HEAT LOSS FACTORS FOR INSULATED BUILDING FOUNDATIONS

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ABSTRACT

Non-steady-state finite element analyses of the heat loss occurring from basement and slab-on-grade constructions have been performed. The amount of rigid foam insulation was varied on the perimeter of the walls and slab to determine the effectiveness of various insulation configurations. Annual heat losses per linear foot of wall or slab are reported for weather conditions and soil types in both Anchorage and Fairbanks, Alaska.

INTRODUCTION

Insulation of basement walls and floor slabs in most Alaskan locations has become the standard design practice for new building construction. Yet no standards exist on the amount of insulation or the method of placing the insulation for an economically justified energy conserving design. This report addresses a portion of this problem by evaluating the transmission heat losses that occur through various basement wall and floor slab insulation configurations. The data presented should assist the 'uilding designer and owner in choosing the most effective means of using insulation for these types of building construction. ASHRAE (1981) does provide a methodology for calculating steady-state heat losses for basements and slab-on-grade construction. The technique does not account for nonsteady heat flow, snow cover or varying soil properties.

ANALYSIS

The heat loss analyses of the basement wall and floor slab insulation systems were performed on a non-steady-state basis. Because of the complexity of the geometry and the nonhomogeneity of the materials, the heat transfer analyses were done using numerical techniques programmed for a digital computer. A non-steady-state, two-dimensional finite element program (Wang 1979) has been implemented on a university computer system. This program uses triangular and/or quadrangular elements allowing the specification of thermal conductivity, specific heat and latent heat of each element. The program accounts for freezing and thawing by using an apparent specific heat. The apparent specific heat is calculated as the sum of the frozen specific heat and the soil volumetric latent heat divided by an assumed phase change temperature range. In fact, most fine grained soils exhibit some subcooling and a release of latent heat over a temperature range as the unfrozen water content freezes.

The apparent specific heat approach to solving the thermal regime in a soil with freezing/thawing using the finite element method can lead to stability problems. Oscillation of nodal temperatures at the freeze/thaw front was typical of the stability problems experienced when using large elements. Numerous runs were made using the Wang program in which element and time-step sizes were varied to investigate their effect on stability. Element and time-step sizes were reduced to minimize this effect. When comparison runs of the annual heat loss were made using a fine mesh and a three-day time step to a coarse mesh with a 14-day time step, results differed by 4% for a 20% moisture content soil and 3.5% for an 8% moisture content soil.

Boundary temperatures or heat fluxes must be specified, but because the model is non-steady-state, these boundary conditions can be varied with time. The model allows convective heat transfer at any of the bounding surfaces, in which case the air temperature rather than surface temperature is specified. Heat fluxes occurring across the isothermal boundaries are calculated. These heat fluxes are integrated with respect to time to arrive at annual heat loss through the basement wall and/or floor slab. The initial conditions for the soil temperature were set equal to those previously calculated for a noninsulated foundation system. The program was allowed to run through two annual cycles to establish equilibrium before integration of the heat fluxes was initiated during the third annual cycle.

Foundation Systems

The thermal energy losses for four different foundation systems have been studied. The characteristics of these four foundations, shown in Figure 1, are outlined as follows.

1. Full Basement
   - 8-inch masonry block wall extending to a depth of 8 feet below the ground surface
   - 6-inch thick concrete floor slab
   - 8-inch thick, 24-inch wide concrete footing
   - 16 feet to building centerline

2. Monolithic Slab-on-Grade
   - 6-inch-thick concrete slab with 1-foot-thick by 18-inch-wide perimeter concrete footing
   - 16 feet to building centerline

3. Slab with Grade Beam
   - 6-inch-thick concrete slab
   - 8-inch masonry block grade beam extending 4 feet in depth
   - 8-inch thick, 24-inch-wide concrete footing

16 feet to building centerline

4. Daylight Basement
   8-inch masonry block wall extending 4 feet below ground surface
   6-inch-thick concrete slab
   8-inch-thick, 24-inch-wide concrete footing
   16 feet to building centerline

Thermal Property Data

The following list of thermal properties and their values were used in the finite element analysis.

Property	Location and Value: Anchorage	Location and Value: Fairbanks
Soil (sandy-silt or silt)		
Dry density, lb/ft^3	124	104
Moisture content, %	10	8
Frozen thermal conductivity, Btu/h•ft•F	1.15	0.55
Thawed thermal conductivity, Btu/h•ft•F	1.0	0.55
Frozen specific heat, Btu/ft^3•F	22	22
Thawed specific heat, Btu/ft^3•F	33.2	26
Volumetric latent heat, Btu/ft^3	1,750	1,250
Gravel		
Dry density, lb/ft^3	135	135
Moisture content, %	7	5
Frozen thermal conductivity, Btu/h•ft•F	2.2	1.6
Thawed thermal conductivity, Btu/h•ft•F	1.9	1.6
Frozen specific heat, Btu/ft^3•F	27.6	26
Thawed specific heat, Btu/ft^3•F	32.4	30
Volumetric latent heat, Btu/ft^3	1,300	950
Insulation (extruded rigid polystyrene)		
Density, lb/ft^3	2	
Thermal conductivity, Btu/h•ft•F	0.015	
Specific heat, Btu/ft^3•F	0.52	

