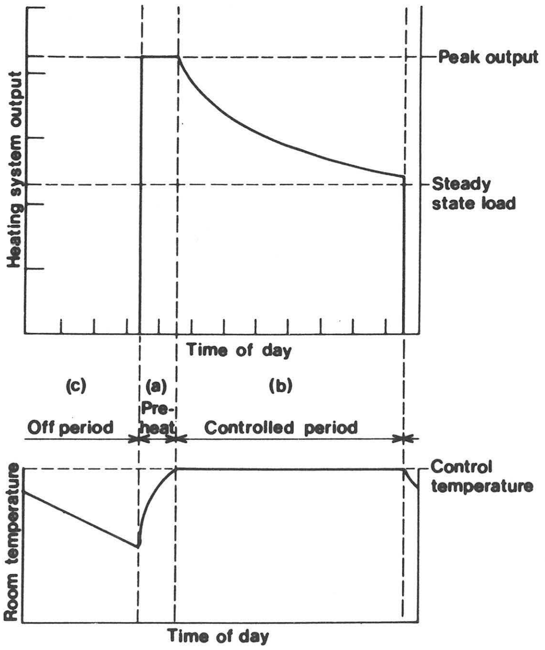

Figure 1

Phases of operation of intermittent heating. Intermittent operation of a heating system may be divided into three phases: preheat; controlled; and off. Peak output occurs during preheat.

If the design day is assumed to have a constant outside temperature, and incidental gains are (for the moment) ignored, the output required of a heating system will be greater than the nominal steady heat loss (calculated from U-values and ventilation rates) throughout both the preheat and controlled periods. During the preheat period, heat is required to raise the temperature of the air, to offset losses to the outside and to offset the heat flow into the relatively cold structure of the building. At the end of the preheat period, the structure will not usually have reached its equilibrium temperature and there will still be a heat flow into it in addition to losses to the external atmosphere. It is found from computer simulations that with common construction methods this flow into the structure remains at a significant level throughout the controlled period for the design day, and the system heat output therefore remains above the nominal house heat loss. During the off period there is a corresponding heat flow from the structure to the space (and thence to the atmosphere).

The peak output required for the heating system occurs during the preheat period and is related to the duration of that period and to the degree of overnight cooling which has taken place. The principal factors which may affect the peak demand (in addition to the external temperature) are discussed in the next three sections.

BUILDING STRUCTURE

The building structure and its insulation influence both the rate of overnight cooling in the house, and the time required to reheat it on the following morning. The infulence of the structure is slightly different in the two cases. It is a limitation of the admittance procedure, including the form used in this report, that it cannot include these subtle differences — this is one reason that in future work, it is planned to use more sophisticated computer simulation methods.

Although a 'heavy' structure cools more slowly than a 'light' one, it also requires the input of more energy per degree rise of internal temperature, and it is not obvious whether it will require a greater or smaller peak heat input. Application of the theory described in Appendix 1 shows that a heavy structure requires a larger peak heat input than does a light structure of the same level of insulation.

Further application of the theory shows that the addition of insulation generally has a greater effect on the nominal, steady-state heat loss than on the peak demand, and so a greater percentage addition is necessary to maintain a similar level of service. The absolute addition, in kilowatts, will however be smaller for the insulated building, i.e. the addition of insulation makes the building behave in a more 'heavy' manner. (It is possible to conceive of structures insulated in such a way that this would not be true — it would be necessary to insulate all internal partitions, floors, furniture, etc., that had significant thermal capacity. This does not seem likely to be a common situation.)

Figure 2 shows the peak loads and percentage additions to the nominal heat loss calculated for an example house of 4.6 kW nominal heat loss, when different forms of construction are assumed. It can be seen that, although in theory the percentage addition can range from zero to 50 per cent for 16 hours per day heating, practical considerations limit the range to about 30 to 40 per cent. The behaviour of this example is thus somewhat closer to the heavy limit than to the lightweight extreme.

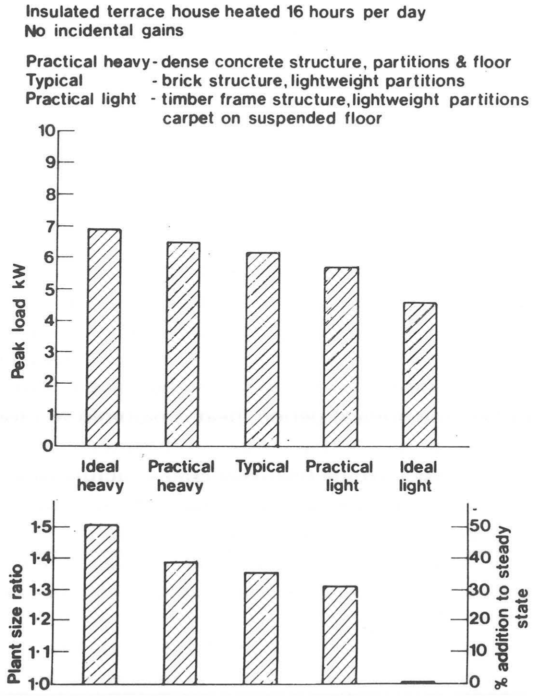

Figure 2

Effect of building mass on peak heat demand. Practical considerations limit the range of effects of building mass on peak heat demand.

The slower overnight cooling of a heavy building means that its average internal temperature is higher than for a light building, and so the heat losses over the whole 24 hour period are also higher. It follows that the heavy building will require, in addition to its greater peak heat demand, a larger total heat input over the 24 hours to balance these losses. (Some of this heat may, of course, be supplied by incidental gains.)

PATTERNS OF USE

The pattern of use of a heating system in a house will change during its lifetime — either through a change of occupants or simply because of their changing needs. In the majority of cases a heating system will have to satisfy, at some time, the needs of:

a young couple, both of whom have jobs
a family with young children
a family with school age children (often with a working wife)
a middle-aged couple, whose children have left home
an elderly couple, or person

The concept of an 'average' pattern of use is of doubtful value and it is necessary to think in terms of the most demanding pattern which is likely. Social trends, particularly the tendency for an earlier completion of childbearing, and the growth in the number of working wives may be expected to increase the proportion of systems which are used intermittently.

The period of non-use — the overnight off period — is really more significant for sizing than the heating period. A long period of use and a correspondingly short off period mean that overnight cooling will be relatively small, and so the energy needed to regain the design temperature is also small. Figure 3 shows that if the period of use becomes very short, the required plant size ratio (the ratio of peak demand to nominal loss) rises rapidly. (It is doubtful whether the procedures developed in Appendix 1 are appropriate to very short periods of use. In practice, when heating systems are off for more than say 18 hours, solar or other significant incidental gains are likely during the off period.)

It is apparent from Fig. 3 that the pattern of use is of some significance. Recorded patterns (Fig. 4) show that a large proportion of occupants might be expected to suffer from insufficiently rapid warm-up if the usually assumed nominal loss plus 20 per cent has been used to size their systems. In fact, it is found that complaints of slow warm-up are rare. A number of factors could explain this discrepancy, but data are not available to allow a satisfactory evaluation of them all. The possibilities are:

(a) Users switch to continuous operation during cold weather. There is evidence that this happens to some extent, but by no means generally. (Many systems are however designed on the implicit assumption that heating will be continuous in cold weather.)

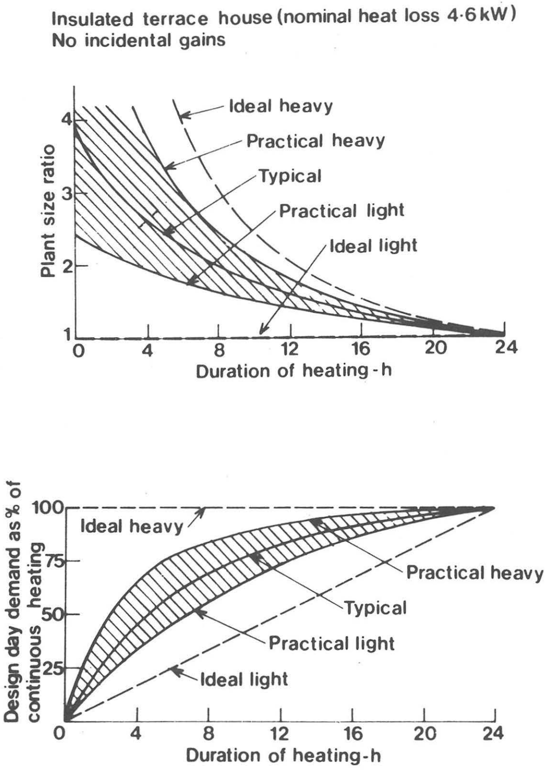

Figure 3

Predicted design day performance. The required plant size ratio, and the energy demand on a design day are dependent on building mass on pattern of use.

(b) Users accept lower temperatures at the beginning of cold days. Activity on first rising is generally higher than when, for example, watching television in the evening, but clothing is less. It is plausible that users may accept a temperature slightly less than ideal when the weather is unusually cold.

(c) Users have supplementary heaters in the principal rooms and use these to boost the initial temperature. It is known that many central heating system users do possess supplementary heaters, such as gas fires (which may be associated with a back boiler). It is not known whether they use them in this manner.

(d) Heating systems are installed with plant size ratios greater than assumed. This is quite likely in houses — there are many examples of safety margins, rule of thumb calculations and 'choosing the next size up' combining to give much larger heating capacities than would be expected. There are also an increasing number of older houses to which insulation has been added some time after the central heating system has been installed, thus resulting in an oversized heating system. It is not known whether this has occurred on a sufficient scale to explain the discrepancy — it seems rather unlikely.

(e) The calculations are in error. The methods used are simplifications of the complicated thermal behaviour of buildings and heating systems and some degree of error is inevitable. Experimental results show broad agreement with the calculations, but are not sufficiently extensive to test the predictions thoroughly. The inclusion of further heating system parameters or of internal heat flows within the building may lead to significant changes in the results.

