THE EFFECT OF BUILDING MASS ON ENERGY CONSUMPTION FOR SPACE CONDITIONING IN COLD CLIMATES

- AN OVERVIEW -

MARCH 10, 1982

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PREPARED FOR THE TECHNICAL RESEARCH DIVISION,
POLICY DEVELOPMENT & RESEARCH SECTOR
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EXECUTIVE SUMMARY

INTRODUCTION

The Technical Research Division of Canada Mortgage and Housing Corporation engaged Scanada Consultants Limited to review the literature on the effects of building mass on energy consumption for space conditioning in a cold climate.

OBJECTIVE

This study was undertaken to organize and present definitive results and guides on the role of mass in the energy balance of buildings, so that these results might be used in general design applications. This objective was not attained.

DISCUSSIONS

Although there is considerable literature on the topic, supported by advanced energy analysis and detailed experimentation, very little of the information in the surveyed literature could be used in a way that is generally applicable. This is not to say that all research and presentation efforts to date, on this topic, are incorrect or of little value. Rather, the literature surveyed was very instructive for the particular examples chosen in each study, and these certainly helped formulate the concepts presented in this report. However, no reliable means currently exists for extracting general rules from particular examples. In this field of study, the choice of the example itself is perhaps the most significant "parameter" affecting the outcome of a calculation or an experiment. An apparently random example building may have a poor opportunity for energy saving with mass, or may not have been designed to take maximum advantage of the available mass in the structure. Adding structural mass to such a building will have little effect on its energy balance. On the other hand, similar buildings may have a significant potential depending on the various parameters that affect the opportunity for saving with mass. No presently available procedure for rating the particular examples chosen in literature according to their predisposed opportunity was found.

A further dilemma exists in the interpretation and use of results reported in the literature. These are produced by a variety of computer models which are not necessarily compatible with one another. The mass effect under question is very complex and yet is considered to be of secondary importance in the overall energy balance of buildings. As a result, even complex computer models can incorporate a number of simplifying assumptions to model the parameters relating to the role of mass. These assumptions are rarely documented in the studies themselves or evaluated for their reliability in modelling the particular phenomenon which is being investigated. There is presently no means of systematically assessing whether established computer programs, and their implementation by various individuals will tend to predict the role of building mass accurately, or underpredict, or overpredict. Deriving generalized design data from results produced by different computer models is therefore not a reliable procedure. Neither is it reliable to derive generalized data from any one model without first examining in detail the manner in which it models the parameters relating to the roll of mass.

In short, there remains a clear need for systematic parametric study of the effect of mass on the energy consumption of buildings. Such a project is beyond the scope of this work. Accordingly, this report focusses on the discussion and elaboration of basic principles, and exposes several elements that should be addressed in the structuring of research designs and computer models.

OBSERVATIONS

In our opinion, the following are the central issues of the phenomenon under question. These are presented and discussed in detail in the body of the report.

- from the outset, if there is no surplus free heat during the heating season, there is no potential for saving heat energy using mass

- as it is surplus free heat that is the indicator of potential for saving energy with mass, the available quantity of that free heat and the coupling between its source and the available mass are the important parameters that require investigation
- heat energy saved by mass in a structure is essentially stored energy that would have been surplus free heat in a lighter structure - stored heat that is not surplus does not represent a potential for energy saving
- **heat storage capacity** and the **lag-effect** are different concepts, involving mass in different roles
- the presence of "lag" does not guarantee energy savings
- the "lag-effect" can have an impact on plant sizing - especially cooling plants in large buildings
- mass location, ventilation, interior air circulation, internal finishes, mass quantity and type all have an effect on the role of mass on the energy balance of a building. The mechanisms involved are discussed in the report but the quantitative evaluation of effects is left for further in-depth study
- different building types and occupancies will generate different levels of surplus free heat, and will have different coupling characteristics between mass and heat sources
- research designs and modelling of the mass effect must account for all of the above factors (at least initially) in order to develop generalized and credible guides and rules on the mass effect

CONCLUSIONS

Our work to date leads us to believe that, for most typical Canadian houses being built in the colder regions of Canada (excludes coastal B.C. and southern Ontario), there is little or no surplus free heat in the winter months, and there is, therefore, little or no opportunity for energy saving with mass over the bulk of the heating season in these houses. However, this can be altered by a trend towards increasing the amount of south glazing or increasing the amount of insulation towards the superinsulation level. If these occur, the opportunity for saving heat energy with mass increases. Indeed, in a highly insulated house with significant amounts of south facing windows, it may be necessary to increase building mass to avoid excessive temperature swings.

In general, the potential role of mass in the heating energy balance of buildings becomes significant where a daily surplus of free heat (overheating) occurs naturally during the heating season. This phenomenon is often observed in large office buildings, south facing apartments, passive solar houses with large south facing window areas, and similar structures.

The basic principles summarized above and elaborated in detail in the report apply generally, but they will be of particular interest to those involved in the analysis and design of buildings that can have significant opportunity for saving through the effective use of mass.

Finally, for the reasons stated above, the overall objective was not attainable within the scope of this project. However, the first principles and qualitative guidance presented in the report do serve as useful first steps in support of the quest for general rules and guidelines on the subject.

RECOMMENDATIONS

In accordance with the findings of this study, a systematic parametric study of the effect of mass on energy consumption of buildings should be undertaken. The following order of approach is recommended:

1. Study of available or surplus free heat. For a wide variety of buildings, occupancies and climates in Canada, investigate how much surplus heat is generated during the heating season. This surplus heat would represent the maximum energy savings possible using mass, and could be used to qualify building type and occupancy in a given climate. The computer model needed to do this does not have to be sophisticated, as it does not have to model the mass effect.

2. Study of practical maximum effect of mass. For those building designs, occupancies and climates showing significant "maximum potentials", investigate what are the maximum practical savings achievable through the use of mass in those buildings. In doing so, note the conditions required to obtain such maximums. The computer model must be detailed enough to model the mass effect adequately.

3. Study the effect of the various parameters affecting the role of mass. For buildings, occupancies and climates that have significant "maximum potentials", undertake parametric studies to quantify the impact of the various parameters affecting mass: mass quantity, location, coupling, air handling system control, etc. Required are a detailed research design and sophisticated computer program which models in detail all the parameters under study.

THE EFFECT OF BUILDING MASS ON ENERGY CONSUMPTION FOR SPACE CONDITIONING IN COLD CLIMATES

1.0 INTRODUCTION

The emergence of more stringent insulation and building performance standards over the last few years has renewed and fueled a long standing debate as to whether the insulating properties of a structure are the only characteristics of that structure that need to be considered in the quest for energy efficiency in buildings, or whether the mass of the structure also has a significant role to play.

