RESIDENTIAL SLAB-ON-GRADE HEAT TRANSFER IN HOT HUMID CLIMATES

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ABSTRACT

Heat transfer through an uninsulated slab on grade is calculated using a simple method developed by Kusuda. The seasonal and annual slab loads are graphed as a function of annual average soil temperature, T_m, for a variety of floor system resistances, thermostat setting and soil properties. Factors affecting T_m are discussed. For a typical carpeted residence in the hottest U.S. climates, the cooling load due to the slab is about 5 million Btu per cooling season. In some climates heat transfer through an uninsulated slab can be beneficial. These benefits are larger if the residence is operated with energy conserving thermostat settings and the soil surrounding the slab has high conductivity.

INTRODUCTION

Simple but reasonably accurate methods of evaluating the monthly or seasonal heat transfer through the slab of a slab-on-grade residence have recently been developed (1,2,3). Claridge has compared these and other methods of evaluating earth contact heat transfers (4).

Recently Christian and Strzepek used the method developed by Shipp to identify the economically optimal level of insulation for a variety of residential floor systems, including slab-on-grade (5). Assuming a constant 73^{o}F interior temperature, they find that the winter slab loads will be much larger than the beneficial summer slab losses (passive cooling) in all climates. For simplicity, they then identify the economically optimal slab insulation resistances after defining the summer passive cooling benefits as zero. This procedure leads to a few puzzling results; e.g., the optimal slab-on-grade perimeter insulation levels are the same in Houston and Chicago. Christian and Strzepek are suspicious of this result and recommend further evaluation of the effects of summer passive cooling by the slab in warm and hot climates.

In this paper we use the Kusuda method to produce graphs of monthly, seasonal, and annual slab-to ground heat transfer in warm and hot climates. We also evaluate the sensitivity of these slab heat transfers to changes in residence design and operating conditions and soil properties.

METHODS and ASSUMPTIONS

The procedure we use to evaluate slab heat transfer was developed by Kusuda, Mizuno and Bean and has been verified by comparison with several independent methods (1,2,6). The Kusuda method is an empirical correlation with an analytic solution; it is restricted to the case where soil thermal properties are constant and homogeneous and the slab surface and soil surface temperatures vary sinusoidally with annual periods. There are assumed to be no other homes which are near enough to the slab to influence its heat transfer to the soil. The analytic solution isotherms show that a slab influences the soil temperatures to a distance of one slab width beyond the slab (1).

The slab floor system must be rectangular and is assumed to have constant thermal resistance across the entire slab and through the year. This method does not include the effects of a perimeter foundation or perimeter insulation. However, the calculated heat transfer does include the 3-dimensional heat transfer (corner effects) between the rectangular slab (with temperatures that vary in time and position) and the sub-grade soil (in which temperatures vary in time and with location). We use the method suggested by Kusuda et al. to correct the resulting slab heat transfer for the effects of thermal resistances in the floor system (e.g., carpet, air film, sub-slab insulation)(1).

The required climatic inputs are the annual average soil temperature, T_m (which for constant homogeneous soil properties is independent of depth), the half annual range of the soil surface temperature, B and the phase, T_o. For this paper T_o was defined so that the minimum soil surface temperature occurs on February 1. This phase is in approximate agreement with the average of data analyzed by Kusuda and Achenbach (7) and in agreement with theoretical arguments (8).

A residence operation input is the annual average interior temperature (taken above the slab air film), T_R . This interior temperature is also assumed to vary sinusoidally with half annual range, C, and has a minimum on February 1. Design variables are the slab area, A, the length to width ratio, R, and the total resistance of the floor slab system, R_f (including all elements between the top of the sub-slab soil and the interior air temperature, e.g., carpet and air film).

CLIMATE, SITE AND SOIL TEMPERATURES

The site soil temperature (T_m and B) is not uniquely determined by the local climate. Except at geothermal sites, the soil temperature at any depth is primarily determined by the soil surface heat balance and by the average thermal diffusivity of the soil. Very complex heat and mass transfers associated with daily and seasonal changes in soil moisture do play a role, but the soil temperature data analyzed by Kusuda and Achenbach at 29 sites can be accurately fit by a simple model which assumes that soil thermal diffusivities are independent of depth and time at each site (7). From a cluster analysis of in-situ soil data taken by others, Labs and Harrington concluded that $a = 0.022$ Btu/ft^2 hr is an average thermal diffusivity and $a = 0.031$ Btu/ft^2 hr is a typical value for moist soil (9).

The deep soil temperature at a "typical" site in a given climate is close to the well water temperature at a nearby site with similar ground surface characteristics. Figure 1 is a map of measured well water temperature contours. In warm climates, these water temperatures are 2°F to 8°F greater than the corresponding annual average air temperatures. Kusuda and Achenbach found similar results and also found that the annual range in soil surface temperature at a given site is very close to the annual range of monthly average air temperatures (the difference between the mean temperatures of the warmest and coldest months) (7). Figure 2 is a map of the mean annual, peak-to-peak range in air temperature. The half range, (which is an input to the Kusuda model), varies from about 20°F along the northern boundary of the sun belt to less than 10°F in South Florida.