Concrete

Density, lb/ft^3	140
Thermal conductivity, Btu/h•ft•F	1.0
Specific heat, $Btu/ft^3 \cdot F$	28.0

Masonry Block

Thermal conductivity, Btu/h•ft•F	0.53
Specific heat, $Btu/ft^3 \cdot F$	12.8

Snow

Density, lb/ft^3	15
Thermal conductivity, Btu/h•ft•F	0.1

Boundary Conditions

Zero heat flux normal to the vertical boundaries was specified. The ground, slab, wall and floor surfaces were chosen as convective boundaries. A surface conductance of 1.08 $Btu/h \cdot ft^2 \cdot F$ (R = 0.93) was used for the slab and floor surfaces and a value of 1.47 $Btu/h \cdot ft^2 \cdot F$ (R = 0.68) was used for the wall surface. The ground surface conductance was seasonally varied to include the thermal resistance of the snow cover. During periods assumed to have no snow cover (April 15 to October 15), a surface conductance of 4.0 $Btu/h \cdot ft^2 \cdot F$ was used. During the remainder of the year, we assumed snow cover was two-feet deep for Fairbanks and one-foot deep for Anchorage. Surface conductance of 0.05 (R = 20) and 0.10 (R = 10) $Btu/h \cdot ft^2 \cdot F$, respectively, were used to simulate the combined snow and surface resistance. Because of the warming effect of the building, the snow cover was varied in depth from zero at the building wall to full depth one foot away. Air temperatures adjacent to the interior wall, slab and floor surfaces were set at 70F. Outdoor air temperatures were assumed to vary according to a sinusoidal function where the amplitude, A_o, and mean annual temperature, T_m, were taken from Hartman and Johnson (1969). The expression used was

$$T = T_m - A_o \cos \left[\frac{2\pi}{365} (t + \phi)\right]$$

where

T_m = 26F, Fairbanks

T_m = 35°F, Anchorage

A_o = 36F, Fairbanks

A_o = 23°F, Anchorage

t = time, daysz

ϕ = seasonal lg

The deep ground temperature for each site was specified as the bottom horizontal isothermal boundary condition. T = 39°F for Anchorage, and T = 34°F for Fairbanks.

RESULTS

The results presented in this paper should be viewed as the upper and lower bounds to the heat loss from slab and basement structures. In actual situations, an absence of snow cover or an undisturbed snow cover of two feet for Fairbanks or one foot for Anchorage for an entire winter is doubtful. Therefore, the "real" heat loss from either a slab or basement should be bounded by the values reported for the snow and no-snow cases.

The base case used in the non-steady-state basement analysis was the uninsulated basement with a snow cover and silty soil conditions. Figures 2 through 7 show the effect of soil type and insulation treatment on the ratio of annual heat loss to base-case annual heat loss for Fairbanks. These results indicate a doubling of heat loss from the base case (when gravel replaces the silt as the surrounding soil; gravel has a higher thermal conductivity) and a 23% reduction of heat loss when two inches of insulation are placed on the entire wall and below the floor slab. Leaving the concrete footing uninsulated allows a thermal bridge for a higher heat loss from this area. Annual heat loss is mainly influenced by snow cover, soil thermal conductivity, insulation, and, to a lesser degree, soil latent heat. Similar results are shown in Figures 8 and 9 for basement located in Anchorage. Finally, a summary presentation of annual heat loss for the non-steady-state basement case is presented in Figures 10 and 11. Annual heat losses per foot of wall perimeter are shown for Anchorage and Fairbanks as a function of soil type and insulation configuration. Silty soils with extensive insulation have the lowest annual heat loss, as expected. However, the cost effectiveness of the under-basement-slab insulation appears questionable due to the "flatness" of the curve. Adding these insulating features to a full basement with insulated walls may not be economically justified.

Figures 12 and 13 show the ratios of annual insulated heat loss to annual uninsulated heat loss for various slab-on-grade insulation configurations in Anchorage and Fairbanks. The results indicate a reduction in annual heat loss of about 12% for just perimeter insulation placed around a slab to 40% to 50% for full insulation treatment. A summary of these figures is presented in Figure 14.

Figures 15 through 22 show the ratios of annual heat loss from a slab with grade beam and/or daylight basement foundation with varying insulation configurations, soil types, and snow cover to the annual heat loss from an uninsulated foundation with snow cover. These results show that annual heat loss is reduced by 19% from the uninsulated case by applying 4 feet of insulation to the grade beam. Adding 4 feet of insulation to the daylight basement foundation wall reduces the heat loss by 20%. A summary of these results is given in Figures 23 and 24 in terms of annual heat loss per foot of foundation perimeter.