Strong arguments exist for either side of the issue. In a strict scientific discussion of the properties of material, thermal resistance is the only property inherent in the structure that has the ability to resist or reduce heat transfer through a component over a period of time. The thermal resistance effect is easily expressed mathematically (one equation can represent the phenomenon adequately) and has not been questioned in principle. However, in the practical application of insulating materials, insulations do not necessarily perform as well as expected (e.g., gaps in insulation, moisture, and air flow through and around insulation all reduce its effectiveness). Also, insulation reduces beneficial winter solar gains through walls and roofs. Structural mass on the other hand has a number of observable, beneficial effects on the building operation (e.g., lag-effects, and load leveling, comfort effect etc.), which could conceivably be responsible for the fact that buildings with little or no insulation do not usually consume the exorbitant amounts of energy that simple analytical models would predict. However these potential benefits of mass are considerably more complex to model and one cannot rely on a simple statement of principle to support the position. As a result, the burden of proof has traditionally rested with the proponents of the mass effect - perhaps unfairly so.

In an effort to gain an understanding of the role of structural mass in the energy balance of buildings, a number of papers, guides and computer analysis methods were reviewed. It was found that this research area has not been comprehensibly dealt with by the majority of technical papers and analytical programs reviewed. Published experimental and analytical work has not answered emerging questions satisfactorily - with apparently authoritative work conflicting in reported conclusions on the topic - for the apparent reason that the questions to be answered were not properly formulated and resulting research designs could not lead to adequate solutions no matter how reliable the test apparatus or the analytical models were.

This technical paper will attempt to properly formulate the questions regarding the role of mass in the energy performance of buildings by reviewing the basic principles of the subject while pointing out misconceptions, and the various factors which are likely to have an impact on the role of mass. It is hoped that this study will lead to the development of criteria for sound research designs, detailed analytical modelling or experimental work on this topic, and eventual formulation of generally applicable rules and guides.

2.0 REVIEW OF PRINCIPLES AND EFFECTS

2.1 CONCEPTIONS AND MISCONCEPTIONS

A popular point of reference in the study of the mass effect in buildings has been the "lag effect" of mass in a wall or roof that separates the interior controlled space and the exterior climate. Observable by simulation or by experiment, the "lag- effect" delays and lessens the impact of diurnal variations of weather on the interior space heating or cooling systems. This is illustrated in Figure 1 for a one-day cycle of temperature variations in the winter.

There are several ways in which this effect can be beneficial in the task of providing a controlled or liveable environment as will be discussed below, however it has been commonly believed that the "lag-effect" was the fundamental explanation for reduced energy consumption in massive buildings. In fact, the "lag-effect" is, at most, a partial explanation of reduced energy use due to mass and, in some circumstances, may not be involved at all - even though the mass may be saving appreciable quantities of energy.

The fact that "lag-effect" has become synonomous with "mass-effect" has unfortunately resulted in

1. extensive research work and publications that use a "lag-effect" explanation to quantify energy saving (e.g. the "M"-factor approach, ref. 1) and ...

2. ... equally extensive work and publications discrediting that research without resorting to first principles (eg. ref. 2), resulting in ...

3. ... the loss of a simple method that may have been useful for calculations that do depend on the "lag-effect" (e.g. design load determination), and ...

4. ... the reduction in credibility of recent modelling efforts because results were not qualified by the ranges for which they applied and by the very important assumptions used in the modelling procedures (e.g. ref. 3, 4, 5).

As a starting point, the concepts of "lag-effect" and "energy-storage" must be differentiated. The ability to store heat is a fundamental property of mass which manifests itself in various ways given various energy flow systems. The "lag-effect" is a derived concept - a particular manifestation of energy storage - arising from the properties of heat capacity and conductivity of a material, when the mass layer is subjected to dynamic temperature differences across it.

There is another important manifestation of the "energy-storage" capability of mass, and this is best illustrated by the role of storage in a solar heating system. Solar collectors are often sized to create a surplus of heat energy during the sunny hours of the day. Heat storage is required if that surplus is to be used later at night, or the next day when there is need for it. The solar-heating example is useful to illustrate that it is not the storage of all collected energy that is considered useful - even though this may occur as a natural course of operation - but it is the storage and eventual use of collected surplus energy that defines the storage role in the energy balance of a building. In fact, the role of structural mass of a building is much the same as that of the storage medium in the solar-heating system.

Stated as a general principle:

> The property of specific heat capacity of a material does not "interfere" with other properties of the material: e.g. thermal conductivity and absorptivity of solar radiation. Additional heat capacity does not resist heat flow, and it cannot induce more absorption of solar radiation. Therefore, for a given set of conditions (interior and exterior temperatures, solar radiation, thermal conductivity of the materials, surface absorptivity and surface film heat transfer coefficients) the gross heat gains and heat losses through the structure over the period of time (say one week) will be unchanged by the presence of more or less mass in the structure. Since mass can neither create nor destroy energy, the heat energy that is saved with additional mass is energy that is available in a less massive structure but could not be used or stored at the time it was available, and would have been vented, cooled or simply lost to the outdoors as indoor temperatures increased.
>
> HEAT ENERGY SAVED BY MASS IS ESSENTIALLY STORED ENERGY THAT WOULD HAVE BEEN <u>SURPLUS</u> FREE HEAT IN A LIGHTER STRUCTURE. STORING HEAT THAT IS NOT SURPLUS DOES NOT REPRESENT A POTENTIAL FOR HEAT SAVING.

The implications of this stated principle in the assessment of the role of mass on the energy consumption of buildings is extremely important: quantification of the "surplus-energy storage" effect of mass is not a question of simulating or measuring the response of a wall or a roof to weather fluctuations over a short period of time. It must involve the proper accounting of all of those factors affecting the creation of a surplus of free heating energy in a building (heat gains from lights, appliances, equipment, the sun), the ability of the mass to store and release that surplus when required, and the variability of all of these conditions over the entire heating season.

As an indicator of the importance of these factors consider two examples: a poorly insulated house with little south facing window area in a cold region of the country, and a well insulated office building with ample south windows in a warmer area of the country. The poorly insulated house will likely need all the solar and internal free heat for heating as it is made available over most of the heating season. There is little role for mass to save energy in that situation. The office building on the other hand may be generating as much surplus free heat during the day as it could use to heat overnight. The potential for reducing the heating bill via the improved use of mass in this case can represent a considerable portion of the heating requirement. Moreover, in the latter example, the quantity and ability of the mass to store and release heat (thermal coupling) become important factors in the analysis.

From these examples and discussion we draw the following conclusions:

- the adequate modelling or monitoring of the role of mass in a structure in the energy balance of a building must take proper account of the dynamic heat gain and loss characteristics of a building, the thermal coupling between mass, heat source and heat loss areas, and the mass quantity.

- the sensitivity of the role of mass to the many factors just described, and the variability of those from one application to another suggests that a reliable chart or table expressing the effect of mass on energy use will have to account for more parameters (i.e. thermal coupling) than those found in literature. Presently available charts, notably the solar load ratio methods, "hide" the quantities that are of interest: amount of mass, thermal coupling.

- the nature and variability of the important factors - free heat surplus and the full spectrum of thermal coupling as it occurs in houses and buildings - should be explored and defined <u>in detail</u>, to expose the important issues involved, both for building designers who are concerned about the use of structural mass in their energy design and for the guidance of future modelling and monitoring activity in this field.

These concerns are addressed in the sections below.