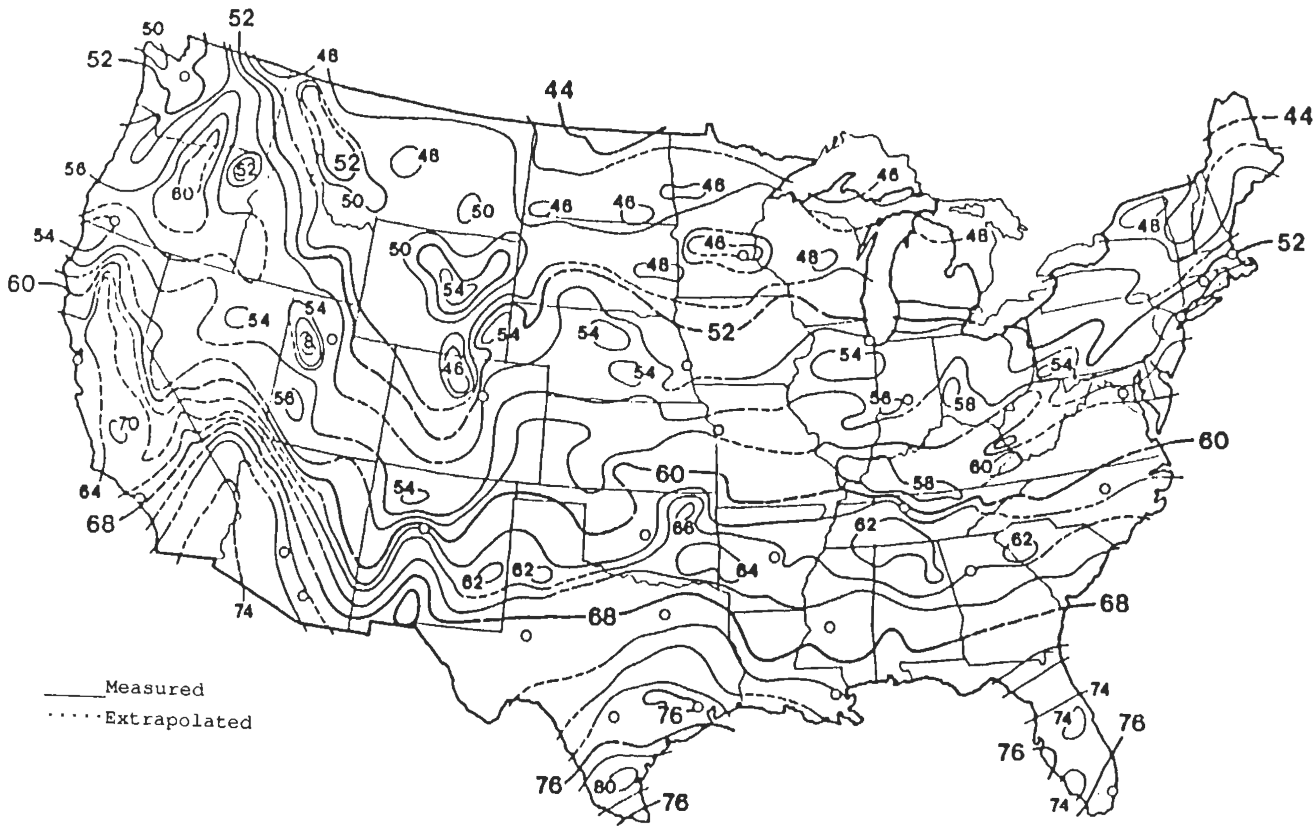

Figure 1. Distribution of Groundwater Temperatures Measured in Nonthermal Wells Ranging in Depth from 50 to 150 ft ($^{\circ}$F)
Source: National Water Well Association.