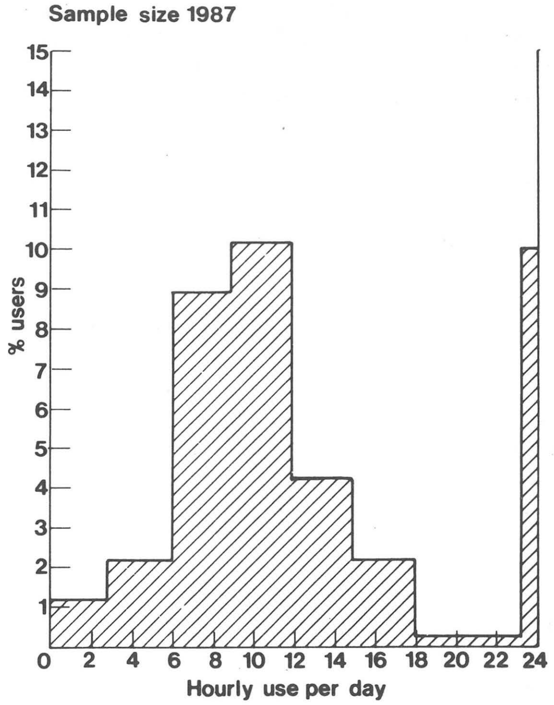

Figure 4

Average hourly use of gas wet central heating. Most heating systems are operated intermittently.

(f) There are significant incidental heat gains, which raise the temperature to the design value. This may sometimes be the case locally — for example in a kitchen during breakfast preparation — but it seems unlikely to be a satisfactory general explanation.

INCIDENTAL HEAT GAINS

For sizing purposes, incidental heat gains may be divided into three types, depending on the time at which they occur:

(a) Gains which occur during the preheat period contribute directly to the useful heat input to the building (provided that they occur in the right places). Reliable gains at this time will generally be small — standing losses from hot water cylinders perhaps, and gains from sleeping occupants.

(b) Gains which occur during the night-time 'off period will reduce the overnight fall in temperature. Their effectiveness will be determined by the building structure, but the gains themselves will be small.

(c) Gains which occur during the main heating period. These result from solar radiation, occupants and their use of domestic equipment, including such activities as washing and cooking and the gains are therefore variable but can be considerable. When they are small and the heating system well controlled the internal temperature will remain close to its design value. There will be energy savings during the day, but, since overnight cooling will commence from the design temperature, the peak demand next morning will not be materially altered. Sufficiently large gains, on the other hand, will raise the internal temperature above the design value (resulting in the heating system being off) and, provided that occupants do not react by opening windows, the overnight cooling will start from a higher temperature. The effect of this on the peak load depends on the thermal inertia of the building — a 'heavy' building will make better use of the gains (and run less risk of overheating during the day) but this must be balanced against its inherently higher predicted peak load.

Figure 5 shows the effect on the example house of steady incidental gains of 1.53 kW (i.e. one-third of the nominal heat loss), calculated by the methods of Appendix 1. Although a heavy structure makes more efficient use of the incidental gains, this is outweighed by other factors, and it has a higher peak load (and a higher total demand) than a light structure. The difference between heavy and light structures is, however, reduced when incidental gains are present. For either structure a plant size ratio of less than unity is possible for periods of use exceeding 16 hours per day.

By definition, a 'design day' for sizing is an extreme condition, and the probability of the occurrence of incidental heat gains is as important as their possible magnitude. Reliable gains which are effective in reducing peak loads are, unfortunately, rather small.

ALTERNATIVE MODES OF OPERATION

A correctly sized and designed heating system will provide an acceptable standard of service with reasonable capital and running costs and a high seasonal efficiency. Increasing the plant size ratio will raise the capital cost of the system and may result in a reduced seasonal efficiency and a wasteful use of fuel. In fact, correctly designed and controlled gas boilers retain high efficiencies at low loads^5 and the second disadvantage can be avoided. Nevertheless systems designed to operate in such a way that the installed system power (and plant size ratio) is lower than for simple intermittent operation may have advantages. Two such types of system have been considered.

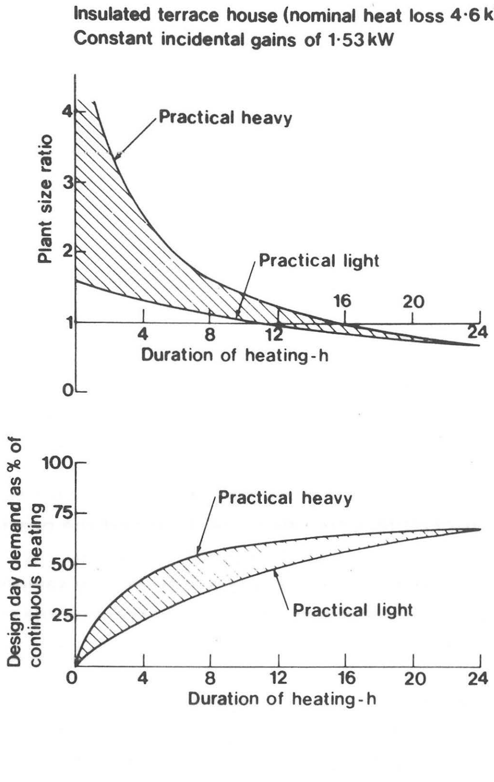

Figure 5

Predicted design day performance with incidental gains. Although a heavy structure makes more efficient use of incidental heat gains, it requires a larger plant size ratio and more energy than a light structure.

Night set-back operation, in which the heating system operates at night to maintain a controlled temperature, lower than the daytime design temperature, reduces the amount of reheating needed and this permits the use of lower plant size ratios. In mild weather the temperature does not fall to the lower controlled temperature and normal intermittent operation takes place.

The other alternative considered, is to size the system so that it can just cope with design steady-state conditions — a plant size ratio of unity. In this case intermittent operation will only be possible during periods of mild weather (when the system will be 'oversized' with respect to the smaller heat losses). During cold weather it must operate continuously. This mode of operation will be referred to as 'continuous cold weather heating'. Ideally, such a system would be controlled by an optimum start controller, but as such systems are not in current use in domestic premises, it has been assumed that the system either operates continuously (in cold weather) or with a fixed 'off' period (in mild weather).

Both these modes of operation reduce the peak load on the heating system, but because they require some night-time operation, they also carry the penalty of a greater number of hours of operation during the heating season and therefore a greater fuel consumption.

The methods described in Appendix 1 have been used to investigate the consequences of these modes of operation. Figure 6 shows the effect of a night set-back from 20°C to 10°C on the example house. If the 'off' period is sufficiently short, the internal temperature will not fall to the set-back temperature and normal intermittent operation will occur. This is the case for the 'typical' structure for periods of use exceeding about 8 hours per day. In general, the 'lighter' the building, the more likely it is that set-back operation will ensue, but the smaller is the reduction in plant size.

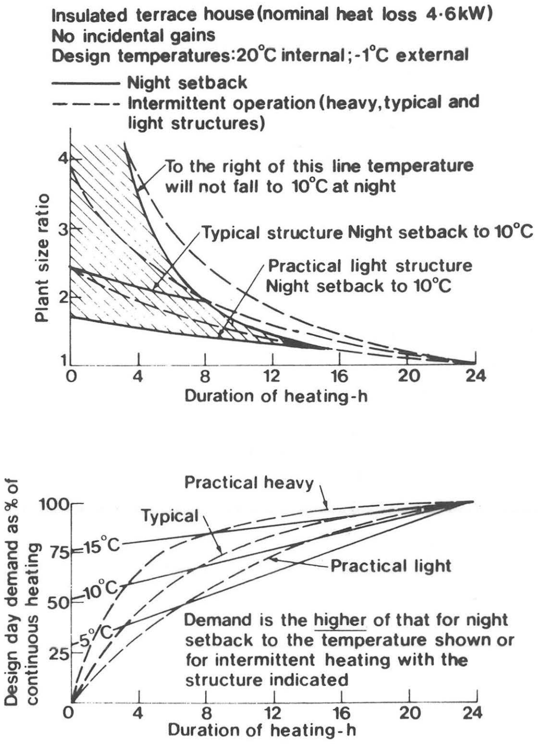

Figure 6

Predicted design day performance with night setback. Night setback operation requires a smaller plant size ratio than intermittent operation, but a greater energy demand.

TABLE 1

COMPARISON OF CONTROL MODES

	Intermittent heating	Continuous heating in cold weather	Night set-back to			
			18°C	16°C	14°C	12°C
Heaviest practical construction						
Plant capacity kW	6.47	4.56	5.73	Temperature does not fall below 17.3°C at night		
Annual energy demand GJ	14.1	14.7	14.3			
Years before intermittent heating is cheaper	–	26.0	26.0			
Present value of savings compared with intermittent £[a]	–	20.3	8.1			
Typical construction						
Plant capacity kW	6.15	4.56	4.97	5.38	Temperature does not fall below 14.1°C at night	
Annual energy demand GJ	11.7	13.0	14.3	12.3		
Years before intermittent heating is cheaper	–	9.6	3.6	10.5		
Present value of savings compared with intermittent £[a]	–	4.9	−19.6	3.2		
Lightest practical construction						
Plant capacity kW	5.70	4.56	4.77	4.98	5.18	5.39
Annual energy demand GJ	9.8	10.8	14.3	12.1	10.6	9.9
Years before intermittent heating is cheaper	–	9.0	1.6	2.5	5.2	23.5
Present value of savings compared with intermittent £[a]	–	2.6	−51.4	−22.7	− 3.6	3.2

[a] Reduction in capital cost minus extra fuel costs over 15 years, discounted at 10 per cent p.a. (all prices as at 1975). A negative value indicates a net loss.

The cost-effectiveness of these options has also been explored and the present value of the resulting savings is shown in Table 1. (Since night set-back to 10°C is not practical in the example house for the 16 hours of use per day assumed, the calculations have been carried out for set-back temperatures of 12, 14, 16 and 18°C.) The cost balance comprises two parts: the saving in boiler and radiator costs; and the extra fuel cost compared with intermittent heating. It has been assumed that a boiler of exactly the desired capacity is available. Boiler and radiator costs were estimated from published installed costs[6] and fuel prices from the corresponding domestic gas tariff. (All prices are as at 1975.) Since the calculations require only price differences between the options, standing charges and fixed costs associated with the heating system can be ignored. No allowance has been made for changes in seasonal efficiency resulting from changes in boiler size – in a well designed system these should be small – nor for changes in the costs of pumps, pipework, controls, etc. The results should therefore be taken as indicative rather than absolute.

Two types of calculation have been carried out:

(a) The number of years before the cost of extra fuel overtakes the saving in capital cost.