3.0 PRINCIPLES IN CONTEXT

3.1 EXTERNAL MASS AND HEATING ENERGY CONSUMPTION

Solar heat gains on the exterior portion of walls and roofs reduce the heating requirements of a building during the heating season by counteracting heat flow from the warm inside to the cold atmosphere. In certain circumstances, the flow of heat may actually be reversed.

In warmer climates, and for certain types of buildings and locations, the winter time solar gains through the walls and roofs may be so high that no heat at all is required during peak sun hours and venting or cooling may be needed to maintain comfortable conditions inside. Such a phenomenon can be quite common since solar gains through the structure and windows, as well as gains generated from equipment, appliances and people often tend to peak at about the same time of day.

In the case of heavy construction, the solar gains accumulated through the walls and roof will only affect the internal space hours after the peak sun hours (the lag effect of massive construction) when there may be no surplus of internal gains and when a lighter building would require some space heating. The lag effect spreads the free heating energy originating from this portion of the structure over time, thus reducing the peaking of indoor temperatures during the day and forstalling the need for heating later in the evening. This is the way heavy construction in walls and roofs saves energy and improves comfort in moderate climates.

In colder climates, such as encountered across most of Canada, the opportunities for saving heat energy by utilizing the mass effect shift from the exterior structure of the building to the interior. Insulation of the outer structure of buildings has the primary purpose of reducing the potentially high heat losses to the outdoors. However, the insulation also reduces solar gains through the opaque portions of the structure in the same proportion as the heat loss reduction (a positive effect in the summer but not in the winter). Mass on the exterior of the insulation layer has less of a role to play because it is not storing the larger quantities of free heat that lead to a surplus inside the building. The internal gains however, remain the same with added insulation. These are gains from equipment or appliances, people and solar gains through windows. On a relative basis therefore, the internal and "window-solar" gains become more significant and contribute to a greater extent to potential heat surplus, which is the indicator of an opportunity for saving heat with mass.

Thus, in colder climates, the most effective use of thermal mass to moderate interior temperature swings and save energy in insulated structures occurs when the mass is placed inside the insulation where it will be in contact with that greater quantity of surplus free heat.

3.2 INTERNAL MASS AND HEAT ENERGY CONSUMPTION

3.2.1 Basic Principles

There are many factors that affect the heating energy balance of a building at any point in time:

- heat loss through the envelope
- heat loss as a consequence of ventilation/air leakage
- heat gains from appliances, equipment, people, lights, etc.
- heat gains from the sun through windows
- heat gains from the sun through the opaque portion of the envelope
- heat stored previously in the mass of the exterior and interior structures
- air circulation within the structure
- heating and conditioning control system (thermostat setting schedules)

These factors combine in the energy balance of a building in the following fashion: all the gross heat losses and heat gains can be added and the difference between losses and gains determines the amount of purchased heat required. (Figure 2A)

Over the course of a day during the heating season, there may be more gains than losses at some periods resulting in a surplus of free heat -- for example, a house with good insulation and south window area. This effect is illustrated in Figure 2B.

This heat must either be vented, removed by cooling, or stored to prevent overheating of the interior air. Venting in the winter time is a waste of energy, and cooling of the air and structure to remove surplus heat is even more wasteful at a cost of more energy. Storing this heat can be particularly useful as these periods of surplus (coinciding periods of high solar gains and internal gains) can be followed by periods of low free heat in the evening or night, for many types of buildings and occupancies. Stored free heat can displace purchased energy later in the day or evening, thus resulting in a net saving of purchased energy. (Figure 2C)

The above discussion illustrates the simple concept of heat saving with mass. In fact the mechanisms are more complicated.

Like any storage system, there must be a means of transferring the surplus heat to the mass, and later a means of transferring heat from the mass to the areas where heat is needed. However, in a building, there are many sources of heat, yet there is no control system to regulate the storing and releasing process. The process of storing heat in, and releasing heat from, the building's mass is more or less automatic. Large increases in interior free heat cause local temperatures to rise. Heat will then flow to mass in quantities that depend on the thermal coupling between heat source and mass and the capacity of the mass to store that heat. As heat is needed later on, air temperatures will drop and the heat stored in the structural mass is available to supply the demand. That stored heat is used instead of purchased heat supplied by the heating system.

As this process uses the building's inherent mass there is no additional capital cost attributable to it nor is there any on-going day-to-day operating cost or attention required. The mass effect is a bonus that can increase with heavier construction materials. On the other hand, the mechanisms just described (air temperature swings, thermal coupling to mass) are not normal design considerations and can easily be overlooked or interfered with in the course of building design and operation.

For instance, the same factors that drive the storage/release cycle (i.e. inside air temperature swings and air circulation) are also controlled by the heating/cooling and air handling systems. The heating and cooling control systems are often designed or operated to eliminate heat surplus immediately as it occurs (e.g. air return inlets located in light fixtures), at a cost of more energy, while leaving no role for the mass to play in the process. Therefore, saving heat energy with mass can be viewed as a bonus, but there are many factors that can improve that bonus and that should be considered at the design state.

These design considerations fall into two categories. Those that define the <u>opportunity</u> for saving and those related to the <u>effectiveness</u> of mass in its energy saving role:

Factors Defining the Opportunity

- solar gains through windows
- internal heat gains
- insulation levels (R values of the envelope)
- ventilation rates

Factors Defining the Effectiveness

- amount, heat capacity and location of building mass
- thermal coupling between mass and heat source
- heating and cooling system control provisions

The role of each of these "effectiveness" factors and how each relates to the "opportunity" factors is discussed in the following subsections.

3.2.2 Quantity of Mass

Most materials undergo an increase in temperature as they absorb heat from an adjacent heat source. Some materials however, can store a given quantity of heat with much less temperature rise than others which occupy the same volume. This characteristic is referred to as "high heat capacity per unit volume". [Other materials store heat by changing phase. There is a good potential for heat storage in such materials. Regretably these are not construction materials.]

The role of "high heat capacity per unit volume" for temperature control and energy saving is as follows: surplus internal heat gains raise the temperature of the inside air quickly because air has an extremely low heat capacity. As the air temperature increases, heat flows from the air to the cooler structure and furnishings wherever they are in contact with the air. Solar radiation through windows is absorbed directly by the structure, without heating up intervening air, by those portions of the structure on which it impinges directly, or by reflection. However, if these structures have low heat capacity, their temperature will increase quickly in turn and the flow of heat from the air will be reduced. In fact, with sufficient solar radiation, a light structure will heat up faster than the air, and the heat flow will reverse. Little heat is stored and the air quickly becomes too warm for comfort.

With a structure that has a high heat capacity, the temperature of the structure does not increase very much and heat continues to flow from the air to the structure. The air temperature is thus moderated and reaches a peak temperature that is comfortable, if there is enough mass. This is the comfort effect of heavy construction.

The process permits a heat energy saving in the winter and a saving in cooling energy in the summer. In the winter, only <u>surplus</u> internal heat (as often occurs in the daytime in well insulated structures) causes the interior air to heat up - the rest is needed to make up for heat losses to the outdoors. If this surplus is stored in the mass, as described above, it can be used later in the day. In the summer the storage effect of mass tempers rapid temperature increases and thus forestalls, or reduces, the need for cooling until a later period in the day, when free cooling may be available.