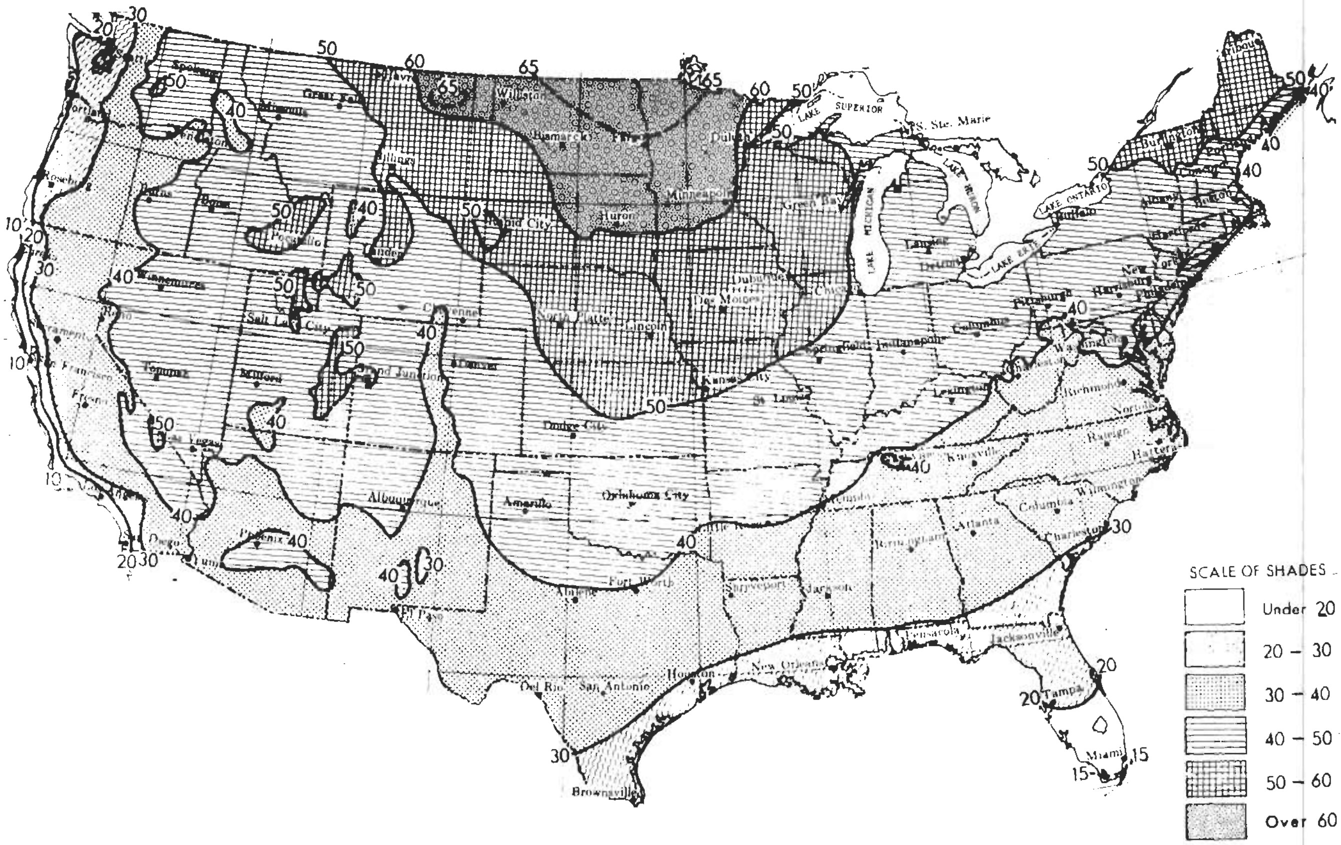

Figure 2. Mean Annual Air Temperature Range (°F). (Difference between mean temperature of warmest and coldest months)
Source: Climates of the United States by John L. Baldwin, U.S. Department of Commerce, 1973.

Experiments and simulations show that changes in the soil surface heat balance due to surface albedo and/or vegetation can produce large changes in the soil temperature. At a site near Washington, D.C., Kusuda (10) showed that a black asphalt surface produces an annual average soil surface temperature 8°F above the annual average air temperature. Monthly average temperatures of white asphalt, bare soil,and short grass covered surfaces agreed with the monthly average air temperature within 2°F. The annual average temperature of a long grass covered surface was about 3°F below that of the short grass covered surface. The results of this type of experiment are site specific; the temperature effects of soil surface albedo changes should be larger at a site with greater insolation.

Figure 3 shows the simulated sensitivity of the deep soil temperature to changes in solar absorptance and infrared mean radiant temperature (MRT) at the soil surface. This figure is the result of an hourly finite difference simulation in which the soil surface heat balance is calculated using typical year meteorological data for San Antonio. (The annual average dry bulb temperature for this typical year is 69°F.) This typical year simulation was repeated until the deep soil temperature reached equilibrium for a particular choice of absorpance and MRT. The soil surface evaporative and convective heat exchanges were simulated as if these heat transfers were suppressed by thick vegetative cover.

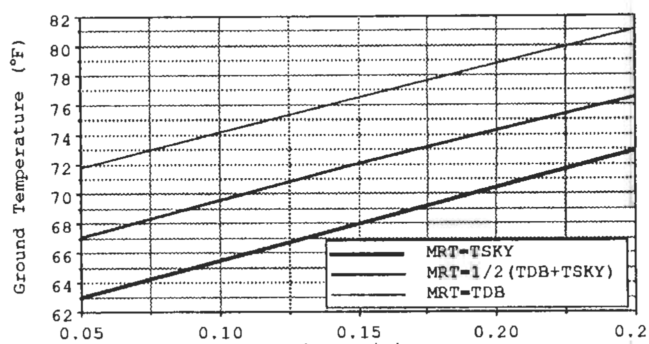

Figure 3 The Simulated Effects of Changing the Ground Surface Solar Absorptivity and the Mean Radiant Temperature (as seen from the ground surface) on the Ground Temperature at 32 feet Beneath the Surface in San Antonio, Texas.

It is clear from Figure 3 that the deep soil temperature is sensitive to both the surface absorptance and the MRT. The MRT of the unobscured sky (Tsky) ranges from 5°F below dry bulb (TDB) for cloudy humid conditions to 30°F below dry bulb for cloud-free, low dewpoint conditions (11). Shade from vegetation decreases the solar absorptance at the ground surface, but the vegetation also raises the MRT above Tsky. Under a thick canopy of leaves, the MRT seen from the ground surface is equal to the temperature of the leaves seen from the ground. In a multilayer canopy the temperature of these leaves approaces TDB (12). The quantitative relationship between solar absorptance and MRT depends on the type of vegetation (and the availability of water). However, if the low value of solar absorptance indicated at the left edge of Figure 3 is achieved by vegetation, the MRT = TDB line would serve as a reasonable approimation. For a solar absorptivity of 0.10 (typical of the soil surface beneath heavy vegetation), the simulated 74°F temperature agrees with the ground water temperature for San Antonio in Figure 1. Note that the curves in Figure 3 should not be extrapolated upward to higher solar absorptance because the strong convective and evaporation heat dissipation which would then occur have been omitted in preparing Figure 3.