Economic Analysis

Because of the wide variation in energy and construction costs in Alaska, no attempt has been made in this report to perform a quantitative economic analysis of insulation systems by region. However, we present a methodology for choosing the optimum insulation configuration based on engineering economic principles. There are several approaches to performing an engineering economic analysis on the optimum insulation thickness and configuration. The approach presented here uses the capital recovery factor to annualize the capital cost recovery factor to annualized capital cost of the project. The annualized capital cost is then added to the annual energy cost to arrive at the total annual cost of the structure. When this analysis is performed for each insulation configuration, a new total annual cost is calculated. The optimum economic insulation configuration is the configuration yielding the lowest annual cost.

The capital recovery factor is $CRF = i/[1-(1 + i)^{-n}]$ where n is the number of periods or useful life of the project, and i is the market interest rate. Market interest rate is a function of the investment activities in financial and business communities as reflected by actual rates of interest. The market interest rate (or minimum attractive rate of return) includes effects of both the earning and purchasing power of money as well as project risk. Therefore, an increase in the rate of inflation or project risk usually results in an increase in the market interest rate. Using the market interest rate places cash flows in terms of actual or out-of-pocket dollars at any time. The CRF is multiplied by the total cost ($\$/ft^2$) of construction (material plus labor cost) to arrive at the annualized cost of the wall. The annual energy cost is calculated by multiplying the present cost of energy (\$/Btu) times the annual heat loss for the construction ($Btu/ft^2 \cdot yr$) divided by the heating system seasonal efficiency. The annualized capital cost and annual energy cost are added together to arrive at the total annual cost ($\$/ft^2$) per year. Figure 25 shows conceptually the results of these calculations for typical insulated constructions.

As seen in the figure, small amounts of insulation yield a low annualized capital cost through a high annual energy cost. Large amounts of insulation yield opposite results. The optimum insulation configuration is the low point on the total annual cost curve. It should be noted that high discount rates, short life projects, and low fuel costs will shift the minimum point toward small amounts of insulation. Opposite trends in these items will shift the optimum to greater thicknesses. This simplified approach does not include such variables as annual maintenance, inflating fuel costs, or salvage value of the building at the end of its useful life.

CONCLUSION

Results of finite element thermal analyses have been presented for (1) full basement, (2) slab on grade (3) slab on grade with grade beam, and (4) daylight basement. Varying amounts of 2-inch-thick rigid foam insulation were placed on the different foundation systems to study the effect of insulation configuration on annual heat loss. Life-cycle costs of the insulation systems were not investigated; therefore, the "optimum" insulation system has not been determined. However, the annual thermal losses we presented are required to conduct the economic analysis.

Our results show that snow cover has a significant effect on the annual heat loss from foundations. A two-foot-deep undisturbed snow cover will reduce annual heat loss by up to 30% compared to bare ground. Soil thermal conductivity also has a great effect on the annual heat loss. Sands and gravels (having a much higher thermal conductivity than silts) cause the annual heat loss to increase by 110%. Full insulation on an 8-foot basement wall will reduce the annual heat loss by 20% with a snow cover and 30% without a snow cover.

Insulating a basement wall with gravel fill without a snow cover leads to a 16% decrease in annual heat loss. As expected, insulating the wall, footing and slab yields the largest reduction in annual heat loss: 26% for snow-covered conditions and more than 32% for bare-ground conditions.

For slab-on-grade construction, insulating the perimeter of the slab reduces the annual heat loss by about 12%, whereas insulating the perimeter and under the slab reduces the annual heat loss by 50%. For the grade beam case in silt, insulating to the top of the footing results in a 19% reduction in heat loss. Removing the snow cover increases the heat loss by 30% for the uninsulated wall, and changing to a gravel soil doubles the heat loss.

Care should be exercised to prevent frost heave when insulating basement walls and slab-on-grade construction. Although the isotherms shown in Figures 5 through 12 do not indicate frost heave problems, periods of extremely cold weather (e.g., -50F for two weeks) can cause the freezing isotherm to penetrate below the slab. Nonfrost susceptible materials must be used to a depth greater than the maximum depth of freeze to prevent frost heave damage.