3.2.3 Thermal Coupling

An important factor relating to the effectiveness of mass in its heat saving role is the thermal coupling between heat source and mass. This is the ability of a building and its components to get surplus heat into the mass, and out again as needed.

Many of the heat sources in a building are not in direct contact with the mass in the structure (e.g. carpeted floors can prevent solar energy from directly entering the floor mass). Many factors tend to de-couple heat sources from the structural mass. The structural mass is distributed throughout the building whereas internal heat gains can be concentrated in particular areas of the building (eg. south facing areas with windows, rooms with high equipment or appliance concentrations, etc.).

Poor coupling can be manifested in two ways:

(i) In the storing phase of the cycle, poor coupling prevents surplus heat from reaching the mass quickly enough and cooling or venting of warm air results, even though the mass may be still cool and has a large potential for storage. <u>The potential to save energy is lost immediately as the surplus heat is removed</u>.

(ii) In the releasing phase of the cycle, if poor coupling exists between mass and areas of heat loss, then the inside air will cool down below acceptable minimums and the heating system will turn on, before the still warm mass is able to contribute its heat. This does not immediately waste the utility of stored heat in the structure, but imposes a lag effect - the heat takes longer to come out. If the coupling is very poor, whole portions of the building mass may stay warm until the next day's period of surplus and then the mass's potential to store heat is reduced. The mass must lose its stored heat in order to be ready to store the next day's excess.

It should be noted that, to the extent that it is variable, it is more important to have effective thermal coupling during the storing phase than during the releasing phase. This is because heat surpluses usually only last for a short period of time (e.g. when the sun is striking a particular window) and ineffective coupling results in an immediate loss of potential savings. On the other hand, release of stored energy can normally take place at a slower pace (e.g. overnight).

Three factors have a bearing on the effectiveness of thermal coupling:

- conductivity of the mass and any finishing materials covering it
- the extent to which air circulation within the building brings all available mass into play
- the location of the mass.

Conductivity

Some materials are better than others for promoting heat transfer between available free heat and mass. For instance, quarry tile or linoleum tile will allow local surplus heat in the air and from the sun to transfer more freely to concrete floors. Thick carpet and underlay will reduce the rate of flow of heat to the concrete floors.

Good conductivity is also desirable in the materials which constitute the mass of a structure. Since massive construction (slabs, walls) can be thick, the mass at the very centre of the structure will only be usefully coupled to surplus heat at the surface if the conductivity of the material itself is high. Otherwise the intervening material would act as insulation.

Designing for adequate thermal coupling can conflict with interior finish designs, and trade-offs have to be made. For instance, thick carpeting may be a desirable feature of the interior design but this would interfere with thermal coupling. Halls and the borders of rooms and offices could be left uncarpeted as a compromise. This illustrates another important factor that must be considered in modelling the effect: only a portion of the structure can be properly coupled to the inside air, and this must be accounted for in establishing the effective mass of the building.

Air Circulation

Thermal coupling can be achieved by natural and forced air circulation. Design of forced circulation systems offers some potential to improve thermal coupling. Forced air systems can be designed to induce air flow from areas of high heat gain (areas with equipment, light fixtures, south facing rooms, areas of activity in houses) bring this air into contact with as much structural mass as possible, and direct it to areas of high heat loss (north facing zones or rooms, peripheral areas, etc.). For example, hollow core floor slabs or the cores of interior masonry walls that are used as integral elements of the air circulation system promote thermal coupling with air circulation.

Location

The effectiveness of structural mass in its thermal storage role will vary according to its location relative to heat gains and losses in a building. For example, mass that is located where sunlight through the windows will fall directly on it plays an important role in moderating temperatures and storing energy. The radiative heat is absorbed into the mass without raising the temperature of the intervening air, thus not immediately requiring modulation of air temperature. It is therefore ideally coupled to the heat source (the sun). Again interior design features can improve or hinder this process. Light coloured or sheer drapes allow sunlight to reach the mass whereas dark heavy drapes absorb the radiation and heat the air next to the window and the energy is immediately lost by conduction through the window.

Another necessary condition for the "energy-reduction" effect of mass is that it must not only be located near the sources of heat gain but also near the areas of heat loss. In the above example, sunlit mass is not only well coupled to the heat source but also, the presence of windows and exterior walls in close proximity assures that the mass will be in a high heat loss area at night. Natural convection during the release phase may be the only mechanism needed to achieve the coupling required.

If the mass is immediately on the inside of the insulation (i.e. part of the building envelope) it is very well coupled to the area of heat loss, in that all stored heat will be used before heat losses through that portion of the structure contribute to the heating requirement. This feature does not hamper its ability to store surplus heat. During the winter, mass in this location will always be ready to accept the next day's surplus of heat. This is an important consideration in buildings with regular daily periods of high internal heat gains.

Structural mass that is not located near the exterior of large buildings may be thermally coupled well enough to store high internal gains generated locally, but adequate coupling to the peripheral areas may not be available to allow that heat to be discharged from the mass. In such a case the forstalling of purchased heat does not occur, and the mass may not be available to store the next day's heat surplus. Forced air circulation overnight could rectify this problem. If gains are high and regular on a daily cycle, more coupling (i.e. forced circulation) is required. If gains are periodic, natural circulation may be enough to discharge the mass in time for the next period of high internal heat gain.

3.2.4 The 'Time Constant' parameter

It is evident from the above discussion that there is a large gap between the concept of "average thermal coupling" used in analytical models today, and the broad spectrum of thermal coupling characteristics that actually occur in buildings. As a starting point in the process of sorting out "what mass" has "what coupling" in buildings, it may be advantageous to make use of the <u>time constant</u> concept.

The time constant is the ratio of the heat capacity of a quantity of mass to the heat transfer characteristics between the mass and heat source or heat sink, and has a unit of 'time'. The parameter thus accounts for quantity of mass, location, convective, conductive and radiation heat transfer characteristics of the environment around the mass, all in one term. There are several uses for this property, one of which is the order of magnitude assessment of whether mass will have an effect or the dynamics of an energy system. The period or duration of a cyclic heat transfer (e.g. solar heat, warm inside air) to the mass has to be the same order of magnitude as the time constant of that mass in order for it to have an effect. If the time constant is too long (say more than one day) the mass cannot charge nor discharge its energy quickly enough to change the energy balance of a building the course of the daily cycle. Long time constants are usually due to poor coupling between mass, and source or sink (a low heat transfer value in the denominator of the time constant expression results in a high time constant).

Short time constants (say less than one hour) indicate that the mass can be used in heat gain cycles that have similarly short periods - for instance solar heat on a variably cloudy day. It is important to be able to store the surplus of heat when it is available. However very short time constants can be an indicator that there is not much mass to do the storing.

The development of this approach to classifying the various mass elements of a building according to class of time constant appears to be the key to systematic analytical solutions to this problem, and the eventual production of design guidelines and simplified analytical methods.

