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LIMITATIONS OF UNDERGROUND BUILDING AS AN ENERGY ALTERNATIVE

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Abstract

Building underground offers a potential for a reduction in heating and cooling loads, in comparison to a similar above ground structure. The resulting energy savings over the life of the structure will be beneficial, both in terms of dollars, and in conservation of resources. However, this mode of construction is subject to technical and economic limitations. The limitations, as well as the potential energy saving processes of underground construction, are discussed with special emphasis placed on the soil properties, structural design and construction techniques... which may unfavourably affect the potential energy savings.

1. INTRODUCTION

Man first inhabited underground dwellings before the dawn of history. Caves and other natural shelters conveniently provided our ancestors with protection from the elements and predators. Through historical times, man has used existing underground space for storage, shelter and protection, and as early as 3000 BC excavated and constructed underground space for a specific need.

The possibility of building underground expressly to save energy has not been considered until very recently. The realization that our present major sources of energy are limited has resulted in research into many areas where energy use may be reduced, or converted to a renewable source. The building of storage facilities, utilities, offices, schools and dwellings underground has been proposed because of the reduction in heating and cooling requirements which would result. This reduction stems from the fact that a soil mass, which in the case of an underground structure serves as the basis for heating and cooling loads, greatly moderates air temperature variations and generally has a higher temperature in winter, lower in summer, than the corresponding average seasonal air temperature.

It is somewhat ironic that in this time of hyper-technology, it is because of the tremendous consumption of energy by this technology that we are intensely searching for "natural" techniques which might save energy resources.

2. POTENTIAL FOR ENERGY SAVINGS

The energy saving potential of underground construction is derived from the reduction of heating/cooling loads and the resultant energy savings. This premise is based on the