(b) The present value of the capital saving plus the extra fuel costs, using standard discounted cash flow analysis. A test discount rate of 10 per cent and a system life of 15 years have been assumed.

The results of this calculation are:

(a) It is possible for a heating system designed to operate either with night set-back or continuous cold weather heating to be more cost-effective than one designed to operate intermittently.

(b) The net savings are, at best, small and may be outweighed by changes in fuel price or by small variations in capital cost (due for example to the need for more complex controls, or variations in appliance costs).

(c) Economical operation of night-set-back control is sensitive to the choice of set-back temperature.

The calculations suggest that a well-adjusted night set-back system should operate on 60 to 70 nights per year, and a system designed for continuous operation in cold weather would run during 30 to 40 nights per year.

SIZING FOR INTERMITTENT OPERATION

Section A2 of the IHVE Guide[4] suggests a 20 per cent addition to the nominal heat loss (i.e. a plant size ratio of 1:2) for an external design temperature of −1°C, but qualifies this by assuming continuous operation during cold weather. Section A9 of the Guide recommends greater percentage additions.

In some ways, it is more helpful to consider the actual kilowatts of power required, than the percentage additions. Figure 7 shows the results of a series of calculations in this form, together with one or two representative values of plant size ratio (1:0, 1:2, 2:0) and a possible new sizing procedure (described below).

It can be seen that, for 16 hours per day operation, the calculated peak demand is slightly higher than that resulting from a plant size ratio of 1:2. As a proportion of the total power the difference is small when the nominal heat loss exceeds about 8 kW (corresponding to houses with little thermal insulation). At lower nominal heat losses it becomes more significant.

There are uncertainties inherent in the calculation of nominal heat loss. The most important is usually the lack of precision with which ventilation rates can be specified. Other factors include site variations of thermal properties of materials, ground conditions, degree of exposure and thermal corner effects. The total magnitude of the uncertainty is probably around ± 1 kW, and there is a case for the addition of a comparable safety margin, or at least ensuring that the installed heating system power exceeds the nominal heat loss by this amount. The simplest sizing procedure may be to add a fixed power, of perhaps 2 kW, to cover both this uncertainty and an allowance for intermittent heating when the nominal loss is below 10 kW. This would coincide with the traditional 20 per cent addition at 10 kW nominal loss, while ensuring a reasonable and easily calculated margin at lower loads. Figure 7 shows this procedure (continued above 10 kW as the traditional 20 per cent addition). Severe patterns of use would still require special measures, and the additional power might need to be a function of the building size.

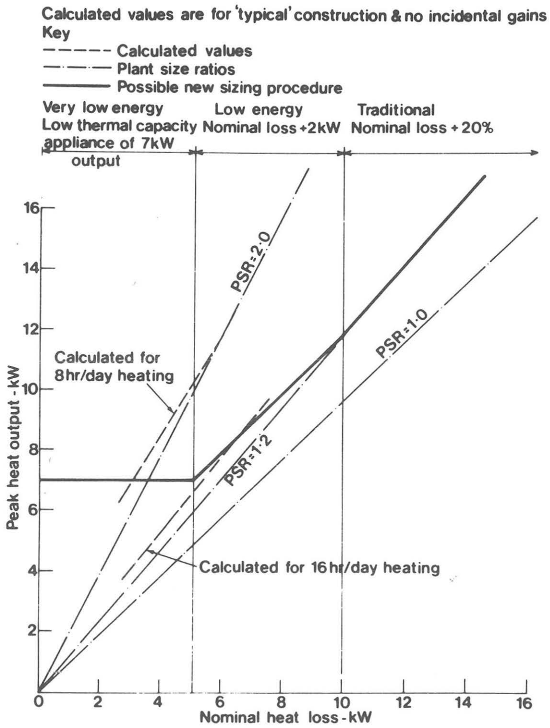

Figure 7

Peak output and nominal heat loss. In well insulated houses it may be preferable to add a fixed power for intermittent operation. In low energy housing a small appliance with good part-load characteristics will be an acceptable solution.

In practice, when the demand is less than 7 kW, the use of a well designed system with a gas boiler of about 7 kW output and good part-load efficiency will carry only slight penalties of running cost.^{5} Figure 7, therefore, shows a system power of 7 kW for nominal heat losses below 5 kW.

DOMESTIC HOT WATER

While the problem of sizing domestic hot water systems is not strictly within the scope of the present paper, it is inescapable when sizing central heating systems which provide both space and water heating.

In highly insulated houses, the annual energy demand for water heating may be comparable with that for space heating, and the boiler output may have to be determined primarily to meet a desired storage cylinder reheat time and hot water demand.

Conventionally, hot water storage and additional boiler power are related to dwelling size and expected demand (often phrased in such terms as low, medium or high rental). In theory a wide variety of combinations of storage capacity and boiler power is possible, ranging from large cylinders with low rates of heat input, to small cylinders with rapid reheat.

When heating is intermittent, there is almost always sufficient spare boiler capacity available in total during the day to meet the domestic hot water needs, although it does not coincide with the pattern of demand. Provided that sufficient well insulated storage were available, and that the system gave priority to space heating (subject perhaps to a manual override), no additional boiler power would be necessary. The cost-effectiveness of this approach depends on the relative incremental costs of boilers and cylinders, as well as the sizes needed. Initial estimates show that conventional sizing is probably more economic at present. In particular, if as has been suggested earlier, a gas boiler of good part load efficiency of about 7 kW maximum output is used for all highly insulated houses, part (and possibly all) of the boiler allowance for domestic hot water is already provided at no additional cost.

CONCLUSIONS

1. Well insulated houses, heated intermittently behave as thermally 'heavy' rather than 'light' structures.
2. The expected pattern of use of a heating system is an important parameter in its sizing.
3. Incidental heat gains which can significantly affect sizing are unlikely.
4. The savings which are possible by departing from the traditional pattern of intermittent heating are sensitive to assumptions about capital cost and interest rates. At present prices they are small.
5. A suggested sizing procedure for well insulated houses is put forward.

APPENDIX 1 THEORY

CALCULATION OF EXTRA CAPACITY FOR INTERMITTENT HEATING

Consider a heating cycle with two phases:

(a) A controlled phase, of duration T hours, during which the internal temperature is controlled at td, and the heating plant produces output Qp_i at each hour i.

(b) An off phase, of duration $24 - T$ hours, during which there is no output from the heating plant.

At any hour, incidental and cyclic heat gains are denoted by Qn_i (these include solar gains and variable gains resulting from fluctuations in outdoor temperature).
For brevity denote

$$\sum AU + C_u \quad \text{as} \quad U$$
$$\sum AY + C_u \quad \text{as} \quad Y$$

where Cu is the ventilation conductance.

Following Harrington-Lynn[1,2] but using the nomenclature above:

At any hour

$$Qp_i + Qn_i = U(\bar{t}_i - \bar{t}_0) + Y(t_i - \bar{t}_i) \qquad (1)$$

In particular during phase (a) (control).

$$Qp_i + Qn_i = U(\bar{t}_i - \bar{t}_0) + Y(t_d - \bar{t}_i) \qquad (2)$$

And during phase (b) (off)

$$Qn_i = U(\bar{t}_i - \bar{t}_0) + Y(t_i - \bar{t}_i) \qquad (3)$$

Summing over the whole period, and noting that by definition

$$\sum_{i=1}^{24} (t_i - \bar{t}_i) = 0$$

$$\sum_{i=1}^{24} Qn_i + \sum_{i=K}^{T+K} Qp_i = 24U(\bar{t}_i - \bar{t}_0) \qquad (4)$$

Also, summing over the control period

$$\sum_{i=K}^{T+K} Qp_i = TU(\bar{t}_i - \bar{t}_0) + TY(t_d - \bar{t}_i) - \sum_{i=K}^{T+K} Qn_i \qquad (5)$$

Then

$$\sum_{i=1}^{24} Qn_i - \sum_{i=K}^{T+K} Qn_i = (24 - T)U(\bar{t}_i - \bar{t}_0) - TY(t_d - \bar{t}_i) \qquad (6)$$

Following Billington (3), write

$$P_0 = \frac{U}{Y}$$

(Note that for a perfectly lightweight structure $P_0 = 1$; for perfectly heavy one P_0 is zero) and

$$Q_d = U(t_d - t_0); \qquad p = \frac{Q_p}{Q_d}$$

For convenience also write $Qn_i = Q_1$ during the controlled period. $Qn_i = Q_2$ during the off period.

We will also take $t_0 = \bar{t}_0$.

From (4) we have

$$\bar{t}_i = \bar{t}_0 + \frac{(24 - T)Q_2 + TQ_1 + TQ_p}{24U}$$

Substituting in (6), we have, after some manipulation.

$$p = \frac{1 - \frac{Q_2}{Q_d} \cdot (1 - P_0 \left(1 - \frac{T}{24}\right)}{P_0 + \frac{T}{24}(1 - P_0)} - \frac{Q_1}{Q_d} \qquad (7)$$

Setting $Q_1 = Q_2 = 0$ we obtain Harrington-Lynn's equation (8)[2] which is itself an alternative form of Billington's equation (7a).[3]

We may write (7) in terms of Barcs' modulus m, by considering the case $Q_1 = 0$. An alternative form of the definition of m is

$$\frac{Q_2}{Q_d} = p(1 - m) \qquad (8)$$

Substituting this in (7) we obtain

$$p = \frac{1}{1 - m(1 - P_0)\left(1 - \frac{T}{24}\right)} \qquad (9)$$

Rearranged, this is seen to be a more general form of Billington's equation (7a).[3]

$$\left(1 - \frac{1}{p}\right) = m(1 - P_0)\left(1 - \frac{T}{24}\right)$$

Another special case of interest is when $Q_1 = Q_2$ (that is incidental gains are constant). Then

$$p = \frac{1 - \frac{Q_1}{Q_d}}{P_0 + \frac{T}{24}(1 - P_0)} \qquad (10)$$

ENERGY DEMAND

The heating energy demand during the day is clearly given by

$$E = pQ_dT \qquad (11)$$

$$E = \frac{TQ_d - TQ_2(1 - P_0)\left(1 - \frac{T}{24}\right)}{P_0 + \frac{T}{24}(1 - P_0)} - TQ_1 \qquad (12)$$

A lightweight building ($P_0 = 1$) will minimise E. The *additional* energy resulting from thermal inertia of the structure is

$$\frac{(1 - P_0)\left(1 - \frac{T}{24}\right)(Q_d - Q_2)T}{P_0 + \frac{T}{24}(1 - P_0)}$$

When $Q_1 = Q_2$

$$E = \frac{T(Q_d - Q_1)}{P_0 + \frac{T}{24}(1 - P_0)} \qquad (13)$$

NIGHT SET-BACK OPERATION

We can use eqn. (7) to calculate the effect of night set-back operation — as we have already done in the derivation of eqn.