CALCULATED SLAB HEAT TRANSFERS

Figure 4 illustrates the monthly heat transfer through a "typical," 30' x 40', uninsulated slab at a site with T_m = 65°F (Q>0 implies heat loss through slab). The 4" concrete slab has a carpet, pad and air film with a total thermal resistance = R3.3. The thermostat is operated so that T_R = 73°F and C = 3°F. The subslab soil has typical properties (a = 0.022 Btu/ft^2 hr, k = 0.75 Btu/ft hr°F). For a typical site with T_m = 65°F, Figures 1 and 2 imply that B is near 20°F. The resulting heat transfer is dominated by winter losses. However, there are significant passive cooling benefits in late spring and early fall.

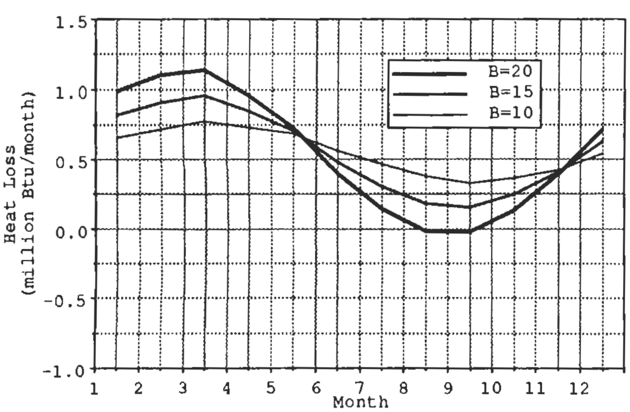

Figure 4 Monthly Heat Loss Through a 40'x30' Concrete Slab. (Tm=65, Tr=73, C=3, k=0.75, a=0.025, Rf=3.3)

Figure 5 repeats the results in Figure 4 for T_m = 76°F. For T_m = 76°F, B = 10°F is realistic and slab heat transfers are small in all months.

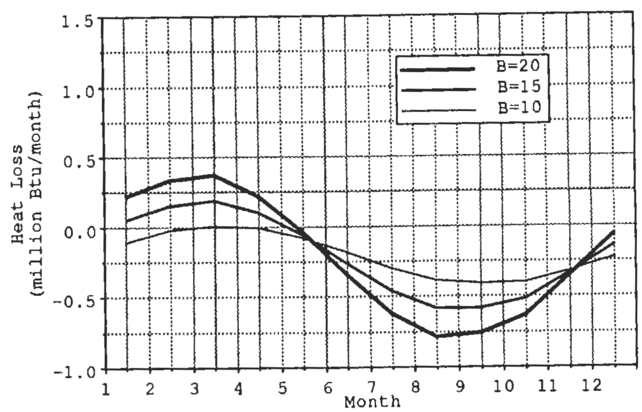

Figure 5 Monthly Heat Loss Through a 40'x30' Concrete Slab. (Tm=76, Tr=73, C=3, k=0.75, a=0.025, Rf=3.3)

On the basis of experience and detailed computer simulations of slab-on-grade residences in warm U.S. climates, we defined the cooling season as May through October inclusive and the heating season as November through February inclusive. (These definitions apply only in the warmest parts of the sun belt.) Figure 6 illustrates the resulting cooling season load and the annual load due to slab heat transfer for the residence used in Figures 4 and 5. ("Loads" are positive for heating season losses or cooling season gains.) Using only those portions of the curves which represent real climates in the sun belt, the uninsulated slab of a "typical" residence is a nearly neutral thermal element on an annual basis.

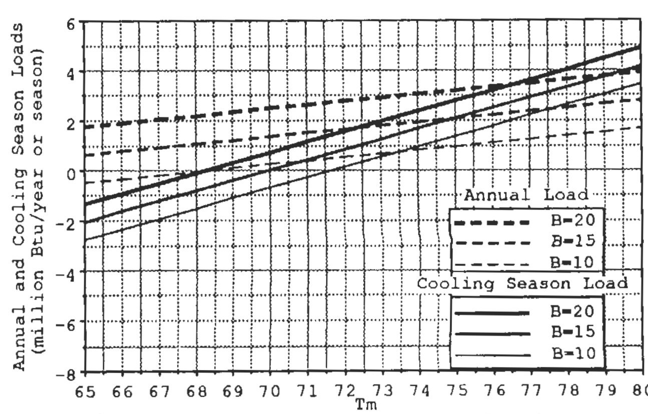

Figure 6 Cooling Season and Annual Loads for the Uninsulated Slab of a Typical Residence. (40'x30'slab, Tr=73, C=3, k=0.75, a=0.025, Rf=3.3)

Due to cancellation of summer benefits by winter loads, the annual loads in Figure 6 are surprisingly insensitive to *changes in the* residence design or changes in soil properties.

Decreasing the length to width ratio of the slab, R, from 3/4 to 1/2 increased the seasonal and annual slab loads by about 1.5 x 10^6 Btu at the extremes of T_m. For the conditions in Figure 6, increasing R to 1 had negligible effect on any of the loads.

Figure 7 shows the result of placing the slab shown in Figure 6 on more conductive soil of higher diffusivity (k = 1.16, a = 0.031 Btu/ft^2hr). The loads shown in Figure 7 were quite insensitive to changes in the length to width ratio of the slab in the range from 1/2 to 1.