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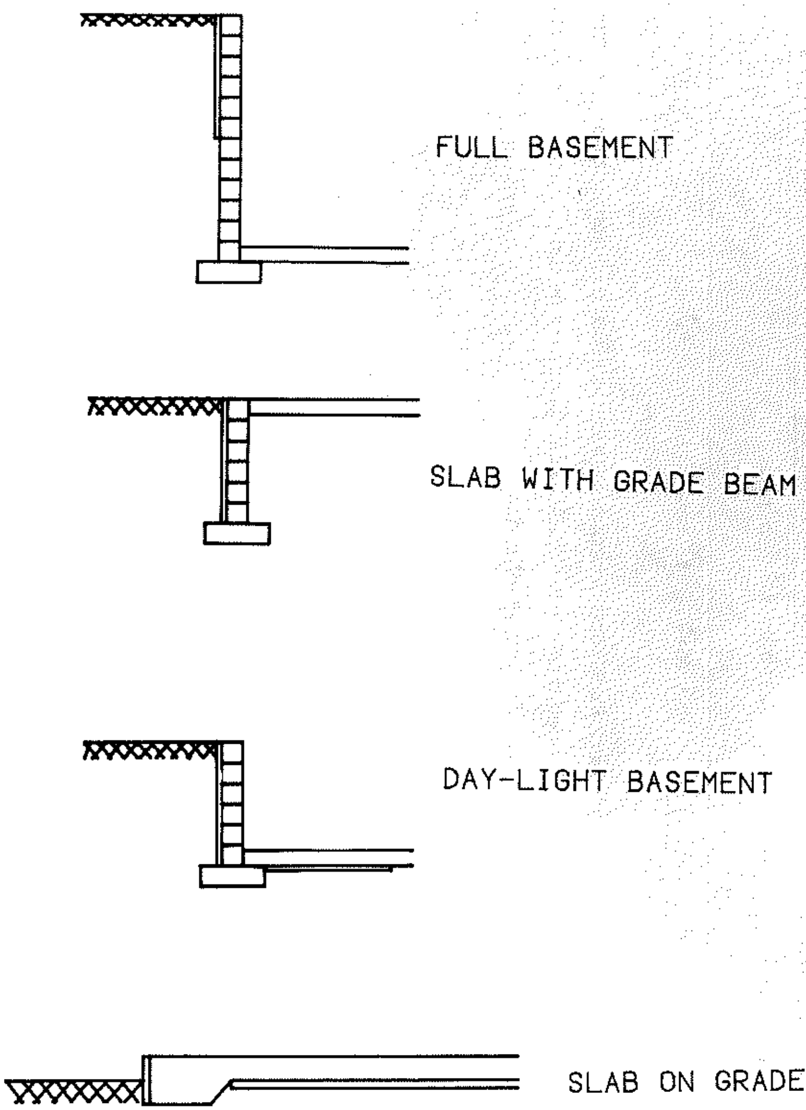