3.2.5 Temperature Control

The important role of small temperature swings of the inside air in driving the storage cycle described above cannot be overlooked. Structural mass will itself moderate large temperature swings yet it is possible to set heating and cooling thermostat settings in such a way that these systems "cut-in" before mass is given a chance to work. If the cooling thermostat is set just above average room temperatures in a cooled building, this leaves little temperature difference available to induce significant heat transfer between air and mass. Winter time surplus free heat will be removed immediately (perhaps even with the use of further energy in the cooling system) rather than stored and used as heating later. Premature opening of windows on a sunny winter day has the same effect.

Structural mass in the interior of the building will moderate temperature swings, but if the occupancy of a building requires a tighter control on temperature swings, the savings opportunity for mass will be reduced.

Variable temperature (ramp) thermostats could be used to prevent very rapid changes in interior temperature, where good thermal coupling between air and mass cannot be achieved. These allow some energy to be stored in mass while maintaining comfort. More discussion of temperature control strategy can be found in Reference 5.

For housing, although there might not be a cooling system that could defeat the work of mass during the heating season, the venting of hot air (i.e. opening windows) during sunny winter days can eliminate surplus heat.

3.3 STRUCTURAL MASS AND HEATING PLANT SIZING

The inertial lag effect of mass acts to smooth the impact of low exterior temperatures on the heating system as illustrated in Figure 1. The important phenomenon at work here is the lag effect induced by the presence of mass in the pathway of heat flow through the building envelope.

Consider, for example, a thin vertical slice somewhere part way through an exterior wall. As the exterior temperature drops toward, say, an overnight low, the temperature of each such slice will tend to drop toward the level it would be at in a steady state temperature profile. If, however, the subject slice has appreciable thermal storage capacity by virtue of its mass, its temperature will drop more slowly than the exterior air temperature. The next inner slice will therefore be subjected to a lower temperature difference than would otherwise obtain and the heat flow through it will be temporarily reduced. When this effect is integrated for the whole thickness of the wall, a significant temporary reduction in heat flow from the interior can result. On the other hand, the massive layers in the wall will be equally slow to respond when the exterior temperature rises in the morning, resulting in temporarily higher heat flow than in light wall. The net result is that, other factors being equal, total heat flow (the area under the curve in Figure 1) is the same for light and heavy envelope components but the peak flow rate is significantly reduced for the massive structure.

This effect is acknowledged by ASHRAE (6) which recommends the use of less stringent design temperatures for heating plant sizing in heavy structures.* For heavy structures with little glass area the 97.5% winter design value is recommended rather than the 99% design value, which is recommended for medium structures.** This can be translated into a reduction in heating plant size of perhaps 5% or more in Canadian cities with moderate climate. However, this saving in plant sizing is only a real saving if designers of light buildings use the 99% design value - it is apparently not common practice to do so.

NOTE: The benefits of mass in lowering required heating plant capacity may be reduced and even reversed if nighttime thermostat setback is used. The winter time design conditions generally occur between 6 a.m. and 8 a.m. (6). As the thermostat is set forward in the morning to accommodate the comfort requirements of occupants, the system may already be running at capacity to accommodate peak loads at that time. The system is asked not only to meet peaking heat losses but also to reheat the now cool massive structure. It is also argued (ref. 7.8)

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* ASHRAE (6) uses the terms "light", "medium" and "heavy" or "massive" to differentiate between various types of construction but gives no quantitative definition of these terms.

**Definition: In a normal winter, only 2.5% of all January hours would be at temperatures lower than the 97.5% winter design temperature value. This definition applies to Canadian cities only - ref. 6.

that due to the discomfort of cooler mean radiant temperatures of the mass after setback, the heating system must overcompensate for this effect by overheating the room - thus creating an even greater demand on the heating system. The implication is that the "thermostat setback" may not be an energy saving measure in heavy construction. More analytical work is required to resolve this issue.

3.4 MASS EFFECTS ON COOLING LOAD AND COOLING ENERGY

During the cooling season, internal heat gains from equipment, people and window solar gains, as well as solar gains through the opaque structure all contribute to the cooling requirements of a building. Mass in the interior of a building can store some of this heat with only a moderate temperature rise, thus delaying the need for cooling. Also, solar gain absorbed in the opaque portion of the exterior structure will only affect interior temperatures hours later (lag effect) again delaying the need for cooling. Both the internal storing and the lag induced by mass in the outer walls and roof tend to reduce peak daytime cooling loads. This would suggest that heavy construction affords a lower cooling plant capacity, all other factors being equal. Analytical modelling supports this hypothesis (ref. 5, 7, 8).

The heat stored in the massive structure during the periods of high heat gain in the summer also represent a potential for saving in cooling energy if this energy can be vented or cooled with less energy during the cooler evenings and night. The cool summer nights experienced by Canadian cities are thus an indicator of the potential for saving cooling energy with mass.

Thermal coupling between mass and heat source, quantity of mass, cooling thermostat control, and night time thermal coupling of mass with exterior air are all factors that affect the ability of mass to save cooling energy and cooling load.

These factors are identical to the requirements for saving heating with mass in the winter time. The difference is one of accounting, not mechanics - the energy stored in the mass represents a deferred cooling load in the summer and a potential displacement of heating load in the winter. In fact, some buildings have an overlap in cooling and heating season (cooling during the day, heating at night). Here, the mass saves daytime cooling <u>and</u> night time heating with the <u>same</u> stored energy. Thus, considerations of thermal coupling discussed in Section 3.3.2 apply equally to cooling saving effectiveness.

The cooling thermostat control can play an important role in saving cooling energy with mass. The interior mass stores excess heat gains with moderate increases in its temperature. Clearly, the higher the inside air temperature is allowed to climb during the day, the more heat will flow to the cooler structural mass and the greater is the potential for saving. Timed cooling system thermostats (called "ramp" thermostats) are available which allow the temperature at which cooling is initiated to be gradually increased from a low setting in the morning to a high setting at the end of the day according to a preset schedule determined at the design stage. The gradual temperature increase, which is designed not to be noticed by the building occupants, allows the air temperature to remain slightly higher than the even more gradually increasing temperature of the building mass and thus the storage mechanism continues to function throughout the day. Because mass is allowed to store energy during the high heat gain periods, the energy stored represents both a reduction in the peak load used in designing the cooling system and, assuming it can be removed by free cooling in the evening, a reduction in cooling energy required. Such a scheme is ideal for daytime occupancies where warmer evening interior temperatures are of little concern with respect to comfort of occupants. For further discussion of cooling thermostat control, see reference 5.

Finally, there is an indirect saving in cooling energy achieved by reduction of the cooling and ventilation system capacity afforded by heavy construction. The cooling plant and fans represent in themselves major cooling loads due to the energy required in operation. Thus for each unit of peak cooling load saved there is an associated ongoing saving in cooling energy due to the reduction in load caused by the plant operation.

Quantification of these savings while properly accounting for heat gains, heat loss, mass quantity and related thermal coupling for heat storage and heat release, weather patterns, and mechanical system characteristics and control requires the detailed energy modelling of a specific building.