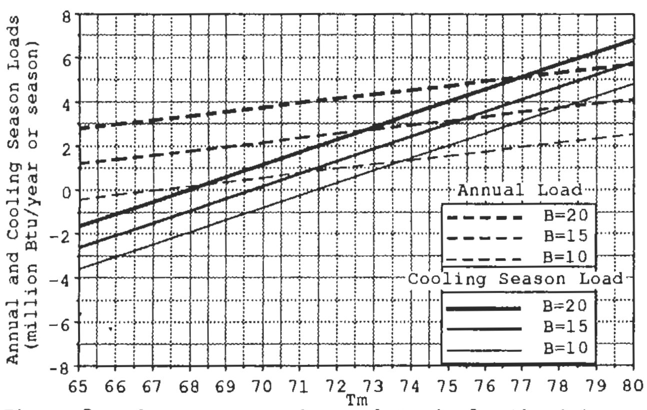

Figure 7 Cooling Season and Annual Loads for the Uninsulated Slab of a Typical Residence on Damp Soil. (40'x30'slab,Tr=73,C=3,k=1.16,a=0.031,Rf=3.3)

Although the annual total thermal effect of the slab in Figure 7 is still small, care must be taken in applying these results. The equality of seasonal loads and counter season benefits (e.g., winter loads and summer passive cooling) does not necessarily imply zero net annual cost. For example, if Tm = 78°F and B = 10°F, the slab in Figure 7 is a source of about 3.8 x 10^6 Btu of additional heat during the cooling season. If electricity costs 10 cents/kwh and the air conditioning system C.O.P. is 2.0, the removal of 1 x 10^6 Btu will cost about $15. This small slab will then produce about $55 per cooling season of additional cooling load. However, the value of the same amount of passive heating due to slab conduction during the winter may be only 1/3 of this cooling cost if the home is heated by natural gas. Conversely, if the home is heated and cooled by a heat pump, a Btu of winter heat may be more expensive than a Btu of summer cooling. The situation can also be complicated by other sources of passive heating and cooling. For example, in cooler climates, ventilative cooling may make the passive cooling due to the slab redundant in early spring and late fall.

Figures 8 - 10 show the sensitivity of the results in Figure 6 to a change in thermostat setting. Figure 8 assumes that the room temperature, T_R, is set at 73°F at all times, i.e., C = 0. (This is the assumption used by Shipp (3) and Christian and Strzepek (5). Compared to Figure 6, Figure 8 shows larger summer and winter slab loads at extreme T_m and decreased summer passive cooling benefits. Figure 9 shows the effect of energy conserving thermostat settings on the slab heat transfer in Figure 6; now T_R = 74°F and C = 5°F. The total floor system resistance has been decreased from R3.3 to R2.9 to account for the effects of ceiling fans on the air film at the floor. (The ceiling fan effect should only be applied in summer, but the Kusuda method requires that R_f be constant. This floor system still has a resistance of R2.6 due to a carpet and pad, so this air film adjustment will have little effect.) Figure 10 shows the effect of increasing C from 5°F to 7°F. Figures 9 and 10 show only modest positive effects on slab loads due to the thermostat settings; the slab heat transfer appears to be limited by the high slab resistance and medium soil diffusivity.

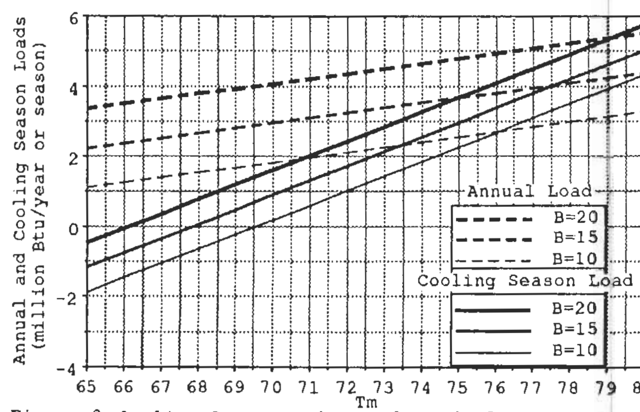

Figure 8 Cooling Season and Annual Loads for an Uninsulated Slab,Typical Residence,73°F Thermostat. (40'x30'slab,Tr=73,C=0,k=0.75,a=0.025,Rf=3.3)

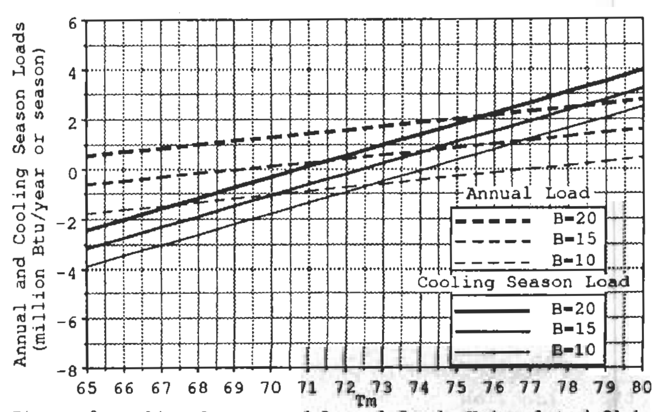

Figure 9 Cooling Season and Annual Loads,Uninsulated Slab, Typical Residence,Energy Conserving Thermostat. (40'x30'slab,Tr=74,C=5,k=0.75,a=0.025,Rf=2.9)

Proceedings of the Sixth Symposium on Improving Building Systems in Hot and Humid Climates, Dallas, TX, October 3-4, 1989