Figure 1. Characteristics of four foundation systems

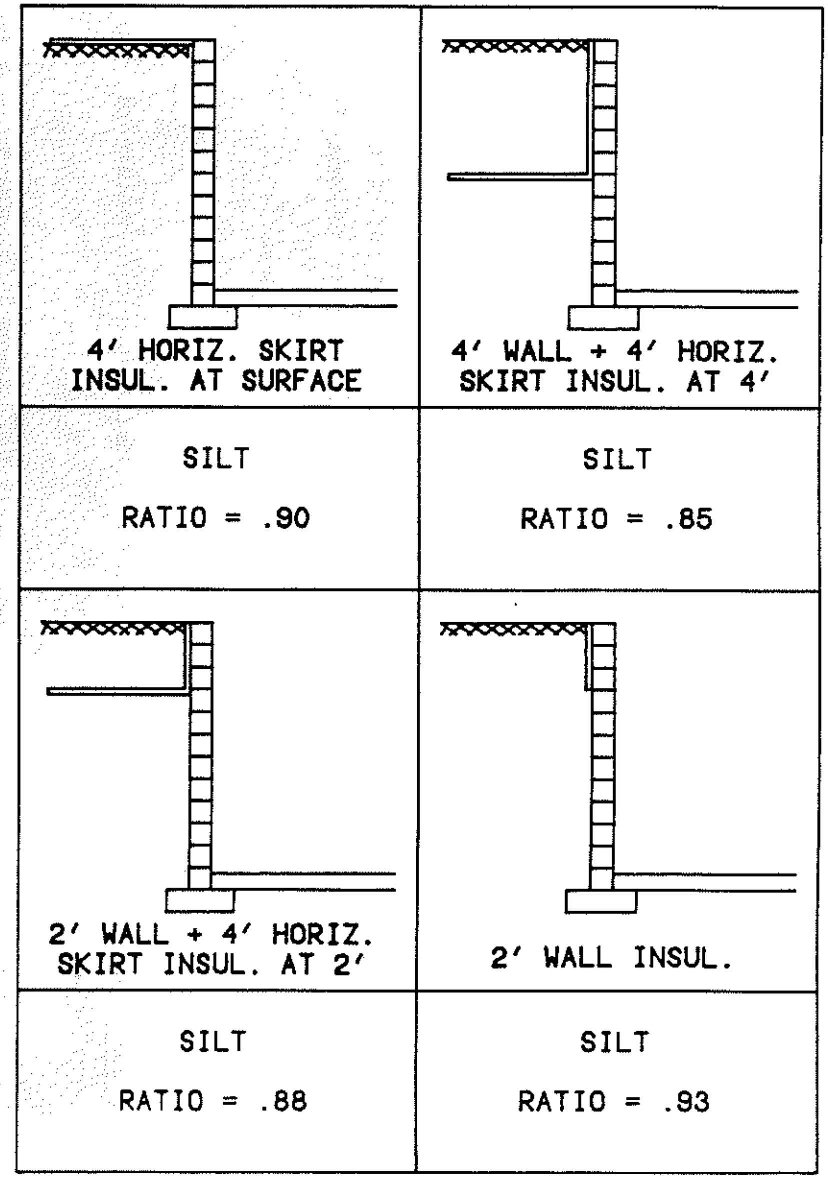

Figure 2. Fairbanks, ratio = heat loss/ uninsulated heat loss in silt

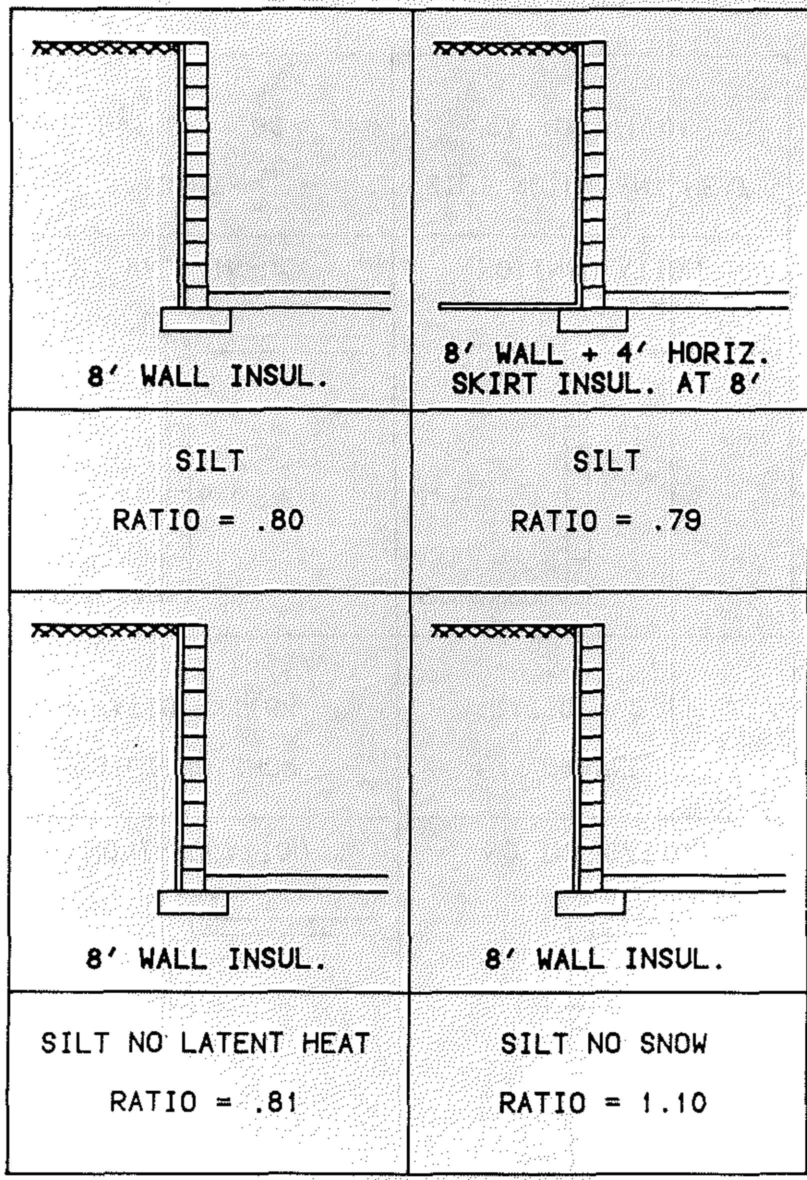