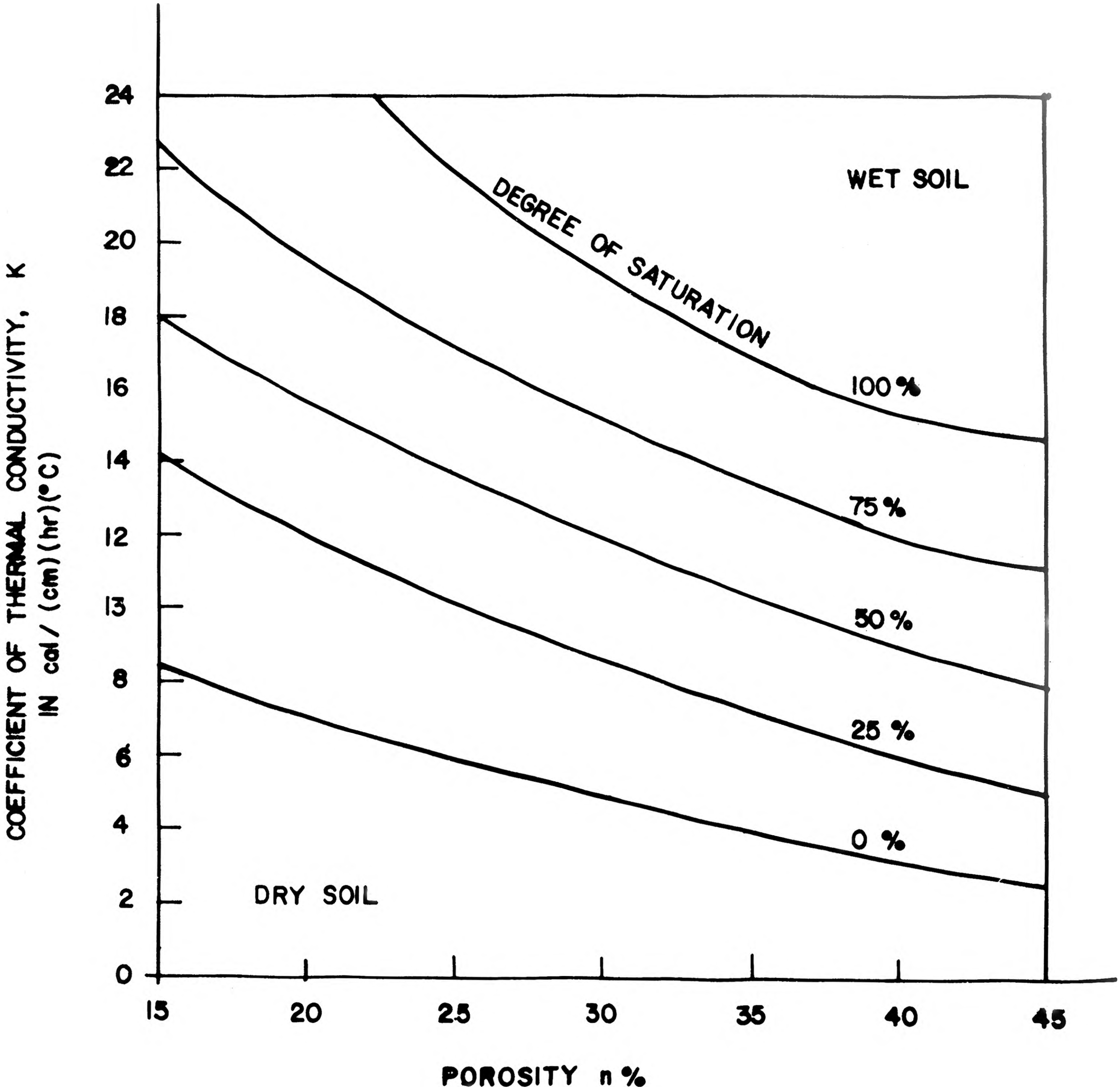

FIG.(1) TYPICAL VALUES OF COEFFICIENT OF THERMAL CONDUCTIVITY OF SOIL.

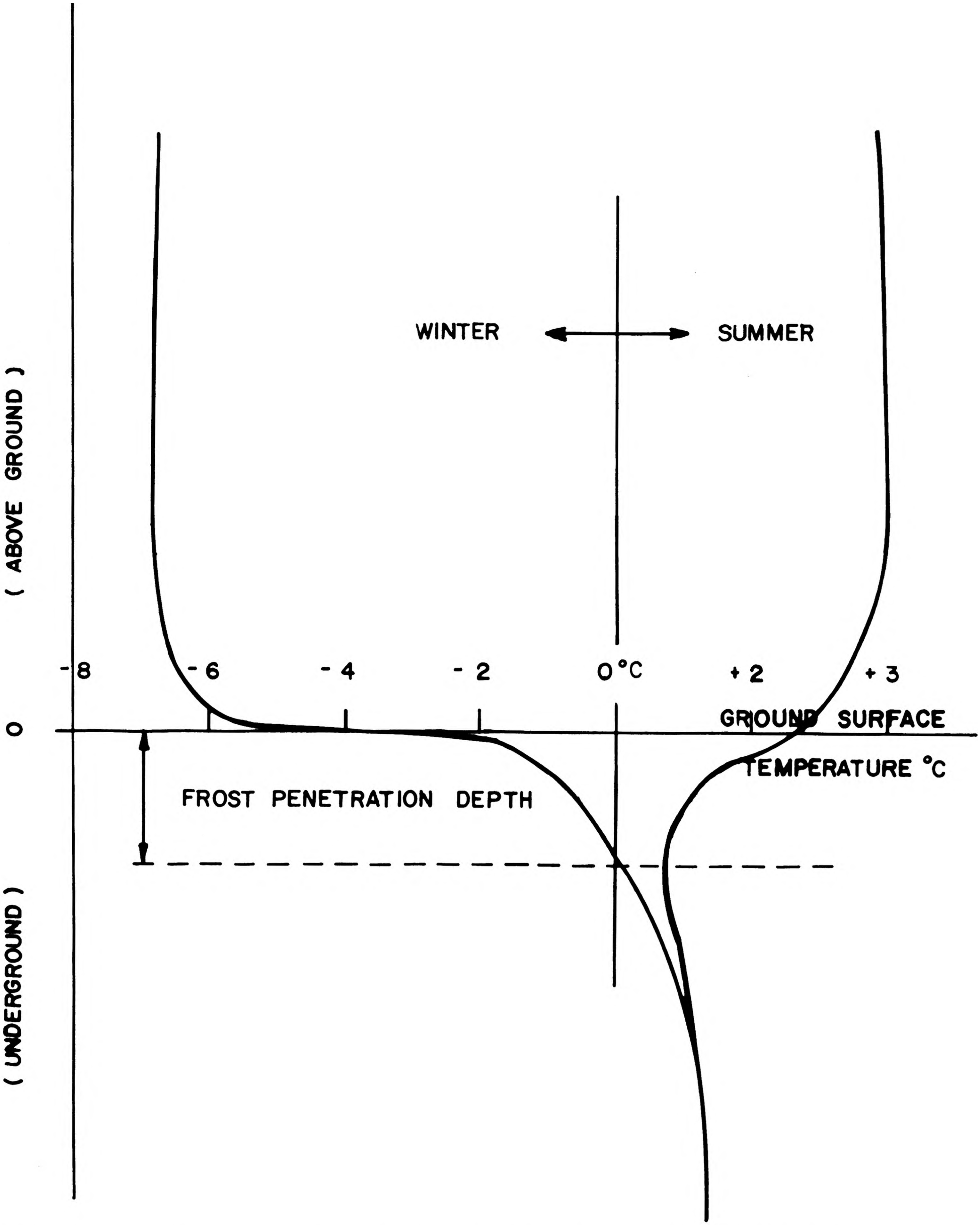

FIG.(2) TYPICAL TEMPERATURE - DEPTH RELATIONSHIP assumption that the proposed structure would in fact, require a heating/cooling system if built underground.