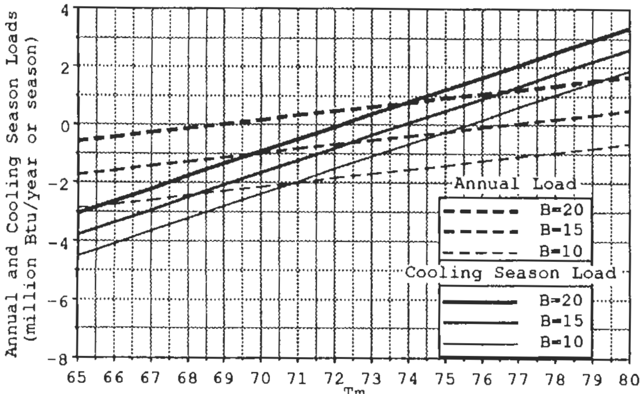

Figure10 Cooling Season and Annual Loads,Uninsulated Slab, Typical Residence,Energy Conserving Thermostat. (40'x30'slab,Tr=74,C=7,k=0.75,a=0.025,Rf=2.9)

Figure 11 shows the effect of removing most of the floor system resistance from the slab in Figure 6 (e.g., remove the carpet and pad and use ceiling fans). This again produces only modest increases in seasonal heat transfers. Figure 12 shows the effect of increasing C from $3^{O}F$ to $5^{O}F$ for the slab in Figure 11; even with the low resistance slab, the medium diffusivity soil limits the benefits of the thermostat settings. With the medium diffusivity soil, further increase of C to $7^{O}F$ had a negligible effect on the heat transfer shown in Figure 12.

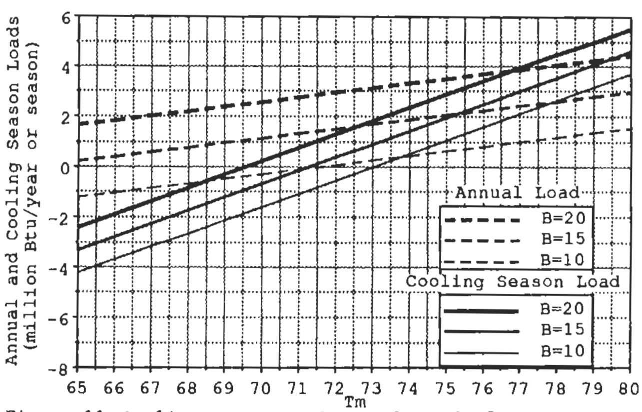

Figure 11 Cooling Season and Annual Loads for an Uninsulated, Low Resistance Slab. (40'x30'slab,Tr=74,C=3,k=0.75,a=0.025,Rf=0.5)

Figures 13 and 14 show the effect of energy conserving thermostat settings with moist soil (k = 1.16, a = 0.031 Btu/ft^{2}hr). These assumptions now allow significant slab conduction passive cooling for T_m = $65^{O}F$. For example, For C=$7^{O}F$, Tm = $65^{O}F$ and B = $20^{O}F$, the slab can dissipate about 6 x 10^{6} Btu during the cooling season; at \$15 per 1 x 10^{6}Btu this could produce a savings of about \$90. The slab is not now a source of summer heat until T_m exceeds $76^{O}F$ (B = $10^{O}F$), but it does produce significant summer load at the highest T_M.

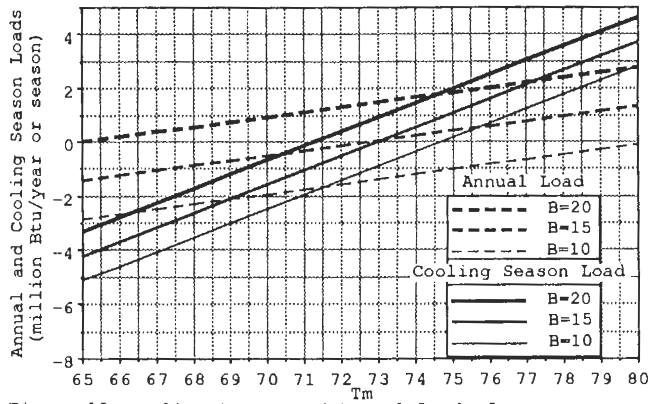

Figure 12 Cooling Season and Annual Loads for an Uninsulated, Low Resistance Slab. (40'x30'slab,Tr=74,C=5,k=0.75,a=0.025,Rf=0.5)

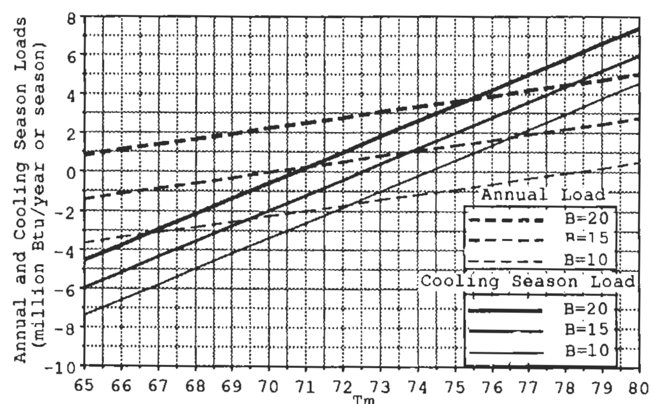

Figure 13 Cooling Season and Annual Loads for an Uninsulated, Low Resistance Slab on Damp Soil. (40'x30'slab,Tr=74,C=5,k=1.16,a=0.031,Rf=0.5)