Additional consideration must be given to the thermal coupling between the mass and the cool night-time outside air. The temperature difference between inside and outside may be too small to release the stored energy by conductive heat loss through the building envelope - especially in insulated structures with little window area. A greater amount of forced ventilation during the cool night can "flush" excess heat stored in the mass at less expense than mechanical cooling. Modelling efforts should therefore take this factor into account in assessing cooling energy savings potential. In such designs, however, certain conditions might cause more energy to be used in the mechanical flushing than is saved by the influx of cool night air. Detailed modelling is required to establish design criteria.

3.5 APPLICATION OF PRINCIPLES IN CONTEXT

As discussed, the process of saving heat energy with mass depends on there being a surplus of internal free heat gains during winter days. Various building types and occupancies achieve a daily heat surplus naturally (eg. large office buildings) while others can benefit from additional winter time free heat gains.

In buildings with low internal gains from people, equipment, appliances, etc. a surplus of winter time free heat will exist if the insulation levels and the proportion of south-facing window area (where the south face of the building is not shaded from the sun) are high enough. Both of these features are heat energy saving measures in themselves, but the presence of mass inside the building will make better use of the incoming additional solar energy with added comfort. Furthermore, the moderation of interior temperatures by means of thermal mass allows for design of even more south window area (and therefore more free heat) for the same comfort level.

The right balance between south facing window area and the quantity of internal mass to store surplus heat must be achieved to prevent overheating. Venting, and thus wasting the energy can result if these components are not adequately balanced.

Passive solar design thus requires the balancing of the amount of insulation, south facing window area and internal mass, while locating as much mass as possible to achieve natural thermal coupling, and providing a forced convection system to effectively couple the rest of the available mass in the structure.

The state of the art of passive solar design is presently developing in Canada and is the subject of various studies. The complex relationship among the building's heat loss characteristics and internal mass, the outdoor temperatures and the timing, amount and direction of available sunshine all require the use of computer modelling techniques to reliably estimate the passive solar contribution to the building's energy requirements and the possibility of excessive temperature swings. As more and more such modelling is done and as more experience with this type of building accumulates, rules of thumb emerge which can be used to develop preliminary designs for subsequent computer analysis. Some considerations that could affect design energy modelling of dwellings are described below.

High-Rise Residental Buildings

For all intents and purposes, high-rise residential buildings can be viewed as a collection of individual units. Code restrictions prohibit air circulation between areas of the building so the mass on one side of the building is thermally uncoupled from mass at the other side. This places some importance on the use of mass in south facing units. Here, the heat losses are relatively low by virtue of the fact that, except for corner units, only one wall per unit is exposed to the outside. Solar gains can be high through south facing windows, and appliance and people gains are concentrated in relatively small areas. Thus, south facing units in apartment buildings are potential passive-solar units, with one disadvantage: they have little available space for heat storage other than the structure itself (detached houses can presumably dedicate portions or all of basement area and structure to heat storage). Heavy construction may be the only practical means of increasing the available mass to moderate living space temperatures and make best use of passive solar gains in apartments.

<u>Highly-Insulated Houses</u> (Single-family, Semi-detached, Row and Townhouses)

As new housing is built to improved insulation standards, the annual heat loss of the houses diminishes but window-solar gains and internal heat gains remain the same. A new breed of houses is thus being developed in which internal heat gains and window-solar gains can be relatively high compared to heat loss. These are a particular version of passive-solar design in which insulation levels are so high that even moderate south window exposure creates the potential for excessive temperature swings. Mass placed on the interior of the house can play an important role in maintaining comfortable living conditions in these houses while saving heat energy in the process. A house of heavy construction can accomodate about 50% more south glazing than a house of light construction without overheating and, as a result, its purchased energy for space heating would be reduced by 10% to 20% (9).

This mass can take a number of forms: masonry walls, hollow core slabs, basement walls and slabs with externally placed insulation and party walls in multiple housing. There are also ways of deliberately increasing interior mass: fireplaces, Trombe walls, etc.

Large Office Buildings

Large office buildings have traditionally had high internal gains relative to heat loss by virtue of large useable floor areas relative to exposed surface area. An entire floor of activity generates heat while only the peripheral walls and windows are losing heat. Furthermore, extensive south facing fenestration generally adds to the surplus of interior heat. All gains are cyclic in nature and peak in the daytime.

Such buildings are ideal for heat storage via massive construction and this can save both heating and cooling energy. The physical size of the spaces involved make it important to plan the thermal coupling of interior and exterior spaces to make best use of winter heat gains and total building mass.

Hollow core floor slabs are also well suited to large office buildings, as the cores can become an integral part of the ventilation system which provides an excellent surface area to expose more of the structural mass to internal gains.

It is likely that innovation will reduce internal heat gains in office buildings (e.g. improved lighting design) but higher insulation standards will maintain the high cyclic heat gain to loss ratio that is the indicator of opportunity for saving with mass.

Retail Buildings

Opportunities for saving with mass in retail buildings will vary significantly from structure to structure depending on application, location etc. Small retail stores often have large windows for advertising purposes. Solar gains through these can be excessive for the space involved and massive construction can be an alternative for temperature control and energy saving. Peaks in customer activity may also be a source of surplus heat requiring control.

Schools and Universities

These structures are similar to office buildings in terms of internal heat gain to loss ratio but experience more cyclic concentrations of heat gains and therefore, potentially greater peaks of excess heat in local areas: filled classrooms with south facing windows, student gatherings for sport, assemblies, etc. Thermal coupling between rooms and other areas of these buildings via forced air circulation is very important to distribute excess heat, and store this in all available mass.

Further, schools and universities have traditionally had large window areas for classrooms. Should insulation requirements of codes increase in the future, south facing classrooms would experience high excess heat - these "passive-solar" rooms would be prime candidates for the use of massive construction.

Warehouses

Warehouses can differ from other types of buildings in four ways that affect their energy requirements. First the owners are often willing to allow a greater range of interior temperature. Whereas in an office building the permissable temperature range might be between 20°C and 26°C during occupied hours, in a warehouse it might be between 13°C and 29°C. Second, because of this, warehouses tend to have less insulation. In fact, since a lower interior temperature is intended, the economic amount of insulation will be lower and this may be recognized in building codes. The third characteristic of warehouses is that they usually do not house activities which generate significant amounts of internal heat gain. Finally, the mass of the inventory within the warehouse can be significant depending on the nature of the stored goods. The combined effect of these factors on energy requirements and the roll of structural mass is complex and depends upon which of these factors are present and to what degree.

The possible combinations of design situations that arise from these different characteristics are numerous. Some examples are discussed in Table 1.

