CIB TG 16, *Sustainable Construction*, Tampa, Florida, USA, November 6–9, 1994.

CRITICAL THERMAL TRANSMITTANCE (U) VALUE FOR THE DESIGN OF GREEN BUILDINGS

Kenneth C. W. Ip

Department of Construction, Geography & Surveying
University of Brighton
Lewes Road, Brighton, BN2 4AT, UK

Abstract

This paper gives an overview of the changes of U values in the UK and the corresponding impact on heat loss reduction through roofs and walls of new dwellings. Proposed U value changes in the new regulations 1994 is expected to increase the level of thermal insulation and lead to new methods of construction. Valuable experience can be learnt from European studies which demonstrates the use of similar building materials and construction methods can achieve higher thermal performance. A methodology is proposed for finding the critical U values for walls and roofs with different kinds of thermal insulation materials. A component based dynamic simulation program is used to compute the environmental emissions from the materials and from the heating systems of buildings. The mammoth tasks of modelling, data acquisition, weighting of impacts, etc. are identified. A model dwelling is tested with four commonly used insulants. The results show that, by using an air emission index to adjust the different degree of environmental impact for different gas emissions, the U values used in some of the highly insulated buildings with gas heating may exceed the critical U values and can result in more air emission over the life of the building.

Introduction

Energy use for space heating in domestic buildings accounts for about 18% of the UK's delivered energy and a similar percentage of carbon dioxide emission to the atmosphere [1]. Heat loss and the corresponding green house gas emissions from dwellings can be reduced by introducing more stringent heat transmittance (U) values in the building regulations. In the past thirty years the UK government has lowered the U values several times. Changes to the existing U values have already been proposed in the Building Regulations 1994. One method to achieve lower U value is by using higher level of thermal insulation. This method, although reduces heat loss and the environmental emissions from the fuel used for heating, will lead to the increase of emissions due to the manufacturing of insulation materials.

In comparison with many European countries, UK dwellings are generally much less energy efficient despite the construction materials are similar and the climatic variations are not significantly different. Studies based on some of the European countries have concluded that valuable experiences on the construction of better insulated buildings can be learnt and adopted to the UK.

The methodology proposed in this paper is to establish the critical U value below which there is no environmental benefit. A dynamic modular simulation program is used to optimise the environmental effects. A mixture of dynamic thermal components and life cycle components are used in the test model. The test model is a dwelling of typical cavity masonry walls and pitched roof construction. It is set up to find the critical U values of the roof and walls using four commonly used insulation materials.

U values and energy use

U value was first introduced in 1965 with the intention to reduce condensation inside buildings. The values were subsequently changed mainly for the purpose of conserving fuel and power. Table 1 shows the changes of U values (base on the *elemental* approach) for roofs and walls from 1965 to 1990. The proposed building regulations 1994 [2] has included the requirements for energy rating of dwellings using a method called Standard Assessment Procedure (SAP) developed for the government by the Building Research Establishment. The proposed new regulations have not reduced the U values for the walls and roofs (table 2) apart from the case when the SAP rating

Table 1 U values (W/m^2K) 1965 - 1990

Element	1965	1976	1982	1990
Wall	1.7	1.0	0.6	0.45
Roof	1.42	0.6	0.35	0.25

Table 2 U values (W/m^2K) 1994

Element	Standard Assessment Procedure (SAP) rating	
	up to 60	over 60
Wall	0.45	0.45
Roof	0.2	0.25

*Number of dwellings from 1993 onward are based on projected estimates. Average outdoor temperature of 5.7°C and 24 hour average internal temperatures are used [1].

Figure 1. Heat loss from roofs and walls of new dwellings

of the dwelling is less than 60. The major change in terms of reducing heat loss is the calculation procedure of U values which will take the heat loss through thermal bridges into account. To comply with the proposed regulations, typical wall insulation level is expected to increase from 50 mm to 75 mm while the increase of roof insulation is from 100 mm to 150 or 175 mm [3]. The new calculation method is estimated to reduce the heat loss through roofs and walls of new dwellings by 25 to 30%.