There are two primary reasons for this reduction of heating and cooling loads. Firstly, any underground structure is protected from the immediate effect of weather. In winter the result is that no heat loss due to wind is experienced, and in summer the structure is shielded from direct sunlight. Secondly, an underground structure uses the surrounding soil temperature as a basis for heating or cooling requirements, rather than the above ground air temperature. Surface air temperature variations are moderated to such an extent by the soil, that at a depth of several meters (depending upon the soil and geographical location) the soil temperature varies only slightly with seasonal changes. At this depth the almost constant temperature is approximately equal to the mean annual surface air temperature, thus providing a cooling effect in summer, and a heating effect in winter to the underground structure. This can result in a much lower heating load, a negligible cooling requirement and generally a smaller operating range for the climate control system of an underground structure in comparison to its above ground counterpart. Further contributing to the reduction of heating/cooling system size are minor factors, such as the lessening of heat loss by radiation and the storage of heat conducted to the surrounding soil.

3. THERMAL PROPERTIES OF SOILS

The thermal properties of a soil are dependent upon the chemical composition of the soil particles, the physical properties of the soil, particle arrangement and the quantity of the water present in the voids between soil particles. Because it is impossible to accurately predict these characteristics, and evaluation of a soil's thermal properties must be based on the testing of representative samples. The water content of the voids is governed by the infiltration of surface water and also by the level of the ground water table. Infiltration and the water table level are not usually constant at any particular location, therefore, any prediction of a soil's thermal properties must take into account the variation with time of the actual quantity of water present.

The parameters which are used to describe the thermal properties are the heat capacities of water and soil, C_{mw},C_{ms}; the thermal conductivity, K; the specific heat, C_{sp}; and the thermal diffusivity, α.

The mass heat capacity C_m of a soil is defined as the amount of heat energy Q necessary to change the temperature of a unit mass by one degree. For a soil medium the volumetric heat capacity $C_v (C_v = C_m . \gamma)$ is dependent upon the porosity (air content) and water content of the particular soil. A completely dry soil (voids completely air-filled) will have a much lower heat capacity than a fully saturated soil (voids completely filled with moisture) because of the high heat capacity of water. The heat capacity of dry soils is of the order 0.20 cal/g.^{o}C, and is increased in direct proportion to the water content. In the case of the water content of a soil being frozen, the heat capacity is reduced because of the lower heat capacity of ice.

The thermal conductivity of a soil K, is the quantity of heat which flows normally across a surface of unit area per unit time and unit temperature gradient normal to the surface. The conductivity of soil particles can vary from 0.001 to 0.006 cal./cm.sec.^{o}C, whereas, the conductivities of water and air are 0.00124 and 0.00005 cal/cm.sec.^{o}C, respectively. Thermal conductivities for soils of varying porosity and water content are shown in Figure 1.

The thermal diffusivity α of a soil is an index of its ability to undergo temperature changes and is defined as the ratio of the thermal conductivity to the heat capacity of a soil.

As mentioned earlier, daily surface temperature variations are greatly moderated by a soil mass. This moderating effect is shown in Figure 2. Seasonal variations are also moderated, the extent of moderation increasing down to a depth which remains at approximately the annual mean surface temperature, as can be seen from Figure 2. Below this depth of constant mean temperature, the temperature increases at a rate determined by Geothermal Factors.

The moderation of surface temperature variation is dependent entirely upon the thermal, and hence physical, properties of a soil. An indication of the moderating ability is most closely given by the thermal diffusivity of a soil. A low thermal conductivity and a high heat capacity (resulting in a low thermal diffusivity) would be desirable for soil surrounding a proposed underground structure in order to reduce to a minimum the effect of surface temperature change. As well as increasing the effect of air temperature moderation, these properties further reduce loads by a second mechanism. A high heat capacity of surrounding soil will also cause storage of any heat transferred to the soil from the structure, thus reducing the heating load. A soil of low conductivity will slow the dissipation of this stored heat into the outlying soil mass.

Another factor indirectly linked to the thermal characteristics of a soil mass, is the insulating effect of snow cover. Snow exists at a constant temperature of $0^{\circ}C$, and will therefore result in a ground surface temperature of $0^{\circ}C$, even if the air temperature is much lower. The result being an even further moderation of sub-surface temperatures.