(9) — by considering the night-time heat output as if it were an incidental gain.

Commonly we will wish to define the internal night-time temperature rather than the heat output. By defining the internal temperature throughout the 24 hour period, we are in effect defining the total heat input at each hour — if incidental gains occur, they are offset by balancing adjustments of the heat produced by the heating apparatus.

We can therefore consider the situation when $Q_1 = 0$ and Q_2 is the total night heat input. If Q_1 is non-zero we may simply subtract Q_1, from Q_p.

We have then

$$p = \frac{1 - \frac{Q_2}{Q_d}(1 - P_0)\left(1 - \frac{T}{24}\right)}{P_0 + \frac{T}{24}(1 - P_0)} \tag{14}$$

Since t_i is defined at all times, during 'day' $t_i = t_d$, during 'night' $t_i = t_n$.

The energy balance eqn. (4) becomes

$$TpQ_d + (24 - T)Q_2 = TU(t_d - t_0) + (24 - T)U(t_n - t_0) \tag{15}$$

$$= 24Q_d - (24 - T)U(t_d - t_n) \tag{16}$$

Eliminating Q_2 from (14) and (16) and rearranging

$$p = 1 + \left(\frac{1 - P_0}{P_0}\right)\left(1 - \frac{T}{24}\right)\left(\frac{t_d - t_n}{Q_d}\right)U \tag{17}$$

or

$$p = 1 + \left(\frac{1 - P_0}{P_0}\right)\left(1 - \frac{T}{24}\right)\left(\frac{t_d - t_n}{t_d - t_0}\right) \tag{18}$$

Where Q_2 now reverts to its original sense of incidental gains only, the heating energy during the day is:

$$E = 24Q_d - (24 - T)\left(\frac{t_d - t_n}{t_d - t_0}\right)Q_d - Q_1T - (24 - T)Q_2$$

This analysis is invalid if the night temperature would have remained above t_n in the absence of heating.

Equating (18) and (7) shows the critical condition when $Q_2 = 0$ to be

$$t_0 = t_d - (t_d - t_n)\left(1 + \frac{T}{24}\left(\frac{1 - P_0}{P_0}\right)\right) \tag{20}$$

LIMIT TO INTERMITTENT HEATING

If the heating plant is sized for continuous heating at some outside temperature t_0, in the absence of incidental gains:

$$Q_p = U(t_d - t_0)$$

At some other outside temperature, t_a, we may consider the effect of the higher temperature to be a constant 'incidental gain' of magnitude $U(t_a - t_0)$.

Intermittent heating will be possible (even in the absence of incidental gains) if, adapting eqn. (10,

$$Q_p \geq \frac{Q_d - U(t_a - t_0)}{P_0 + \frac{T}{24}(1 - P_0)} \tag{21}$$

$$t_d - t_0 \geq \frac{t_d - t_a}{P_0 + \frac{T}{24}(1 - P_0)}$$

$$t_a \geq t_d - (t_d - t_0)\left(P_0 + \frac{T}{24}(1 - P_0)\right) \tag{22}$$

The value of t_a may be altered by a change of T: this is the principle of the optimum start control.

It is implicit in the admittance procedure that, at any moment, the internal temperature is determined by the building parameters, the mean indoor and outdoor temperatures and the heat input at that moment. It is therefore not possible to separate the heating period into a preheat period and a controlled-temperature period. The preheat period is therefore undefined.

The admittance procedure does not include any heating system parameters and cannot distinguish different types of heating system, nor does it model transient heat flow in the structure with great precision.

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The estimation of heating energy use in buildings

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CONTENTS

GLOSSARY

TERM		UNIT	FIRST USED
a	A constant of Rey's equation	Cs	2.3
A_j	Area of building element j	m^2	2.1
b	Annual total incidental heat gains	J	2.3
c	Specific heat	$Jkg^{-1}\ C^{-1}$	2.1
d	Heat conduction term	$W\ C^{-1}$	3.3
$D\ (t_b)$	Temperature-time term, base t_b	Cs	2.6
e	Ventilation heat loss term	$W\ C^{-1}$	3.3
E	Annual heating energy demand	J	2.2
f	Unuseable annual incidental heat gains	J	2.3
g	Temperature dependent ventilation term	$W\ C^{-2}$	3.3
G	Incidental heat gains	W	2.1
$\mathcal{I}$	Incident solar radiation	W	3.8
j	Building element subscript	—	2.1
k	Time subscript	—	2.4
K	Partially heated building term	—	3.5
ℓ	Solar radiation term	W	3.4
L	Overall conductance	$W\ C^{-1}$	2.1
L^*	Modified L to include solar radiation effects	$W\ C^{-1}$	3.4
M	Radiation/temperature constant	$W\ C^{-1}$	3.4
N	Heating season duration	s	2.2
Q	Total heat loss	W	2.1
Q_h	Heat supplied by heating system	W	2.1
Q_j	Heat loss via element j	W	2.1
r_c	Thermal resistance; controlled area to outside	$C\ W^{-1}$	3.5
r_u	Thermal resistance; uncontrolled area to outside	$C\ W^{-1}$	3.5
r_i	Thermal resistance; controlled to uncontrolled area	$C\ W^{-1}$	3.5
t_b	Base temperature	C	2.4
t_b^*	Modified base temperature	C	3.4
t_c	Internal temperature: controlled area	C	3.5
t_{gw}	Glass wall temperature	C	3.8
t_i	Internal temperature	C	2.1
t_o	External temperature	C	2.1
t_{sc}	No heating temperature	C	2.5
t_u	Internal temperature: uncontrolled area	C	3.5
u_j	Thermal transmittance of element j	$W\ m^{-2}\ C^{-1}$	2.1
V	Ventilation volume flow rate	$m^3\ s^{-1}$	2.1
ρ	Density	$kg\ m^{-3}$	2.1
Υ	Solar transmission factor	—	3.8

1. INTRODUCTION

Energy consumption is being given increasing weight as a factor in building design. Consumption predictions are also fundamental to assessments of the cost-effectiveness of energy conservation measures for both new and existing buildings.

In many classes of building, the greatest energy use is for space heating and this is clearly an element which can be modified by changes to the design of a building.

Complex computer based mathematical models of the thermal behaviour of buildings can be useful research and development tools and their use as design aids may be justified for large building projects. The best of these use real weather data and a detailed building model to calculate heating energy requirements hour by hour. This approach is used for example, in the British Gas Corporation program THERM (1). The cost of these models sometimes make their use impractical for small projects and the engineer or architect must use much simpler models, which can be handled by paper-and-pencil or calculator methods. These models may also be preferable in the early stages of design, when the building cannot be specified in the detail required for the more complex models.

This paper reviews some of the simpler models, with particular attention being given to the 'degree-day' method. It is written specifically with the heating of dwellings in mind, but many points apply equally to other building types. In existing dwellings, space heating remains the dominant energy use, but improvements to insulation standards have reduced its importance and it is possible that water heating could eventually become the largest use of energy in domestic premises.

The paper primarily considers the application of models to the design of new buildings. Some models are also useful in monitoring the fuel consumption of existing buildings. In this application some of the problems raised in the paper are of less significance, but new problems are also raised.

2. MODELS OF ENERGY DEMAND FOR HEATING

2.1 Basic Model

Consider the idealised case of a building at a uniform steady internal temperature t_i situated in an atmosphere at constant temperature, t_o.

It is implicitly assumed that, in each case, a satisfactory single internal temperature and corresponding external temperature can be defined. This may be an 'environmental temperature' or an air temperature, for example. The effects of this approximation are not considered in this paper, having been discussed elsewhere in some detail.

Each element of the building has a thermal transmittance u_j, area A_j and heat loss Q_j.

$$Q_j = U_j A_j (t_i - t_o) \qquad (2.1.1)$$

There will also be an exchange of ventilation air, volume flow rate V, density ρ specific heat c, between the atmosphere and the building interior.

The total heat loss rate Q is thus:-

$$Q = C\rho V (t_i - t_o) + (t_i - t_o) \sum_j A_j U_j \qquad (2.1.2)$$

writing $L = C\rho V + \sum_j A_j U_j$ (2.1.3)

we have $Q = L (t_i - t_o)$ (2.1.4)

If there are incidental heat gains from occupants, equipment or solar radiation, G, the heating system will be required to supply Q_h.

$$Q_h = Q - G \qquad (2.1.5)$$

If $G > Q$ then $Q_h = 0$ (2.1.6)

In real buildings there are many departures from these idealised conditions. They remain, however, the basis for most simple models.

2.2 Mean Values

Equations (2.1.5) and (2.1.6) may be rewritten

$$Q_h = L (t_i - t_o) - G \qquad (2.2.1)$$

with $Q_h = 0$ if $t_o > t_i - \frac{G}{L}$ (2.2.2)

It is sometimes suggested (2, 3) that the annual total heating energy demand E, during a heating season of duration N, may be estimated by the use of mean values of the remaining parameters:-

$$E = N \left\{ \bar{L} (\bar{t}_i - \bar{t}_o) - \bar{G} \right\} \qquad (2.2.3)$$

While this is so, the approach is of limited practical value since

$N, \bar{L}, \bar{G}, \bar{t}_o, \bar{t}_i$ are interdependent

Even if it is possible to establish the appropriate values in a particular case, a change in any one of them necessitates a modification to the others.

A variant to this, which is often implied, though rarely stated explicity is the assumption that E is proportional to L. Thus halving the design heat loss is expected to halve the space heating energy demand. This approach effectively ignores the incidental gains.

2.3 Rey's Equation

An alternative approach was suggested by Rey (4). His argument, expressed in the nomenclature used above, may be summarised thus:-

Over a whole year,

if $G = 0$, then $E = a\,L$ (2.3.1)

Where a is a constant associated with the local climate.