The lowering of U values in the past three decades has resulted in better insulated dwellings with substantial heat loss reduction. Taking into account the dwellings built during this period [4], the estimated heat loss reduction from roofs and walls due to higher level of thermal insulation in new dwellings is shown in Figure 1. It can be seen that the percentage of energy saving is much less significant in the recent changes. The inclusion of any "material" alteration (e.g. a new roof) of existing dwellings to comply with the new regulations may further reduce the energy use for heating.

Europe standards and practices

A comparison [5] of energy consumption for typical semi-detached houses of the same floor area and with same mean internal temperatures based on the UK climate is shown in table 3. It shows that the UK dwellings are less energy efficient than their counterparts in Europe which are better sealed and with higher level of thermal insulation. Based on the insulation thickness required to satisfy the standards in different countries in Europe [6], the U values for roofs and walls are shown in figure 2 which indicates the U values used in the UK is higher than many European countries.

Table 3 Relative space heating consumption of similar buildings in different countries applying the UK climate

Country	Annual space heat consumption* GJ	%
UK	37	100
Netherlands	29	78
Germany	28	76
Switzerland	19	51
Sweden	15	41

*Include fabric, ventilation and infiltration losses

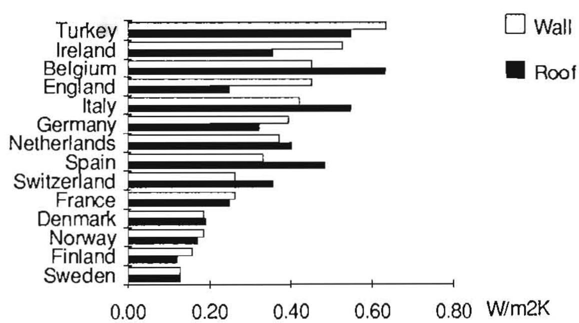

Figure 2. Wall and roof U values used in European countries

Table 4 Typical roof and wall construction

Country	Roof		Wall	
	U value	Construction	U value	Construction
Netherlands	0.3	100 mm expanded polystyrene	0.4	Cavity wall with 70 mm mineral fibre
Germany	0.21	150 mm mineral fibre between rafter	0.4	200 mm dense concrete block with 50 mm mineral fibre or expandable polystyrene externally rendered
Switzerland	0.18	175 mm mineral fibre between rafter	0.38	150 mm dense masonry, plastered internally, 80 mm mineral fibre in cavity, 120 mm masonry rendered

Table 4 shows a comparison of typical roof and wall construction among Switzerland, Germany and the Netherlands [5]. Studies based on these countries where large number of energy efficient constructions are underway show that there are similarities in the dwelling construction. Their experience can be adopted to the UK despite the weather conditions in the UK favour the use of cavity walls rather than dense solid walls.

Life cycle of insulant

Extra thermal insulation is commonly used for achieving lower U values. The dominant insulant used for the insulation of dwellings are glasswool, rockwool, expanded polystyrene (EPS) foam and the cellulose fibre [7]. Except for some similarities between the rockwool and glasswool, the manufacturing process and raw materials used for each of these insulants are different. However the main stages of the life cycles of insulants can be outlined by the same diagram in figure 3. Various works are underway to establish quality databases [8,9] which are necessary for assembling the full picture of the materials' life cycles. Key factors with the greatest environmental impact also need to be identified, together with the acquisition of quality data can then a detailed life cycle analysis be possible.

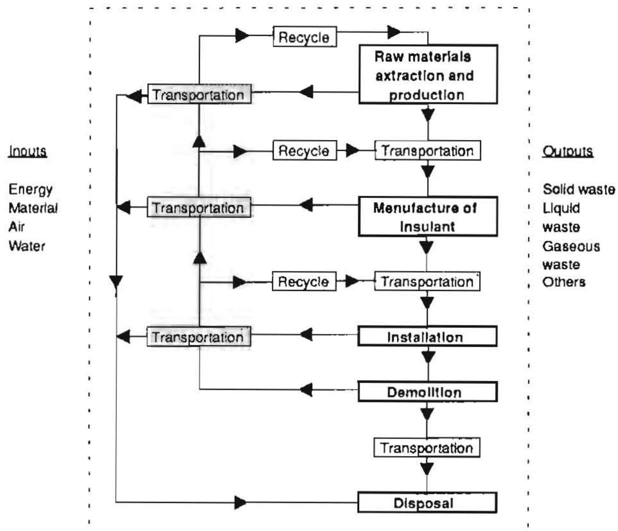

Figure 3. Life cycle of insulation materials

Methodology

To find the critical thermal transmittance value of the building fabric would involve:

1. the calculation of environmental emissions during the life cycle of the materials used;
2. the calculation of the environmental emissions due to the fuel used for space heating of the building and;
3. the optimisation of the fabric materials and fuel used which will result in the minimum environmental impact during the life of the building.