Figure 3. Fairbanks, ratio = heat loss/ uninsulated heat loss in silt

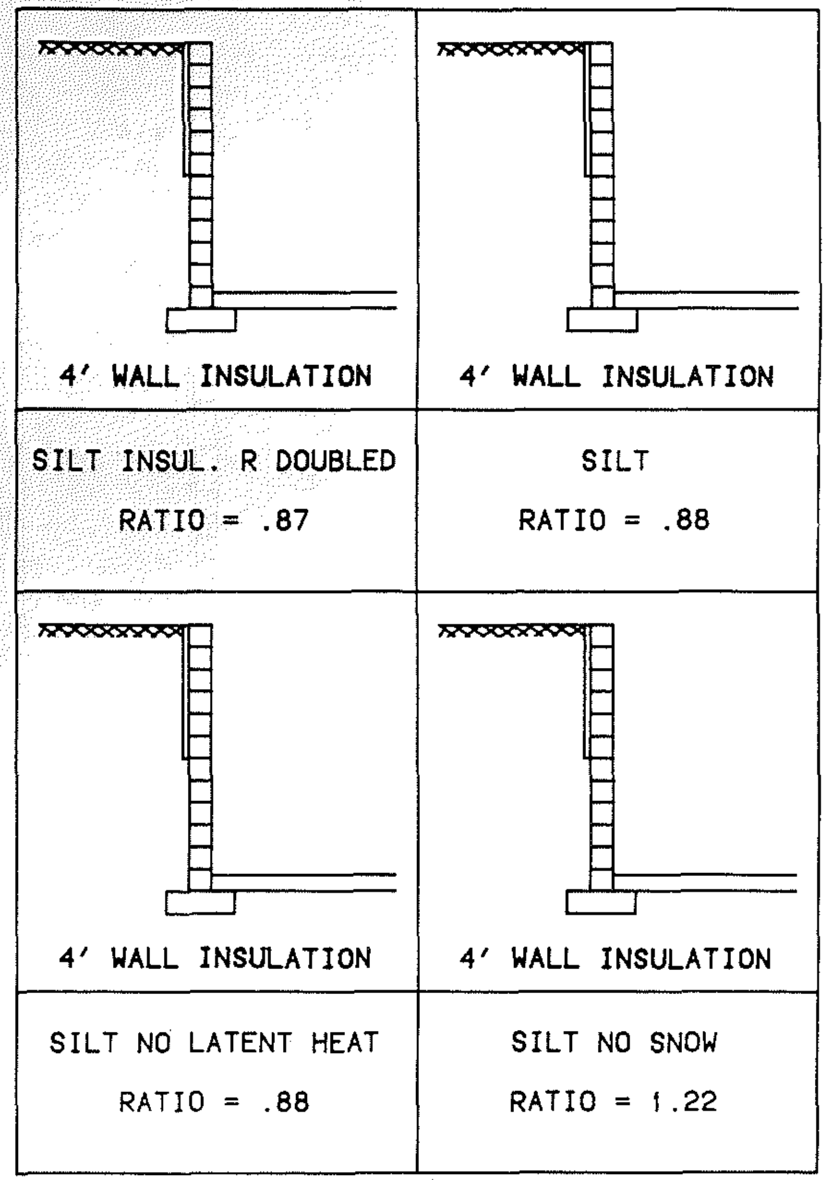

Figure 4. Fairbanks, ratio = heat loss/ uninsulated heat loss in silt

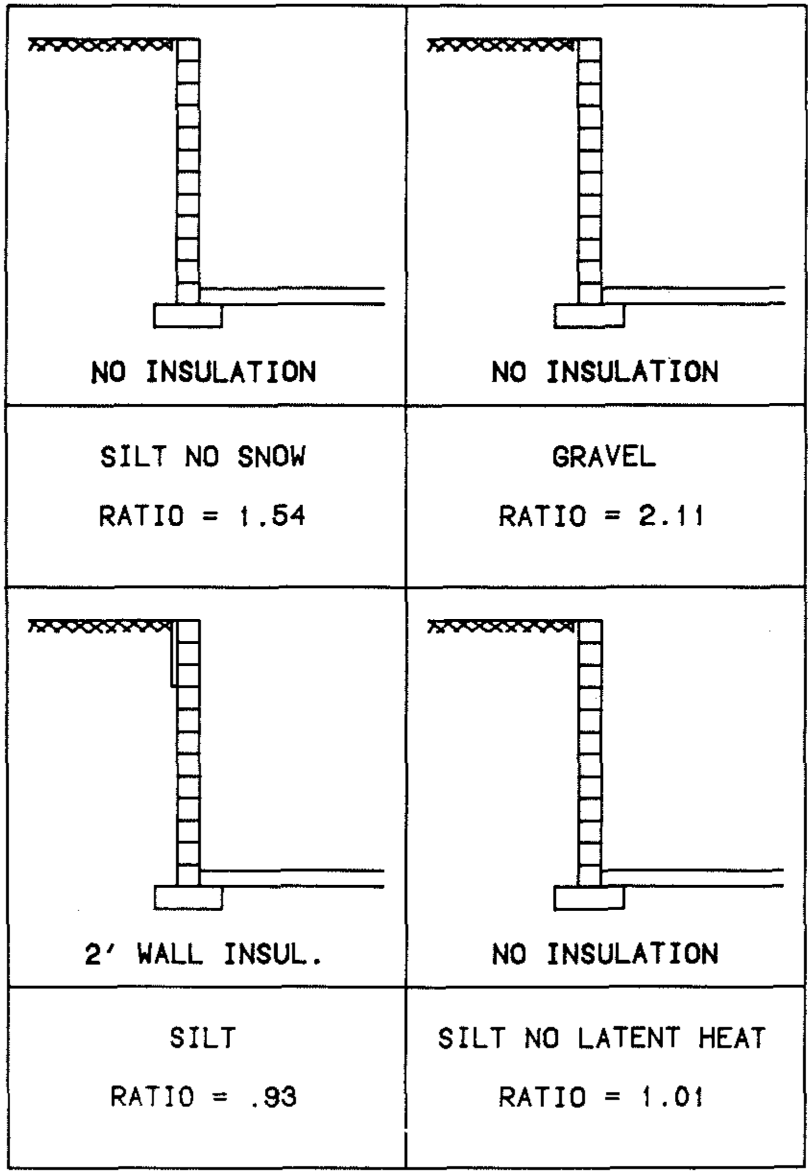