Denote the total annual incidental gains by b (if G is constant $b \propto G$).

If these were entirely useful, we would have

$$E = aL - b \tag{2.3.2}$$

In practice the gains are not always useful and we require some function of b and L to describe the 'wasted' gains.

$$E = aL - b + f\,(L, b) \tag{2.3.3}$$

If the conditions that at L = 0, E = 0 and $\frac{dE}{dL} = 0$ are imposed, it can be shown that a suitable solution is:-

$$E = aL - b + \frac{b^2}{aL + b} \tag{2.3.4}$$

Values of a have been deduced for various regions of France (4).

Equation (2.3.4) may be written more compactly as:-

$$E = \frac{aL}{1 + \frac{b}{aL}}$$

It is not apparent why this equation is to be preferred to other possible solutions (except for simplicity) and it does not appear to have been checked against specific building consumptions.

The constant 'a' must in practice be a function of internal temperature as well as climate. It will be shown in 2.6 that it is closely related to the concept of degree-days.

2.4 Degree-Days

The degree-day method takes as its basis equation (2.2.1). For each period of time – say one hour – k, we have (for constant values of each parameter within the time interval).

$$Q_{hk} = L_k\,(t_i - t_o)_k - G_k \tag{2.4.1}$$

$$\text{if } L_k\,(t_i - t_o)_k \geqslant G_k$$

$$\text{and } Q_{hk} = 0 \tag{2.4.2}$$

$$\text{if } L_k\,(t_i - t_o)_k < G_k$$

$$\text{and } E = \sum_k Q_{hk} \tag{2.4.3}$$

If L_k is constant and we can contrive to carry out the summation only over terms for which (2.4.1) is valid, we have

$$E = L \sum_k (t_i - t_o)_k - \sum_k G_k \tag{2.4.4}$$

We may define the base temperature t_b as

$$t_b = t_i - \frac{G}{L} \tag{2.4.5}$$

$$\text{so} \quad E = L \sum_k (t_b - t_o)_k \text{ provided } t_b \geqslant t_o \tag{2.4.6}$$

The term $\sum_k (t_b - t_o)_k$ has dimensions of temperature times time and is commonly expressed in 'degree-days'. (For consistency, its units throughout the present paper are degree C – seconds unless otherwise stated). The degree-day method has a number of limitations, some of which are discussed in the second part of this paper.

In the United Kingdom, monthly values of degree-days for each region are published for a standard (and fixed) base temperature of 15.5°C (60°F). This task was formerly carried out by British Gas but is now undertaken by the Department of Energy. These figures are not produced exactly in accordance with the equation above, but are estimated from daily maximum and minimum temperatures using empirical formulae (5).

Monthly degree-day figures for London for the years 1952–1971 have been recomputed from hourly temperature data by Watson House. This has shown that at the standard base temperature, differences of annual totals between published values and the new values are small but differences of monthly values can exceed 5%.

With higher levels of insulation (and thus lower values of L) becoming more common, there is an increasing need for degree-day figures for base temperatures below the standard 15.5°C. While such figures have been tabulated for a number of sites in Eire (6) they are not readily available for the United Kingdom. The CIBS Guide (7) gives correction factors to be applied to standard degree-days, but direct calculation of degree-day totals from hourly data reveals significant errors in the CIBS factors at base temperatures below 12°C. These can have important effects on the estimation of the cost effectiveness of insulation measures. In general the new figures suggest that energy savings will be lower than would be predicted from the CIBS factors. It is hoped to publish this work shortly.

2.5 Temperature Sans Chauffage

Uyttenbroeck and Heikhaus (8) have recently proposed an alternative method, closely related to the degree-day method. Instead of absorbing incidental gains into a modified internal temperature – the base temperature, they propose that they should be incorporated into a modified external temperature – the temperature sans chauffage or temperature without heating.

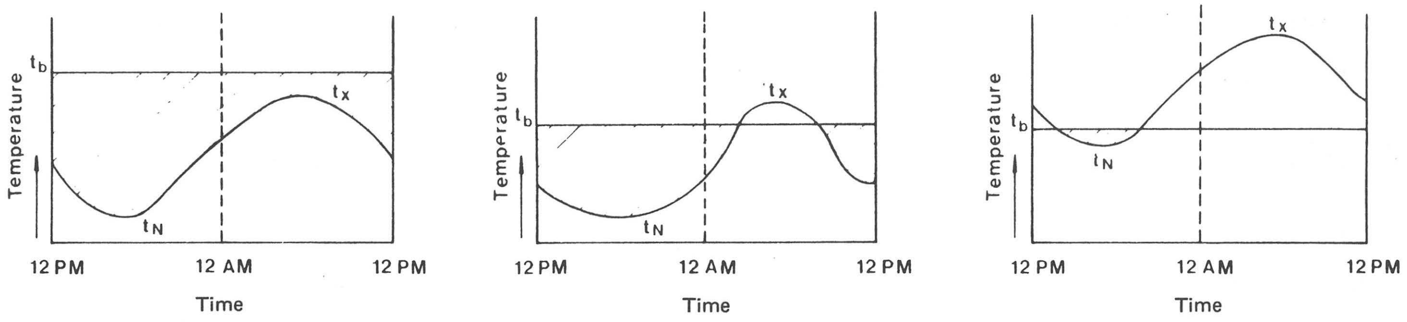
This leads to equivalent equations to those of the degree-days method:-

Degree-Day		**Temperature Sans Chauffage**	
$t_b = t_i - \frac{G}{L}$	(2.4.5)	$t_{sc} = t_o + \frac{G}{L}$	(2.5.1)
$E = L \sum_k (t_b - t_o)$	(2.4.6)	$E = L \sum_k (t_i - t_{sc})$	(2.5.2)

Clearly $(t_b - t_o) = (t_i - t_{sc})$

Whereas the degree-day method permits the calculation of general degree-day values (assuming constant tb), this method requires the gains to be estimated for each design and added to the external temperature hour by hour. However, t_{sc} unlike t_b may be measured directly in existing buildings as Uyttenbroeck has demonstrated.

The mean value of t_{sc} is simply the mean internal temperature of the unheated building. By this means, solar heat gains through the structure and seasonal variations of solar gain may be taken into account. On the other hand this direct observation is not practical in occupied buildings and so incidental gains from occupant activities are not included. The



(A) (B) (C)

Case 1

$t_x < t_b$

$$D t_b = t_b - \frac{(t_x + t_N)}{2}$$

Case 2

$(t_x - t_b) < (t_b - t_N)$

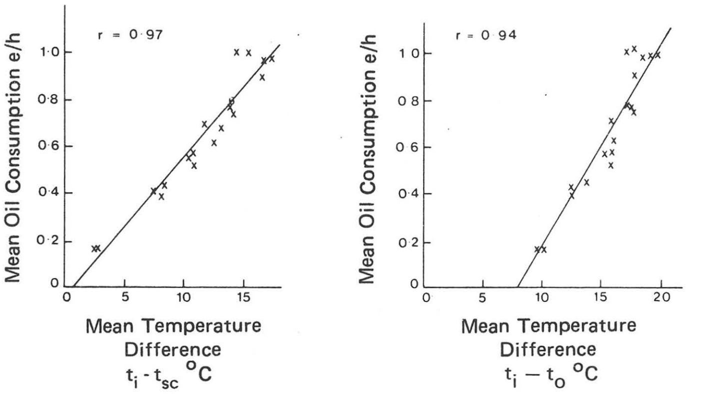
$$D t_b = \frac{(t_b - t_N)}{2} - \frac{(t_x - t_b)}{4}$$

Case 3

$(t_x - t_b) > (t_b - t_N)$

$$D t_b = \frac{(t_b - t_N)}{4}$$

Figure 1



COMPARISON OF CORRELATION OF CONSUMPTION WITH t_{sc} AND t_o

Consumption measured in 3 unoccupied, continuously heated houses

t_{sc} measured in similar houses

(Taken from J. Uyttenbroeck & H. Heikhaus "Mesures de la consommation d'energie dans dix maisons neuves non - habitees")
CSTC Revue March 1978

Figure 2

observed values are also specific to the particular building type and site and cannot be easily generalised.

The method has certain attractions but does not seem to offer real advantages to the designer at present.

2.6 Comparison Between Models

For comparison, it is convenient to write the equations for each model in terms of the temperature — time term $\frac{E}{L}$. We then have:-

Mean Values:

$$\frac{E}{L} = N\left(\bar{t}_i - \bar{t}_o - \frac{G}{L}\right) \qquad (2.6.1)$$

Rey's Equation

$$\frac{E}{L} = \frac{a}{1 + \frac{b}{aL}} \qquad (2.6.2)$$

If there are no incidental gains b = 0 and G = 0 and a is seen to equal to the 'degree-day' term $\sum_k (t_i - t_o)_k$ for the case $t_b = t_i$.

Degree Days

$$\frac{E}{L} = \sum_k (t_b - t_o)_k \qquad (2.6.3)$$

This is more conveniently written

$$\frac{E}{L} = D\,(t_b) \qquad (2.6.4)$$

In practice D (15.5) is normally used in conjunction with a correction factor. The published factors (7) are found to be described by 0.1213 (tb — 7.275), although this does not accord with the recalculated values described in 2.4.

The approximate degree-day equation is

$$\frac{E}{L} = 0.1213\,D\,(15.5)\;\left(t_i - 7.275 - \frac{G}{L}\right) \qquad (2.6.7)$$

This is equivalent to the mean value equation for the special conditions

$$N = 0.1213\;D\,(15.5)$$
$$\bar{t}_o = 7.275$$

Example

A numerical example demonstrates the differences between the annual demand predictions of the models.

Assume $\bar{t}_i = 18°C$, $\frac{G}{L} = 5°C$ (G assumed constant).