TABLE 1. Role of Structural Mass in Energy Consumption of Warehouses

Design Situation	Role of Structural Mass
1. Low inside temperatures are tolerable and therefore there is little insulation of the structure. Inventory is light* and only moderate temperature swings are acceptable.	Little or no insulation in the structure results in relatively high solar gains through the opaque walls and roofs. Masonry and concrete walls and roof moderate the temperature swings due to solar gains through those components and may require less heating energy than light structures.
2. Same as 1. but large temperature swings are acceptable and inventory has considerable mass.*	Large allowable temperature swings indoors, and high mass of the inventory signals an already high heat storage capacity of the inventory. Masonry or concrete structures would allow a large array of south facing windows to increase free heat component.
3. "Liveable" inside temperatures (20°C) moderate temperature swings allowable. Inventory has little mass.	Such structures normally require insulation to reduce heat loss. Here, the combination of insulation on the outside of the mass layer in the structure and ample south facing windows can combine to produce and store significant quantities of solar heat - i.e. a passive-solar warehouse.
4. Same as 3. but considerable mass in the inventory. See Figure 3.13.	Such warehouses could probably tolerate very large south window exposures due to combination of inventory mass and structural mass inside the insulation. The potential exists for a very low space heating requirement.

* Light and heavy inventory from the thermal standpoint is approximately the same as for the weight standpoint: heavy to lift indicates potentially lots of heat storage capacity.

4.0 MODELLING CONSIDERATIONS

4.1 DETAILED ANALYTICAL MODELLING

The quantification of annual heat energy saving due to the additional mass in heavy construction of a building can only be done reliably by detailed energy modelling of a building for a full heating season.

To date, no sophisticated program is available that specifically models the dynamic energy flows inside a building where mass is "doing its work". In these models, factors that are believed to be important (eg. thermal coupling between mass, heat sources and heat loss areas) are usually estimated for the purpose of first approximations of the mass effect. This is not to say that they are inadequate for the purpose for which they are designed (i.e. energy demand prediction); rather, they are simply not designed to investigate the mass effect in detail.

Perhaps the largest single error in these approximations is that all or large portions of interior mass is assigned an average thermal coupling. As discussed in the main text some portion of the structural mass is well coupled, other portions are not, depending on location, surface finish, air circulation, etc. The assumption of average coupling may overestimate the amount of mass that can be "called into service" in the structure. This modelling simplification can reduce the apparent benefit of "heavy" construction if the models show light structures storing more of the available surplus in its mass then is achievable in normal practice.

Proper modelling of the mass effect in insulated buildings must (among other things) account for the structural mass in different categories according to their respective thermal coupling characteristics.

Therefore, when a particular design is being evaluated and there is a desire to quantify the mass effect, care should be taken in the modelling of thermal coupling of the various mass components.

4.2 RESEARCH DESIGNS AND PRESENTATIONS

In all likeliehood, the derivation of simplified rules-of-thumb or graphs showing the effect of mass on the energy consumption of a building will result from a large number of detailed simulation of example buildings. It becomes imperative therefore that the example buildings and the models used to analyse these are properly qualified or described in terms of those factors that effect the mass role directly.

Important parameters that describe the building are:

- location of mass relative to the insulation layers

- the ability of the building design to generate surplus free heat in its location of intended use, and how this might compare to extremes and averages found in practice

- the coupling characteristics between all the important mass layers and heat sources and heat loss areas. This would involve description of interior finishes, location of mass, air circulation system, or alternatively classification of mass according to 'time constant' category.

- heating and cooling system control and thermostat settings, or a description of the assumed occupant reaction when overheating occurs.

Important parameters that describe the model are:

- period of analysis
- model of interior and solar heat generation
- handling of interior heat transfer dynamics
- model of the heating and cooling system response to overheating and overcooling
- model of the heat transfer dynamics of the walls, roofs, basements and infiltration.

Presentation of results that are not qualified by these factors cannot be used reliably in the construction of more simplified rules or guides concerning the mass effect.

As studies of this nature improve in quantity and quality, it will become possible to eliminate factors that are less important, and establish which are indispensible in expressing the role of mass in buildings.

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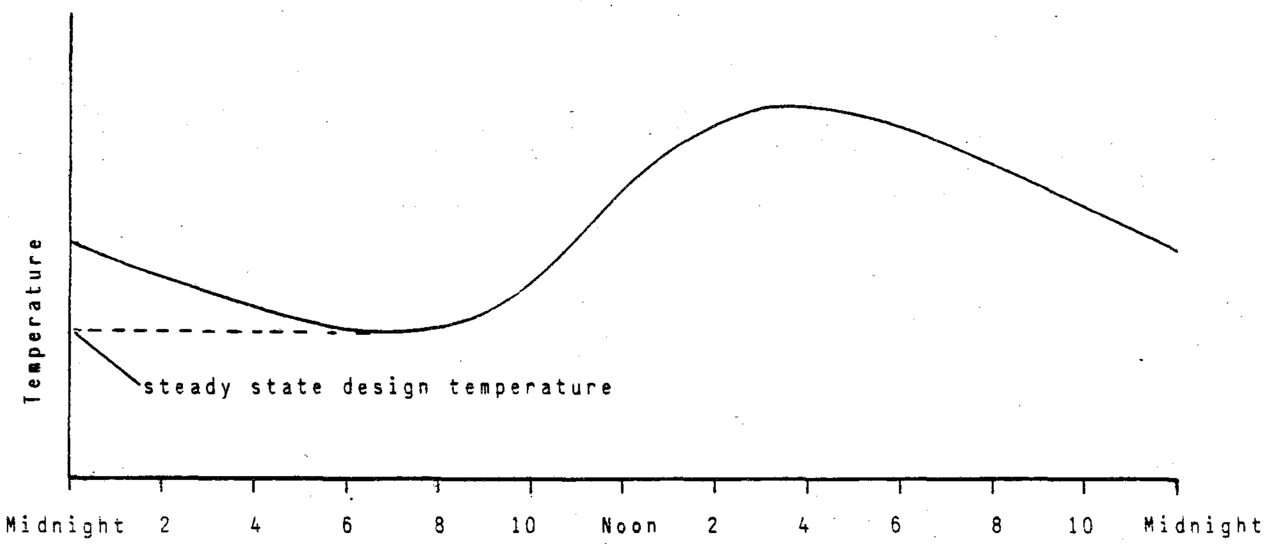
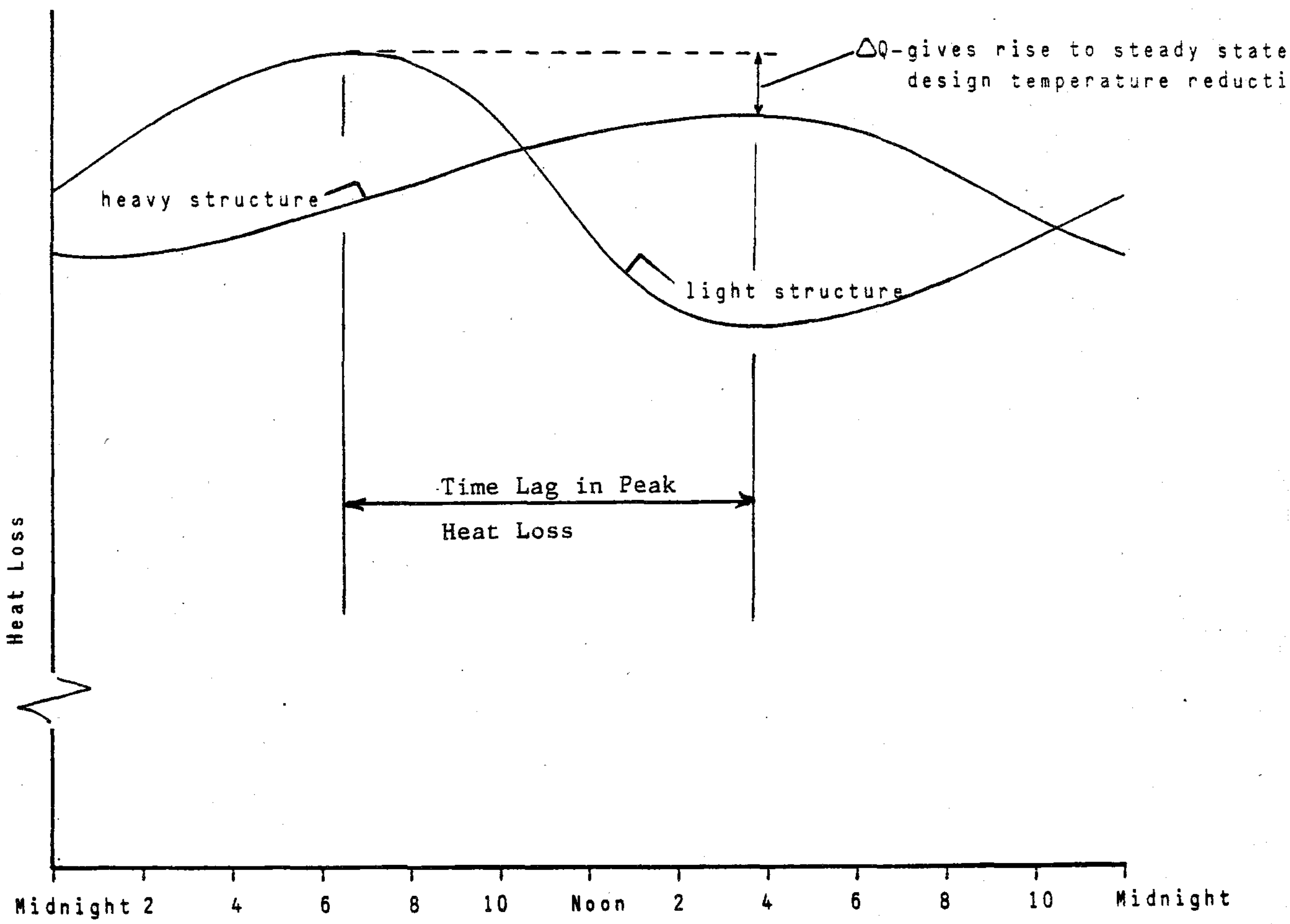