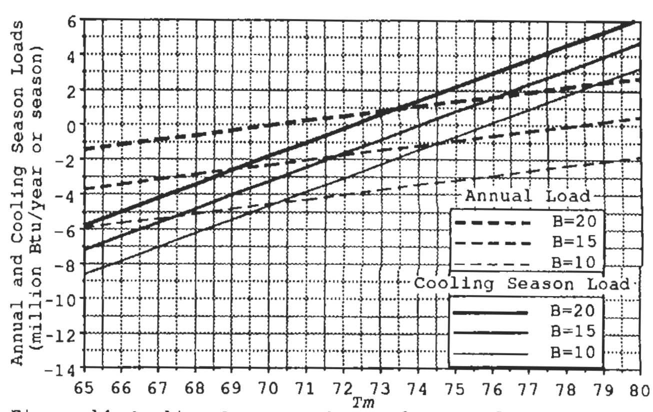

Figure 14 Cooling Season and Annual Loads for an Uninsulated, Low Resistance Slab on Damp Soil. (40'x30'slab,Tr=74,C=7,k=1.16,a=0.031,Rf=0.5)

Figures 15 - 18 repeat some of these sensitivity analyses for a 2000 ft^2 slab. Additional calculations not shown imply that for high and low R_f and medium and high soil k and a, the heat transfer through the 2000 ft^2 slab is insensitive to the length to width ratio of the slab in the range $1/2 < R < 1$. Figures 15 - 18 assume R = 3/4.

Figure 15 illustrates heat transfer for the high R slab and typical soil with $T_R = 74°F$ and $C = 3°F$. (This is like Figure 6, but with slab area increased to 2000 ft^2.) The larger slab does produce more heat transfer at extreme T_m. Figure 16 shows the modest increase in heat transfer at extreme T_m due to damp soil. Figures 17 and 18 show the effects of energy conserving thermostat settings with damp soil. Summer heat gains are significant at high T_m and passive cooling benefits are significant at low T_m. For $C = 7°F$, $T_m = 65°F$, $B = 20°F$ and \$15 per 1×10^6Btu, the 9×10^6Btu passive cooling benefits of the 2000 ft^2 slab could save about \$135 per cooling season. Under these conditions the heating season slab losses are about 6×10^6 Btu and the slab produces annual benefits, even in a heat pump heated home. This slab produces nearly zero summer heat transfer for T_m near 76°F (B = 10°F).

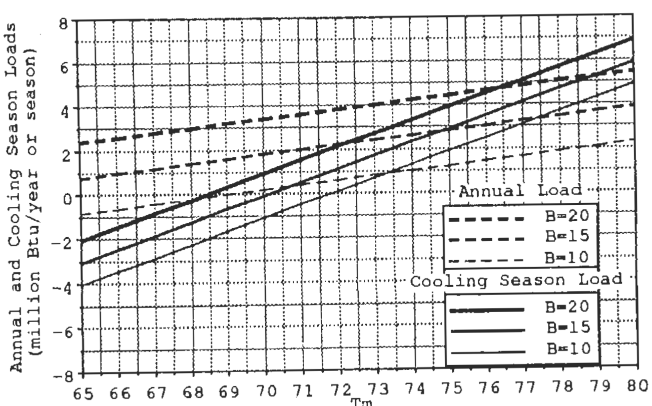

Figure 15 Cooling Season and Annual Loads for the Uninsulated Slab of a Typical Residence. (51.64'x 38.73'slab,Tr=73,C=3,k=0.75,a=0.025,Rf=3.3)

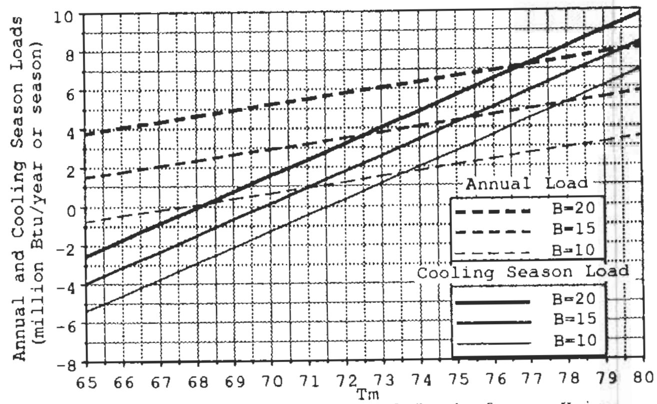

Figure 16 Cooling Season and Annual Loads for an Uninsulated Slab,Typical Residence,Damp Soil.(51.64' x38.73'slab,Tr=73,C=3,k=1.16,a=0.031,Rf=3.3)

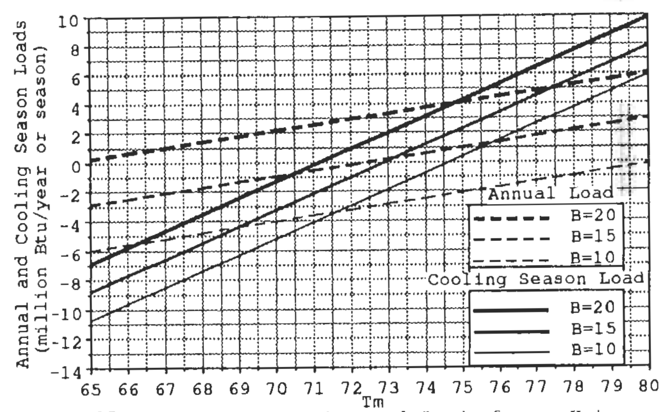

Figure 17 Cooling Season and Annual Loads for an Uninsulated,Low Resistance Slab on Damp Soil.(51.64' x38.73'slab,Tr=74,C=5,k=1.16,a=0.031,Rf=0.5)