The calculation of environmental emissions (land, water, air, noise) and the comparison of their relative environmental impact, which is still under development, is complicated and hard to perform with the present information and knowledge. The analysis in this paper has been focused on the study of air emission due to energy use. Although data on energy use is normally monitored and measured during the manufacturing process, detailed data at each life cycle stage in the manufacturing process is still difficult to obtain.

Table 5 Air emission by fuel

	CO_2 g/MJ	Particulates g/MJ	SO_2 g/MJ	NO_x g/MJ	CO g/MJ	HC g/MJ
Distillated oil	72.1	0.0065	0.23	0.2	0.015	0.002
Natural gas	50.5	0.006	0.0002	0.09	0.007	0.008
Coal	87.5	0.11	0.85	0.27	0.02	0.003
Coal fire electricity	248.9	0.31	2.36	0.75	0.17	0.008
UK electricity*	182.1	0.2239	1.709	0.548	0.123	0.0059

*72% coal, 17% nuclear, 3% oil, 0.55% gas [10]

Table 6 Admissible concentration

	Particulates	SO_2	NO_x	CO
Concentration limit (g/m^3)	0.00012	0.00003	0.00006	0.006

The study sets to find the critical U value at which the air emission over the life of the building will be minimum. The main air emission involves carbon dioxide, sulphur dioxide, nitrogen oxides, carbon monoxide and a broad range of volatile organic compounds from uncombusted fuel. The emission from different fuel is shown in table 5 [11]. Each of these air pollutants has varying degree of environmental impact; one method proposed for weighting the relative environmental impact is by introducing an air emission index [11] which is defined as:

$$\text{Air emission index} = \frac{\text{Concentration of pollutant } (g/m^3)}{\text{Admissible concentration } (g/m^3)}$$

The National ambient air quality objectives set by the Canadian Environmental Protection Act shown in table 6 [11] will be used as a reference for the admissible concentration.

Simulation tool

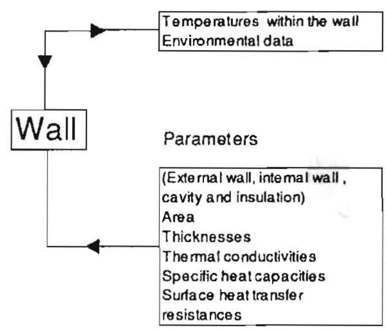

Figure 4. A wall component

The calculation and optimisation are carried out by using a general purpose dynamic module simulation program [12]. In this modular simulation program, a system is represented by components which are linked together by nodes. Each component represents a process or a physical object in the real world, performs a distinct identifiable task. Communication between components is through nodes which convey information and allow the components to influence each other. The variables which describe the components are stored in the *parameters* and *internal states* (figure 4). The *parameters* are numerical variables which describe the 'size' of the component; these variables generally do not vary with time. The *internal states* are variables which are held 'inside' a component and reflect the current condition of that particular component. Users can create the components and change their properties through standard subroutines.

The number of components used to represent one or more systems can vary, depending on the details required by the user. Such flexibility allows the refinement of simplified models by additional components or changing the properties of the components as more data is available.

Simulation model

The model house is of typical masonry cavity wall with tiled pitched roof construction. The house is 5.4m by 8.1m by 5.2 m high, with an external wall area of $98m^2$ and roof area of $44m^2$. Four commonly used insulants (rockwool, glasswool, expanded polystyrene and cellulose) [7] are tested as wall and roof insulants. External temperatures are generated by using the simulated outdoor temperatures from the CIBSE guide [13]. Two forms of heating, gas and electricity, are compared. The house is maintained at an internal temperature