Degree-days for Heathrow; D (15.5) = 2170°C days

$\frac{E}{L}$ expressed in degree-days

Degree-days (new data)

$t_b = 13°C$ $\quad$ $\underline{D\,(13) = 1506°C \text{ days}}$

Degree-Days (Published Figures)

$$\frac{E}{L} = 0.1213 \times 2170\ (18 - 7.275 - 5) = \underline{1507^{\circ}\text{C days}}$$

Rey's Equation

$$a = D(18) = 2944 \qquad \frac{b}{L} = 5 \times 365 = 1825$$

$$\frac{E}{L} = \frac{2944}{1 + \frac{1825}{2944}} = \underline{1817^{\circ}\text{C days}}$$

Mean Values

$N = 231$ days. $\overline{t_i} - \overline{t_o} = 7^{\circ}C$ (As Ref. 2)

$$\frac{E}{L} = 231\ (7 - 5) = \underline{462^{\circ}\text{C days}}$$

It is suggested in (3) that $\overline{t} - \overline{t_o} = 10^{\circ}C$ is appropriate to centrally heated houses. In this case

$$\frac{E}{L} = 231\ (10-5) = \underline{1155^{\circ}\text{C days}}$$

If we now consider the predicted changes in annual demand which follow a given change of the term $\frac{G}{L}$, further differences are revealed.

$\frac{G}{L}$ may be increased either by an increase in incidental gains G, or an increase in insulation levels (resulting in a decrease of L).

Figure 3 shows variations of $\frac{E}{L}$ as predicted by the different models for the example.

Tables 1 and 2 summarise the predictions for the example and the effect of changing $\frac{G}{L}$ from 5°C to 7°C either by varying G, or by varying L.

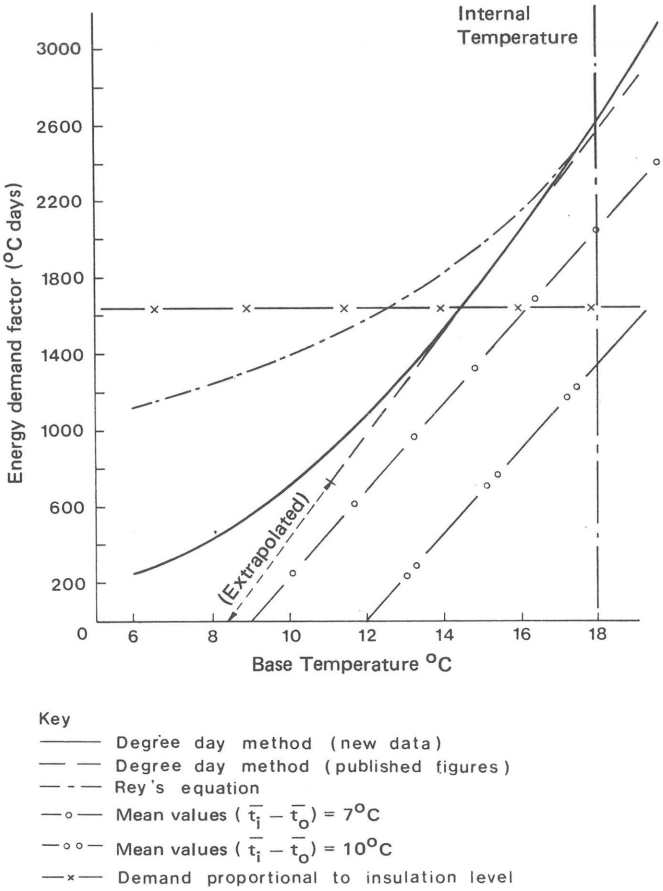


Figure 3

Variation of demand with heat gain.
Various models. Internal temperature = 18°C. Heathrow data.

TABLE 1

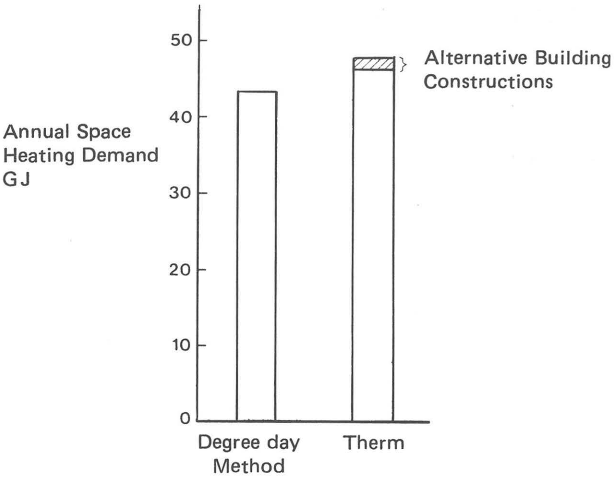
EXAMPLE COMPARISON OF MODELS

Model	Predicted Demand (°C Days)			Reduction in Energy Demand (%)	
	Basic	Increased Incidental Gains	Increased Insulation	Increased Gains	Increased Insulation
Degree-day New Data	1506	1066	761	29	49
Degree-day published figure	1507	980	700	35	54
Rey's Equation	1817	1576	1126	13	38
Mean Values ($\Delta t = 7$)	462	0	0	100	100
Mean Values ($\Delta t = 10$)	1155	693	495	40	57
$E \propto L$ ($\Delta t = 7$)	1617	1617	1155	0	29

TABLE 2

COMPARISON OF PREDICTED SAVINGS

Model	Predicted Savings (°C Days)	
	Increased Gains	Increased Insulation
Degree-day New data	440	745
Degree-day Published Figure	527	807
Rey's Equation	241	691
Mean Values ($\Delta\bar{t} = 7$)	462	462
Mean Values ($\Delta\bar{t} = 10$)	462	660
$E \propto L$ ($\Delta\bar{t} = 7$)	0	462



Continuous heating, constant ventilation
1964/5 Heathrow weather

Figure 4

Comparison between degree day method and computer simulation.

3. THE DEGREE-DAY METHOD

3.1 Background

Of the models described in Section 2, the degree-day method is the most complete (with the possible exception of 'temperature sans chauffage' which is in effect a variant of the degree-day method), and used with published correction factors, is probably the most widely accepted. It is not without problems, which are discussed below, but seems to be prone to attract misunderstanding of its possibilities and limitations. Thus, it has recently been claimed that it "ignores heat gains within the building and from the sun" (3).

The use of degree-days for heating problems seems to have originated in the American Gas Industry. Dufton (9) in 1934 drew the attention of British Engineers to this work and this was followed by a series of further papers (10, 11, 12) which, on the whole confused rather than clarified the method, not least by abandoning the American practice of adjusting the internal temperature to allow for incidental gains.

In 1946 McVicker (13) laid the foundations of good practice, drawing on methods which had been proposed in the nineteenth century (14) and used by the London and Counties Coke Association since 1938. Computation of the figures was still a problem in the 1950s (15, 16) but this did not prevent suggestions that special figures be produced for intermittently heated buildings (17). Billington (18) in 1966 presented a rational analysis of the problem upon which current procedures are based and to which the analyses of section 2 owe a great deal.

3.2 The Nature of Problems with the Method

Problems with the degree-day method fall into two categories; inherent shortcomings of the model; and difficulty in assigning values to the parameters (in part due to the fact that they are often not constant).

The method takes no account of the storage of heat within the structure of the building. However, the thermal capacity of a house is typically 10^6 to 10^7 J/°C. Since the change in the mean temperature of the structure between the beginning and end of the heating season is likely to be a few degrees at most, the difference in energy stored in the structure will be two to three orders of magnitude lower than the annual heating demand.

The effects may be more serious in shorter periods, since the structure will be able to absorb heat during periods when the heating system is not required to operate (the conditions of equation 2.4.2) and release it during subsequent periods, in effect increasing G_k and causing t_b to vary.

Figure 4 shows a comparison between the predictions of the THERM computer program and the degree-day method, for a set of conditions in which most of the assumptions of the degree-day method are constrained to be valid. The building modelled is a 4.5 kW nominal heat loss semi-detached house, in which the ventilation rate is held constant, there are no incidental heat gains except for solar radiation and the whole house is continuously heated (though not all rooms are at the same temperature). The consumptions are calculated for October 1964 to April 1965 (inclusive) using Heathrow weather data. Degree-day figures for the appropriate base temperature were calculated directly from the same weather database.

There is a range of values for the THERM results because several runs with different building constructions were carried out. The prediction of the degree-day method (which includes solar gains through both windows and structure) is about 7% lower than the THERM results. The reasons for the discrepancy have not been investigated in any detail, but it appears that the degree-day figure implies that almost all the solar gains are useful, whereas the THERM simulation used a multi-room model in which local over-heating sometimes occurred. In the THERM simulation the controlled temperature was the room air temprature, whereas the degree-day method implicity assumes 'environmental temperature'. (This, however, would be expected to lead to a high degree-day estimate, rather than a low one).

The wide range of consumptions which is found in practice in identical buildings (Fig. 5) demonstrates that consumption cannot be predicted from a knowledge of a building design alone — its use must also be known. If the degree-day method is to be used, the choice of values for the parameters must reflect the usage pattern.

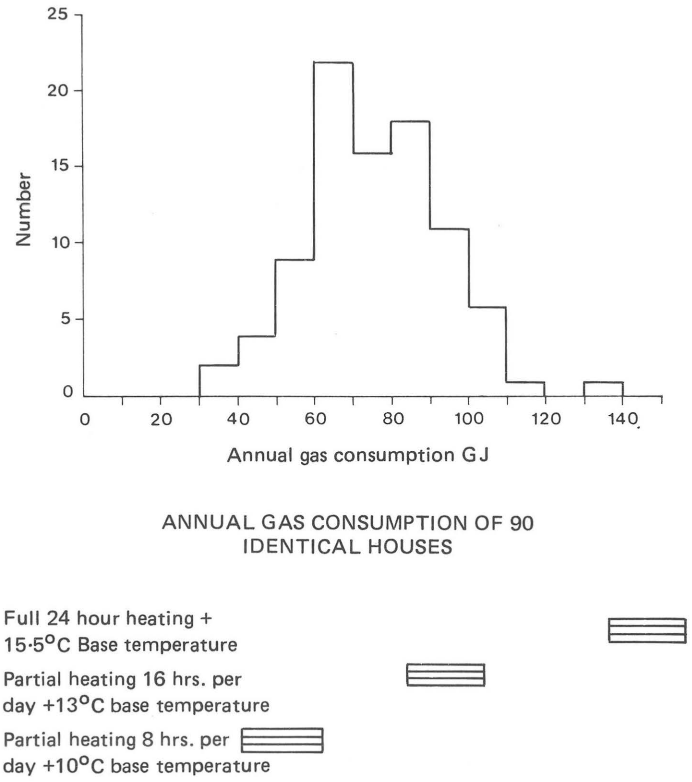


Figure 5

Degree-day predictions for same houses.
Ranges reflect different assumptions for cooking and DHW.