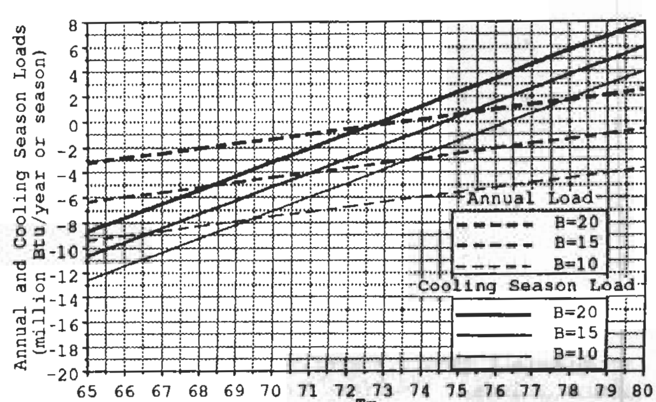

Figure 18 Cooling Season and Annual Loads for an Uninsulated,Low Resistance Slab on Damp Soil.(51.64' x38.73'slab,Tr=74,C=7,k=1.16,a=0.031,Rf=0.5)

CONCLUSIONS

All of the following conclusions are based on a heating season of November through February inclusive and a cooling season of May through October inclusive. These definitions apply only in warm and hot climates and would underestimate winter slab heat losses in cooler climates.

*For typical soil properties and typical thermostat settings, the seasonal heat transfer through an uninsulated, carpeted slab-on-grade is dominated by summer heat gain in warm U.S. climates.

* For energy conserving thermostat settings the summer slab heat transfer is near zero for Tm near 76°F.

* The simulated slab heat transfer is insensitive to the length to width ratio,R, of the slab in the range $1/2 < R < 1$.

* The slab can provide significant passive cooling if the thermostat is energy conserving, the floor system has low thermal resistance, the slab is on damp soil and T_m is less than 70°F. At Tm = 65°F, such a 1200 ft^2 slab can displace about $90 worth of electricity for air conditioning during a cooling season. For a 2000 ft^2 slab this cooling benefit would be worth about $135.

The availability of significant passive cooling does not argue against insulating the perimeter of the slab. In fact the suppression of summer heat gain by perimeter insulation would increase the rate of summer passive cooling in all warm climates. Perimeter insulation is of greater benefit where the annual range in T_m is large.

REFERENCES

1. Kusuda, T., Bean, J.W., and Mizuno, M., "Seasonal Heat Loss Calculation for Slab-On-Grade Floors," National Bureau of Standards, 1982, NBSIR 81-2420.

2. Kusuda, T., and Bean, J.W., "Simplified Methods for Determining Seasonal Heat Loss from Uninsulated Slab-on-Grade Floors," ASHRAE Trans., 1984, Vol. 90, Part 1B, pp. 611-632.

3. Shipp, P.H., "Basement, Crawlspace, and Slab-on-Grade Thermal Performance," Proceedings, ASHRAE/DOE Conference on Thermal Performance of the Exterior Envelopes of Buildings II, ASHRAE SP38, Atlanta, Georgia, December, 1982, pp. 160-179.

4. Claridge, D.E., "Design Methods for Earth-Contact Heat Transfer," Advances in Solar Energy, Volume 4, American Solar Energy Society, Inc., Boulder, Colorado, 1988, pp.305-351.

5. Christian, J.E., and Strzepek, W.R., "Procedure for Determining the Optimum Foundation Insulation Levels for New Low Rise Residential Buildings," ASHRAE Trans., 1987, Vol. 93, Part 1, pp.909-938.

6. Krarti, M., Claridge, D., and Kreider, J., "Interzone Temperature Profile Estimation – Slab-on-Grade Heat Transfer Results," Heat Transfer in Buildings and Structures, 1985, HTD-Volume 41, ASME.

7. Kusuda, T., and Achenbach, P.R., "Earth Temperature and Thermal Diffusivity at Selected Stations in the United States," ASHRAE Trans., 1965 Vol.71,Part 1, pp, 61-75.

8. Labs, K., "Earth Coupling," Solar Heat Technologies: Fundamentals and Appplications, Volume 8, Passive Building Cooling, M.I T. Press, 1990.(In Press)

9. Labs, K., and Harrington, K., "A Comparison of Ground and Above-Ground Climates for Identifying Appropriate Cooling Strategies," Passive Solar Journal, 1982, AS/ISES, Volume 1.

10. Kusuda, T., Earth Temperature Beneath Five Different Surfaces, National Bureau of Standards Report 10373, Washington, D.C., 1971.

11.Clark, G., "Passive/Hybrid Comfort Cooling by Thermal Radiation," Proceedings of the International Passive and Hybrid Cooling Conference, Miami Beach, Florida, 1982, pp.682-714.

12.Gates, D.M., and Papian, L.E., 1971, Atlas of Energy Budgets of Plant Leaves, Academic Press, New York, New York, 1971.