4. FACTORS TO BE CONSIDERED IN UNDERGROUND CONSTRUCTION

Soils having a high density or excessive moisture content will have a relatively high thermal conductivity, see Figure 1. Such a soil will have less of a moderating effect on soil surface temperature variations than a soil with a lower thermal conductivity. However, the moderation will nevertheless be enough to average out minimum and maximum daily temperatures and result in a reduction of the daily heating/cooling load compared to a similar above ground structure.

The geology of a proposed construction site must always be thoroughly investigated. However, problems typically encountered in excavations will be magnified in the case of underground construction. By definition, underground structures will intrude deeper beneath the ground surface than an above ground structure of similar function, thus the liklihood of encountering technically difficult situations will be greater. A surrounding soil of high permeability and a high water table will necessitate dewatering and either drainage or waterproofing provisions for the completed underground structure. The presence of large rocks or bedrock in the volume to be excavated will increase initial costs, and in the extreme case, completely preclude the option of underground construction.

Although most situations encountered can be handled with existing technology, the costs involved may be too great to even consider constructing the proposed structure underground.

The structural design of an underground structure poses no serious problems. Apart from the outer walls having to resist earth pressures, design details are similar to a corresponding above ground structure. Environmental controls such as ventilation may warrant closer attention, as will fire preyention and control systems, due to the restricted environment. In the case of a multi-stored underground structure, escaping from a fire will require climbing up, not down. This will considerably slow down any evacuation procedure and exit may prove difficult for needy or handicapped persons. The absence of windows will cause smoke to rapidly fill the structure, as well as inhibiting any attempt to control the fire. Structurally, the underground Building would consist of retaining walls to resist earth pressure. The walls would be out of sight thus negating the effect of any imaginative design, and restricting architectural innovation to interior space. However, the opportunity would exist for extensive landscaping over and around (on the surface) the structure.

From an architectural viewpoint the underground structure is less desirable aesthetically than its above ground counterpart. The lack of windows, balconies and lawns would seem to restrict underground structures to storage and working environments. However, relevant literature indicates that man can adapt quite easily to such stressful living conditions as an underground or windowless above ground situation. Yet there is a need for further psychological studies on the long-term effects, if indeed there are any, of working and living in an underground environment.

One further aspect for consideration is that the higher initial costs of underground construction, hopefully offset by savings in maintenance and energy, would have to be borne by the initial developer. Presently, there is little incentive for a private developer to put up the additional capital so that energy and maintenance costs, usually paid by the tenant or buyer, will be reduced. Unless a demand for this type of construction is created, or some form of governmental funding provided to offset the increased capital cost, it is unlikely that commercial developers will build underground. Government and Public Agencies should set an example by the serious consideration of underground constructions where feasible.

5. EVALUATION

The evaluation of whether or not a proposed underground structure is feasible must be carried out on the basis of one assumption. The potential energy savings gained over the life of the structure must be greater than the additional initial costs, both in dollars and energy, compared to a similar above ground structure.

To determine the potential energy savings of an underground structure compared to an above ground structure, the thermal properties of the surrounding soil must be determined as well as meteorological data for the location. For a particular location and underground design, the average annual heating/cooling load may be estimated. From previous experience at that location the annual heating/cooling load of a similar above ground structure can be determined and the expected energy savings of the underground structure estimated. In the case of a thermally poor soil and very moderate surface climate it is possible that the potential energy savings of the underground structure are negligible. In view of the additional costs of construction the underground structure will offer few advantages.

If, however, the potential energy savings are considerable, a site investigation should be undertaken and any problem conditions identified. Again on the basis of local experience, an estimate of the energy and dollars needed to excavate and construct the proposed structure may be made.

At this point, it is necessary to compare the present costs of the construction with the future value of the energy saved. Although several methods exist for this analysis, an estimate of future costs of energy must be made, and as we have seen over the past decade, this is a difficult task. Some attempt must be made however, and as more underground structures are built, experience will be gained and the quality of these estimates will improve.

6. CONCLUSION

Although a definite potential for energy savings exists, soil conditions,architectural considerations and technical problems may increase initial costs, or reduce the heating/cooling savings to such an extent, that an underground construction proposal must be rejected.

A decision to build underground structures must be based upon an understanding of the possible benefits and limitations. The additional investigation required prior to making the decision, as well as the considerably greater initial costs reduces the liklihood of a developer even considering this alternative. For this reason both research and experience are necessary to reduce costs, and provide codes or standards by which the decision-making process can be made easier.

If it can be shown that the potential energy savings of underground construction actually exist, governmental incentives for the contemplation and implementation of this alternative must be applied to private and public agencies.

7. ACKNOWLEDGEMENT

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