Published correction factors permit the degree-day method to accommodate a wide range of possible consumptions, but even assuming that the factors accurately reflect the differing usage patterns (which is unproven), the predictions shown illustrate the large effect of alternative assumptions on predicted consumption. The effect of variation of base temperature is particularly notable.

It is usually found that observed heating energy use is fairly well correlated with degree-days measured over periods of about a month. In using this to monitor plant performance it is not necessary to assign values to L, G or t_i since deviations from the historical relationship are sufficient to indicate malfunction or change in use. For new and proposed buildings, these parameters must be given values.

The derivation of the degree-day equations in 2.4 requires that L, G. t_i are constant. In practice this is not so — each varies with time according to the use of the building and its heating system. These variations strictly require the qualifying conditions of (2.4.1) and (2.4.2) to be evaluated continuously and Q_h to be calculated accordingly. This has been proposed (19) but requires hour-by-hour calculations and thus the use of a computer. It also re-introduces the problem of the energy demand of intermittently heated buildings. For the best estimate of the effect of incidental gains, base temperature should be based on the internal design temperature during the hours for which heating may be required. In order to carry out a heat balance for a day or longer period, the mean internal temperature is needed, and it is difficult to see how these requirements may be reconciled without a fairly sophisticated building model.

The following sections discuss the main problem areas of the degree-day method and suggest ways in which some of the difficulties may be overcome by modification to the basic equations, but it cannot be too strongly emphasised that there is a good deal of scope for practical research to determine the accuracy of this type of approach.

3.3 Variable Ventilation

The main cause of variation of the conductance term, L, is variations of ventilation rate. In principle ventilation rates may be predicted from a knowledge of the building and the local weather conditions (20). In practice this approach is difficult to use because of uncertainties of open areas (particularly for proposed buildings), and it requires the use of computer calculations.

Most dwellings have opening windows, and the behaviour of the occupants is likely to be a major influence.

Dick and Thomas (21) observed that in occupied houses, the ventilation rate tended to be a linear function of outdoor temperature. More recent work by Brundrett (22) tends to confirm this view.

If this is so, L may be described by a conduction term (which may be considered constant) and a ventilation term which is a function of to.

$$\text{Thus } L = d + (e + g\,t_o) \qquad (3.3.1)$$

$$\text{And } Q_{hk} = (d + e + g\,t_{ok})\,(t_i - t_o)_k - G_k \qquad (3.3.2)$$

$$\text{if } t_i \geqslant t_{ok} + \frac{G_k}{d + e + g\,t_{ok}}$$

$$Q_{hk} = 0 \text{ if } t_i < t_{ok} + \frac{G_k}{d + e + g\,t_{ok}} \qquad (3.3.3)$$

$$E = (d + e) \sum_k (t_i - t_o)_k + \sum_k G_k + g \sum_k t_{ok}\,(t_i - t_o)_k \qquad (3.3.4)$$

Base temperature cannot now be defined except as a function of to and the simplications possible for the development of the degree day method cannot be made.

It is clear that the ventilation rate which is assumed in sizing the heating system is unlikely to be appropriate to the estimation of energy consumption of occupied houses. It underestimates the heat losses in two ways — firstly by simply underestimating the ventilation losses in mild weather (when windows are likely to be open), and secondly by overestimating the value of incidental heat gains during these periods.

Unfortunately, the variation of ventilation rate cannot be directly incorporated into the degree-day method. As a rule of thumb it may be possible to use an 'average' ventilation rate, although it is not clear what the value of this should be. For the houses studied by Dick and Thomas, it would probably be about 2 to 2.5 h^{-1}, but it is to be expected that the appropriate value would vary with the design and use of the house.

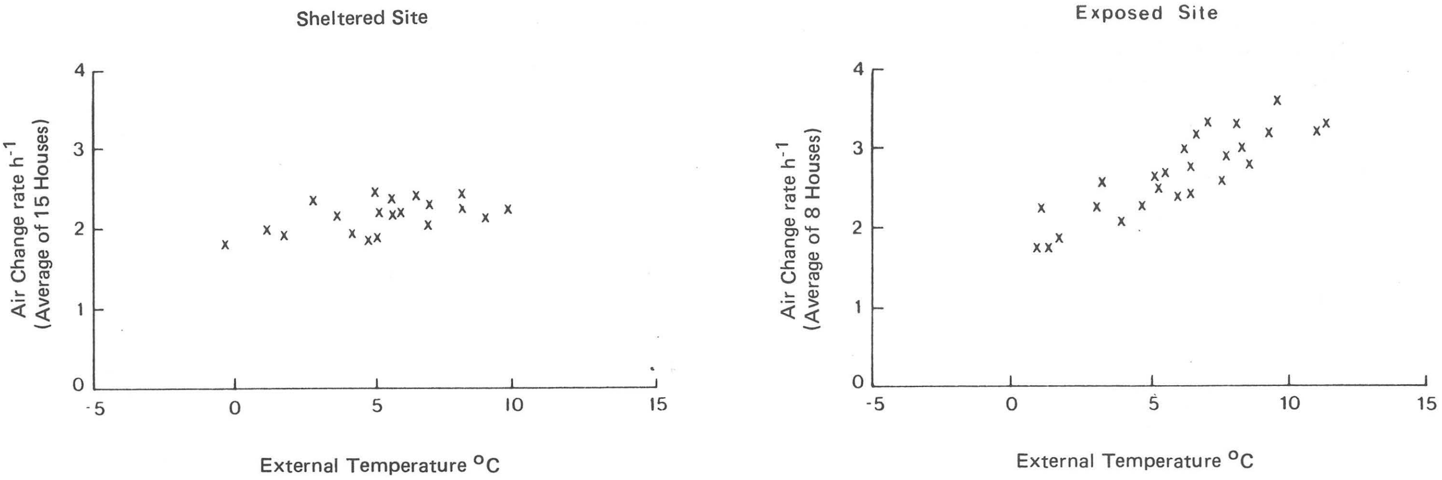


Figure 6

Variation of ventilation rate with external temperature.
(Taken from J.B. Dick & D.A. Thomas "Ventilation Research in Occupied Houses" IHVE J1 1951).

3.4 Seasonal Variation of Solar Radiation

Most incidental heat gains are irregular in character, but one component — solar gains — has a marked seasonal variation (in addition to unpredictable variations). On a short-term hour-by-hour basis, solar radiation and ambient temperature are poorly correlated, but if monthly means, averaged over several years are considered there is closer correlation. In practice there is a difference between the relationship in autumn and that during spring because of the lag between annual temperature and radiation cycles. Nevertheless it is possible to approximate the average solar radiation incident on either vertical or horizontal surfaces as a linear function of outdoor temperature.

$$I = l + m t_o \qquad (3.4.1)$$

In this case, we have

$$Q_{hk} = L_k (t_i - t_o)_k - G_{ok} - l - m\, t_o \qquad (3.4.2)$$

Where G_{ok} represents the non-solar incidental gains

If a modified definition of base temperature, and a modified val value of L are used:-

$$L^* = L + m \qquad (3.4.3)$$

$$t_b{}^* = \frac{L}{L^*}\, t_i - \frac{G_o + \ell}{L^*} \qquad (3.4.4)$$

The form of the degree-day method is preserved, while the seasonal nature of solar radiation is taken into account.

$$E = L^* \sum_k (t_b{}^* - t_o)_k \qquad (3.4.5)$$

Calculations based on Kew weather data suggest that m will be about 200 — 300 W/°C and l will be negative — about –300 to –900 W. These figures suggest that the seasonal nature of solar radiation can have a significant effect on predicted heating energy demand. Although most solar gains are via windows, indirect gains through the structure are not negligible. The latter gains will be reduced by the addition of insulation.

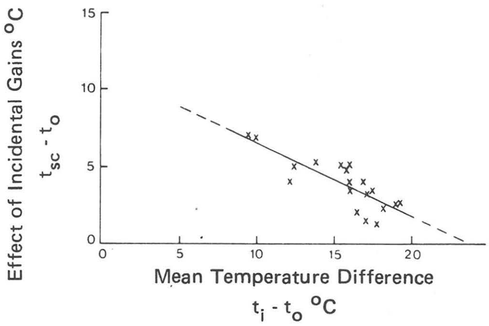


Figure 7

Variation of incidental gains with outside temperature.
Continuously heated unoccupied houses February - April.

(Based on figures in J. Uyttenbroeck & H. Heikhaus "Mesures de la consommation d'energie dans dix maisons neuves non - habitées") CSTC Revue March 1978

3.5 Partial Heating and Single Point Control

It is common for the heat input to one area of a house (for example the living room) to be controlled to maintain a set temperature in that area, while the heat output from the heating system to the rest of the house is approximately proportional to the heat output to the temperature-controlled area. A special situation occurs when only one part of the house is heated.

These conditions can be accommodated within the degree-day method in principle, although it may, in practice, be difficult to determine the values of some parameters.

It is necessary to define several additional terms for this situation:-

Subscripts c and u denote respectively, the temperature-controlled area and the rest of the house.

t_c, t_u are internal temperatures

r_c, r_u are thermal resistances between the space and outside

r_i is the resistance between the spaces.

(1-K) Q of heat from the heating system is output to the temperature-controlled area, KQ to the rest of the house.

Figure 8 summarises the principle parameters.

It may be noted that $L = \frac{1}{r_c} + \frac{1}{r_u}$

And K = 0 corresponds to special condition of partial heating.

For the controlled temperature area, we have

$$(1 - K)\,Q + G_c = \frac{t_c - t_o}{r_c} + \frac{t_c - t_u}{r_i} \qquad (3.5.1)$$

And for the rest of the house

$$KQ + G_u = \frac{t_u - t_o}{r_u} - \frac{t_c - t_u}{r_i} \qquad (3.5.2)$$

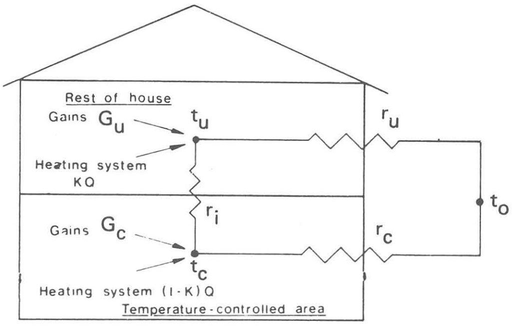


Figure 8

Diagram of principal parameters for 3.5.