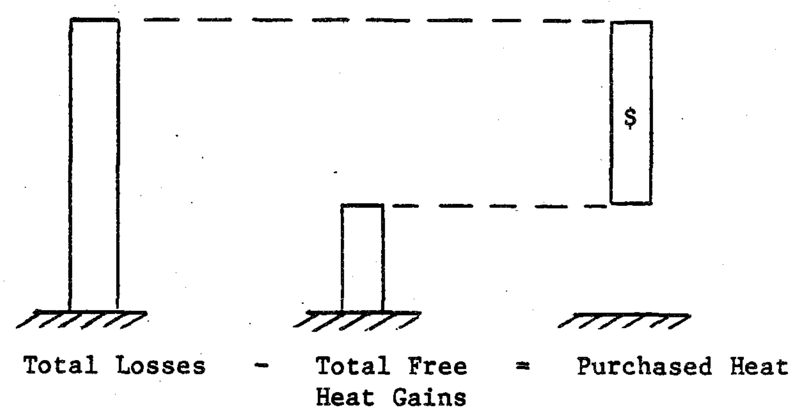
A Typical Winter Day Temperature Profile



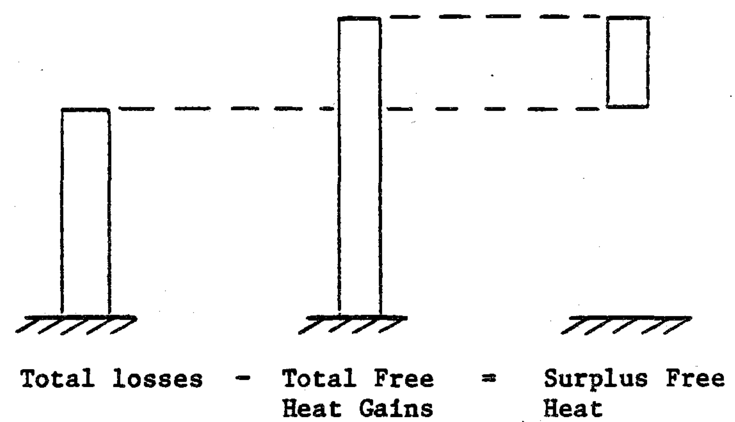
Corresponding Heat Loss Profiles

Figure 1 The lag effect in heavy structures

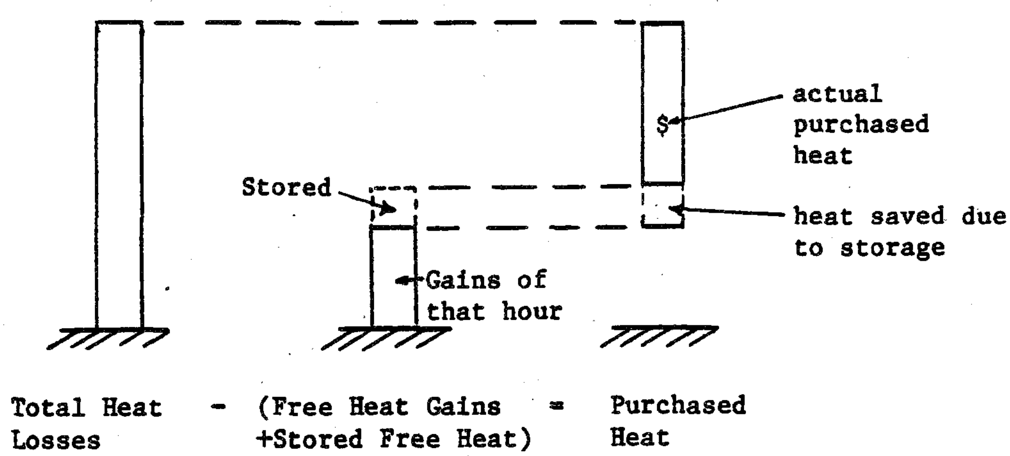
FIGURE 2. AN ILLUSTRATION OF THE WAY IN WHICH MASS CAN SAVE HEAT ENERGY BY STORING SURPLUS FREE HEAT. (not to scale)



A. HEAT BALANCE FOR AN HOUR OF THE DAY IN WHICH THERE IS A NET HEATING REQUIREMENT.



B. HEAT BALANCE AT AN HOUR WHEN THERE IS A SURPLUS OF FREE HEAT



C. HEAT BALANCE LATER IN THE DAY WHEN SOME OF THE STORED HEAT IS AVAILABLE & REQUIRED.