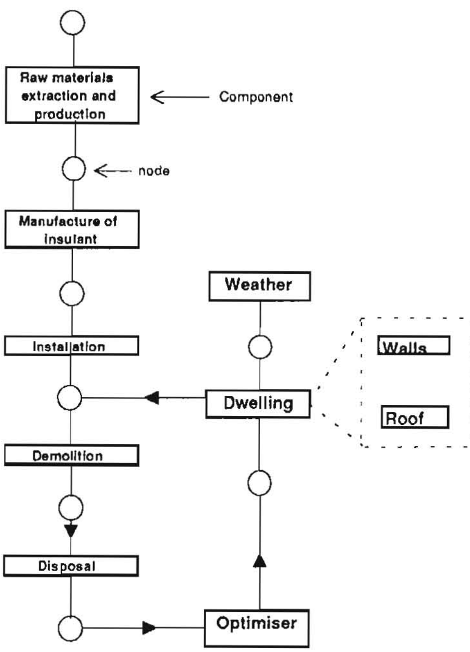

Figure 5. Simulation model

of 21°C between October and March for a building life of 60 years.

The different stages of the life cycle in figure 3 are simplified and converted to simulation components as shown in figure 5. Lumped data [14] has been used for the life cycles of the insulants since quality data for different stages of all the insulants is not available. A dynamic thermal component for calculating the heat transfer through the dwelling, an optimiser for finding the critical U of the insulant and a weather component which generates the external weather data are added to complete the modular simulation model.

Results

Graphs of the resulting air emission indices for using glasswool as insulant are shown in figure 6 to 9. The summary of the critical U values for the four insulants is shown in table 7. By using air emission index to account for the different degree of environmental impact, the results indicated that there is a wide difference in the critical U values among insulants. As air emission from the generation of electricity is high, critical U value for electric heated dwellings is approximately seven times lower than gas heated dwellings. In such cases it is true that in practice the higher the thermal insulation the greater is the environmental benefit. However, some of the critical U values for gas heated houses are close or even higher than those used in some of the highly insulated houses, in particular for the roof insulation. In such cases the use of U values lower than the critical U values will increase the environmental impact during the life, which has been taken as 60 year in the simulation model, of the building.

Table 7 Critical U values based on air emission from insulants

		Wall insulant			Roof insulant		
Heating system	Material	Thickness m	AEI	U W/m^2K	Thickness m	AEI	U W/m^2K
Gas	Rockwool	0.5	2.45E+08	0.067	0.5	1.38E+08	0.068
	Glasswool	0.35	3.30E+08	0.093	0.4	1.85E+08	0.084
	EPS	0.15	4.45E+09	0.02	0.2	3.83E+08	0.161
	Cellulose	0.25	4.31E+08	0.127	0.3	2.42E+08	0.11
Electric	Rockwool	>2.4	>1.49E+09	<0.014	3.1	7.67E+08	0.011
	Glasswool	>2.4	>1.96E+09	<0.014	2.3	1.05E+09	0.015
	EPS	1.3	6.69E+08	0.026	1.3	2.54E+09	0.027
	Cellulose	1.9	2.65E+09	0.018	2.1	1.46E+09	0.017

Conclusion

This paper has highlighted the influences of U value to the energy use and its impact to the environment. A holistic quantitative analysis of the critical U value requires taking the life cycle of the materials, the performance of the heating system and the dynamic thermal behaviour of the building into account. The complexity of such an analysis would need the aid of computer simulation. The dynamic modular simulation program described in this paper is a possible mean. The modular approach allows mixed types of systems to be simulated together in the same model and users can decide the model complexity; system boundaries can easily be redrawn and a single component can be broken down into more refined components as more data or information emerges. Simplified model has been used in this paper; further work is needed to refine the model such as comprising the emissions to water and land, the environmental impact of the heating systems and the other materials used in the fabric. There is a need to identify the key emissions that have the major environmental impact and the collection of quality data in order to build models closer to the reality. Using the air emission index as a weighting criterion for the relative impact of air pollutants, the simulation results indicated that the U values used in some of the highly insulated gas heated dwellings are close to the critical U values. As there is a trend towards the use of high level of thermal insulation in the dwellings, future determination of U value should therefore no longer base on energy saving alone, but to include a holistic determination of the environmental impact from the materials and the building thermal systems on life cycle bases.