Figure 5. Fairbanks, ratio = heat loss/ uninsulated heat loss in silt

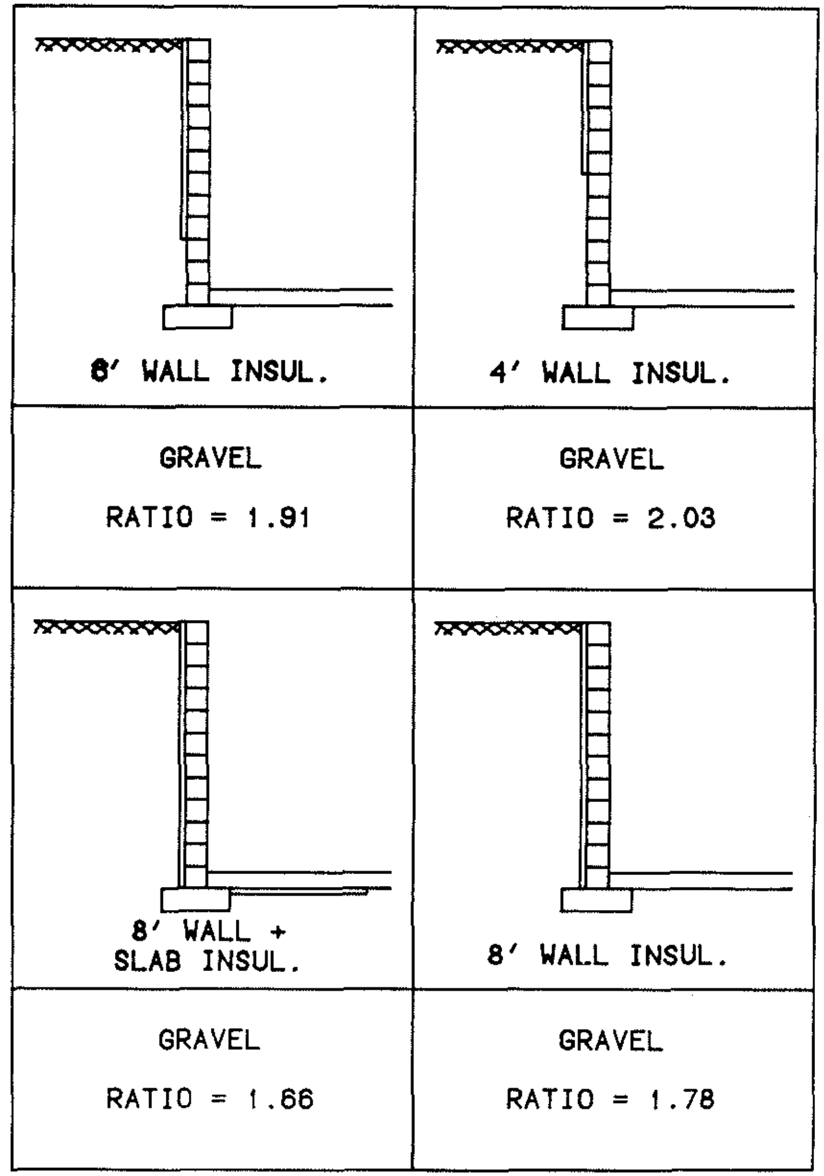

Figure 6. Fairbanks, ratio = heat loss/ uninsulated heat loss in silt