From (3.5.1)

$$t_u = t_c + (t_c - t_o)\frac{r_i}{r_c} - r_i\,(1 - K)\,Q - r_i\,G_c \qquad (3.5.3)$$

Substituting into (3.5.2), after manipulation

$$Q = \frac{(t_c - t_o)\left(L + \frac{r_i}{r_u r_c}\right) - \left(G_c + G_u + \frac{r_i}{r_u} G_c\right)}{1 + (1 + K)\frac{r_i}{r_u}} \qquad (3.5.4)$$

This is of the same form as the basic equation for the degree-day method, though modified values of L, t_b must be used:-

$$\hat{L} = \frac{L + \frac{r_i}{r_c + r_u}}{1 + (1 + K)\frac{r_i}{r_u}} \qquad (3.5.5)$$

$$\hat{t_b} = t_c - \left(\frac{G_c + G_u + \frac{r_i}{r_u}\,G_c}{\hat{L}}\right) \qquad (3.5.6)$$

K may be determined from the design temperatures and heat losses of the area of the house.

In practice, $\frac{r_i}{r_u}$ is typically in the range 2 to 4, the lower value corresponding to high insulation levels, while $\frac{r_i}{r_c + r_u}$ varies between about L and 2L.

3.6 Intermittent Heating

Most houses are heated intermittently and this presents problems for the degree-day procedure. Conventionally a correction factor is applied to the predicted demand for continuous heating, but there is no simple way of determining the correct value of this factor.

The use of a correction factor is based on convenience rather than on any evidence that it is more accurate than a modified base temperature, for example. Application of the admittance procedure to the problem (23) suggests that a correction factor is the correct form of adjustment. The validity of the admittance procedure in predicting energy demand is, however, at present unproven.

Published values of correction factors (7) are derived from computer simulation of a relatively limited range of weather conditions (24) and require the user to make a subjective interpolation between values for 'heavy' and 'light' buildings.

3.7 System Efficiency

It is usual to allow for the effects of system efficiency by applying a further correction factor representing the reciprocal of the overall system efficiency. This may not be appropriate in all applications of the method.

The heat losses from a heating system can often be separated into two types (25, 26) — losses associated with the system operating time; and losses proportional to the quantity of useful heat supplied. Field trial results (27) in occupied houses suggest that in practice, the first type of loss is not generally affected by the useful heat supplied (or if it is, these losses can be absorbed into the second class).

This leads to two complementary ways of presenting the same information, demonstrated in Figure 9.

Overall efficiency is required if the total consumption is to be calculated, but in the common situation of evaluating the results of conservation measures such as insulation, it is the reduction in consumption which is important. In this case the 'fixed' losses are common to both 'before' and 'after' states. Use of the overall efficiency (which includes these 'fixed' losses) will lead to an over-estimate of the savings. The reciprocal of the slope of the 'energy in' versus 'energy out' line is more appropriate to this problem and may be termed the 'effective efficiency'. Initial studies based on a re-analysis of existing data, suggest that the error in using overall efficiency may be as high as 30%.

3.8 Base Temperature as an Indicator

It is tempting to look upon the value of the base temperature of a building as an index of its heating energy requirement. In many cases this is justifiable — an increase of insulation level or an increase of incidental gains will decrease both base temperature and energy requirement.

There are situations where this does not hold good, however, and the effect of changing glazing area is one such situation.

Consider an enclosure with a window of area Aw, conductance u_w, solar transmission factor · L^1 is the total enclosure

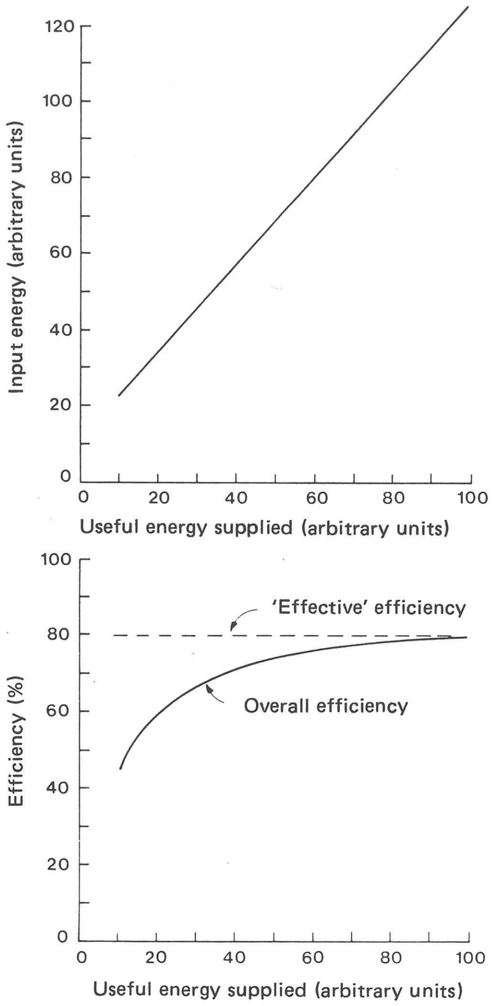


Figure 9

Characteristic form of input/output and efficiency curves.

conductance excluding the window, incident solar radiation level is $\mathcal{I}$. There are non-solar heat gains G_i

$$G = G_i + \mathcal{I}\Upsilon A_w \tag{3.8.1}$$

$$\text{And } t_b = t_i - \left(\frac{G_i + \mathcal{I}\Upsilon A_w}{L^1 + U_w A_w}\right) \tag{3.8.2}$$

$$\frac{\delta\ t_h}{\delta\ A_w} \text{ is negative only if } \frac{G_i}{L^1} < \frac{\Upsilon \mathcal{I}}{U_w} \tag{3.8.3}$$

$$\text{Energy demand, } E = (L^1 + A_w U_w)(t_i - t_o) - \mathcal{I}\Upsilon A_w - G_i \tag{3.8.4}$$

$$\frac{\delta\ E}{\delta\ A_w} \text{ is negative only if } t_i < t_o + \frac{\mathcal{I}\Upsilon}{U_w} \tag{3.8.5}$$

Davies (28) has defined 'glass wall temperature' as

$$t_{gw} = t_o + \frac{\mathcal{I}\Upsilon}{U_w} \tag{3.8.6}$$

Which is the 'stagnation temperature' which the enclosure would attain if perfectly insulated apart from the window.

The conditions (3.8.3) and (3.8.5) may be rewritten as:-

(a) An increase in window area is associated with a decrease in base temperature only if $t_o + \frac{Gi}{L^1} < t_{gw}$

(b) An increase in window area is associated with a decrease in heating requirement only if $t_i < t_{gw}$.

There are four possible situations:-

(i) $t_i < t_{gw}$ and $\frac{G_i}{L^1} + t_o < t_{gw}$

Base temperature *is* an indicator of heating requirement.

(ii) $t_i > t_{gw}$ and $\frac{G_i}{L^1} + t_o > t_{gw}$

Base temperature *is* an indicator of heating requirement (when solar radiation is zero — at night, for example — this is the only realistic case for a heated building).

(iii) $t_i < t_{gw}$ and $\frac{G_i}{L^1} + t_o > t_{gw}$

Base temperature *is not* an indicator of heating requirement.

(In this case $\frac{G_i}{L} + t_o > t_i$ and the enclosure is overheated, with no heating requirement).

(iv) $t_i > t_{gw}$ and $\frac{G_i}{L^1} + t_o < t_{gw}$

Base temperature *is not* an indicator of heating requirement.

During the course of a heating season, each situation is likely to occur from time to time, and it will not usually be possible to determine whether base temperature is or is not a reliable indicator of heating requirement.

The full degree-day method will, however, give a better indication (within its limitations described above).

Of the four possible situations, (i) and (ii) present no problems, and (iii) is fairly easily identified as overheating. It might be suspected that (iv) represents conditions which are unlikely to occur in practice. A simple demonstrates that this is not the case.

Consider a room with a heat loss (excluding window) of L^1 = 50 W/°C. There is a double-glazed window of area $A_w = 1\ m^2$; $U_w = 2.5\ W/m^2\ {}^\circ C, \gamma = 0.60$. Incident radiation is $\mathcal{I} = 60\ W/m^2$, other incidental gains total 300 W. The room is heated to 20°C with an outdoor temperature of 0°C.

$$t_{gw} = \frac{0.60 \times 60}{2.5} + 0 = 14.4^\circ C$$

$$\frac{Gi}{L^1} + to = \frac{300}{50} + 0 = 6.0^\circ C$$

$$t_b = 20 - \frac{0.60 \times 60 \times 1 + 300}{50 + 1 \times 2.5} = 13.6^\circ C$$

$$Q = (50 + 1 \times 2.5)\ (20 - 0) = 1050\ W$$

Increase the window area to 2 m^2 (and for completeness assume that 1 m^2 of wall of U value 0.3 $W/m^2\ {}^\circ C$ has been removed.)

L^1 is now $50 - 1 \times 0.3 = 49.7\ W/^\circ C$

$$t_b = 20\ \frac{0.60 \times 60 \times 2 + 300}{49.7 + 2 \times 2.5} = 13.2^\circ C$$

$$Q = (49.7 + 2 \times 2.5)\ (20 - 0) = 1094\ \text{W}$$

Thus the heating requirement has increased, while the base temperature has decreased.

4. CONCLUSIONS

Several simple mathematical models for the prediction of the heating demand of buildings have been described and compared. Overall the 'degree-day' method appears to be the most satisfactory of these, although its assumptions are not completely in accord with physical realities.

Problems relating to the use of the degree-day method have been examined, and while some are amenable, in principle, to being relieved by modifications to the method, others present more fundamental difficulties. Even where modifications are possible in principle the choice of appropriate values for some parameters remains a problem. A number of other difficulties (such as the application of the method to systems with night set-back control) have not been addressed.

Thus, although the method appears to be the theoretically most useful of the procedures not demanding the use of computers, it has significant weaknesses which are easily overlooked, especially when the calculations are carried out by designers who are unfamiliar with the basis of the method. This risk is particularly high when the calculations are carried out with a programmable calculator, because most of the operations are hidden from the user.

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