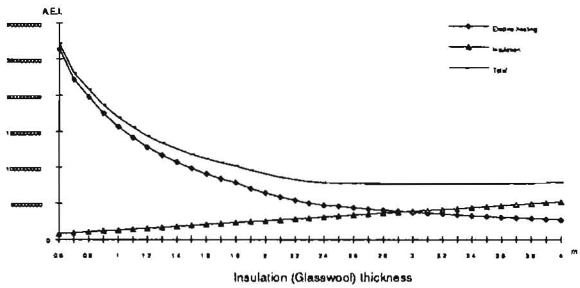

Figure 6. AEI emission (glasswool) for roof - electric heating

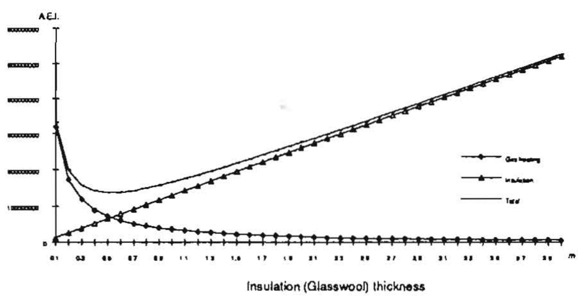

Figure 7. AEI emission (glasswool) for roof - gas heating

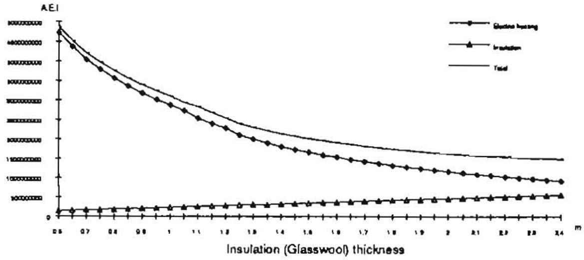

Figure 8. AEI emission (glasswool) for wall - electric heating

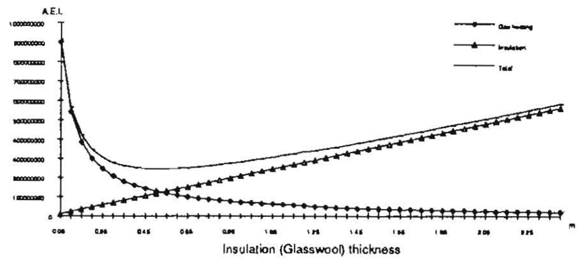

Figure 9. AEI emission (glasswool) for wall - gas heating

References

1. Shorrock L.D., G. Henderson & J.H.F. Bown, 1992: *Domestic energy fact file* BRE.

2. Blount K., 1994: Conservation of fuel and power - proposed amendments to part L of the building regulations *The "New" building regulations 1994 conference,* The Cafe Royal, London.

3. Davis I., 1994: Implications for the housing industry *The "New" building regulations 1994 conference,* The Cafe Royal, London.

4. *Annual Bulletin of Housing and Building Statistics for Europe and North Amer*ick L.D., Henderson G. & Bown J.H.F., 1992: *Domestic energy fact file* BRE.

5. Olivier D., 1992: *Energy efficiency and renewables: recent experience on mainland Euurope,* Energy Advisory Associates.

6. Johnson S., 1993: *Greener Buildings - Environmental Impact of Property* Macmillan.

7. Johnson L. & S. Whittome, 1993:*The UK market for thermal insulation,* BSRIA, UK.

8. Krogh H. & K. Hansen, 1994: Data needed for environmental assessment of building projects *Buildings and the Environment International Conference* BRE.

9. Folkenberg J., 1994: Environmental declaration of building materials *Buildings and the Environment International Conference* BRE.

10. Annual Abstract of Statistics, 1994: Central Statistical Office, HMSO.

11. Cole R. J. & D. Rousseau, 1992: Environmental auditing for building construction: energy and air pollution indices for building materials *Building and Environment*, Vol.27, No.1, pp.23-30.

12. Ip K., B. Day & D. Richardson, 1989: Fluid flow and heat transfer in pipework systems I: Mathematical model for dynamic modular simulation *Building Services Research and Technology* , Vol.10, no.4.

13. CIBSE guide 1986*: A2 Weather & solar data* CIBSE.

14. Bowdidge J. R. 1994: *Private communication.* Rockwool limited.