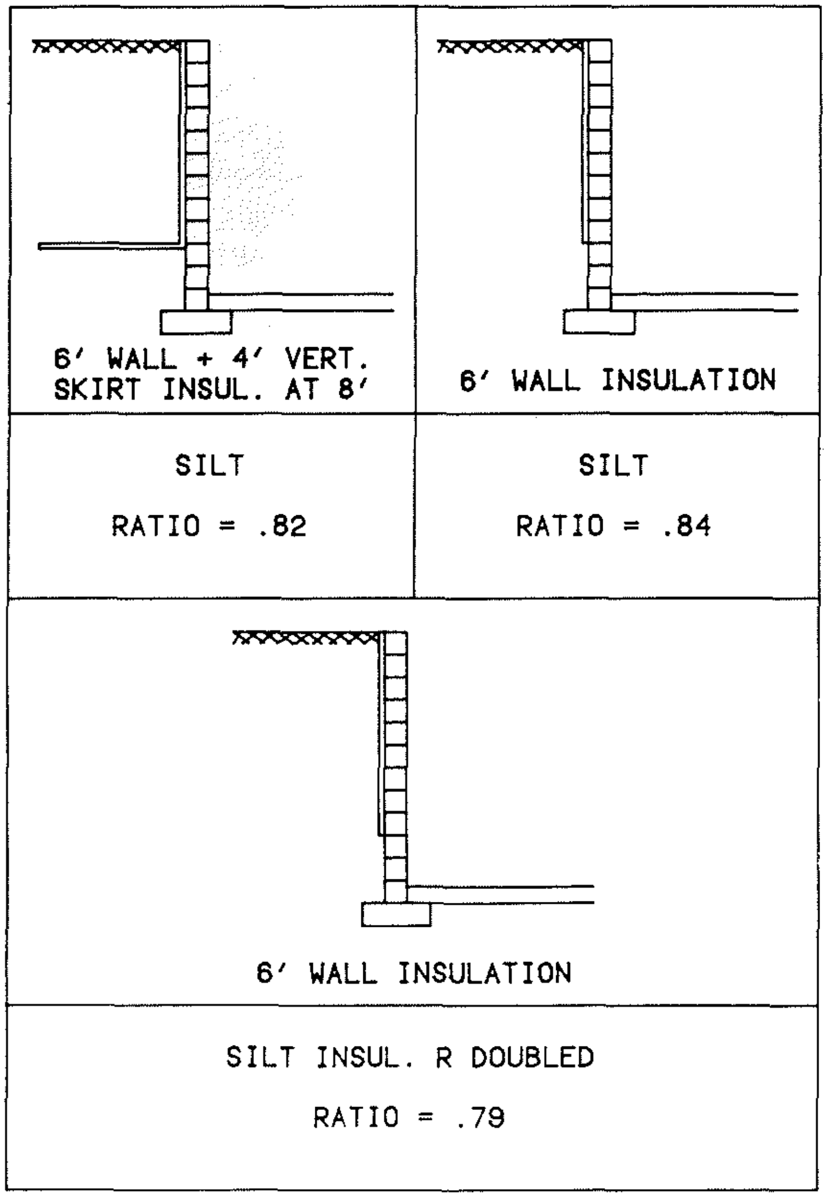

Figure 7. Fairbanks, ratio = heat loss/ uninsulated heat loss in silt

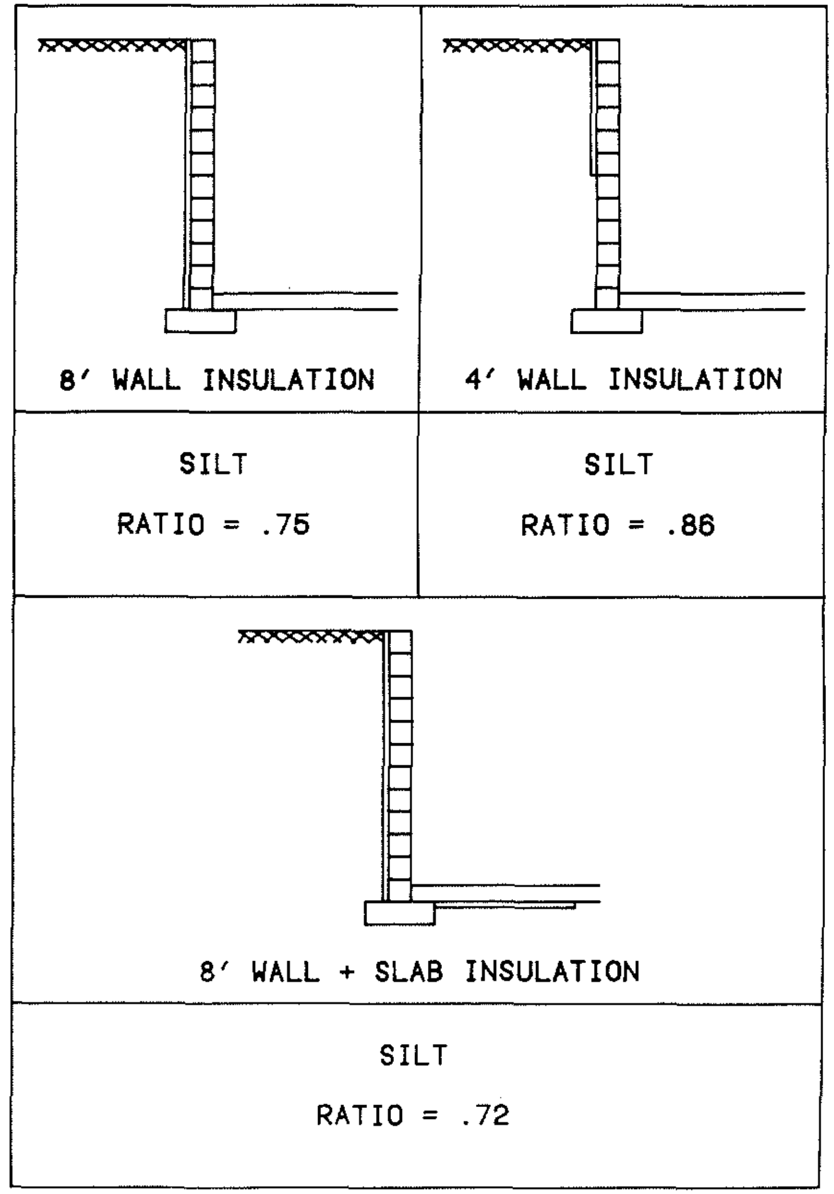

Figure 8. Anchorage, ratio = heat loss/ uninsulated heat loss in silt

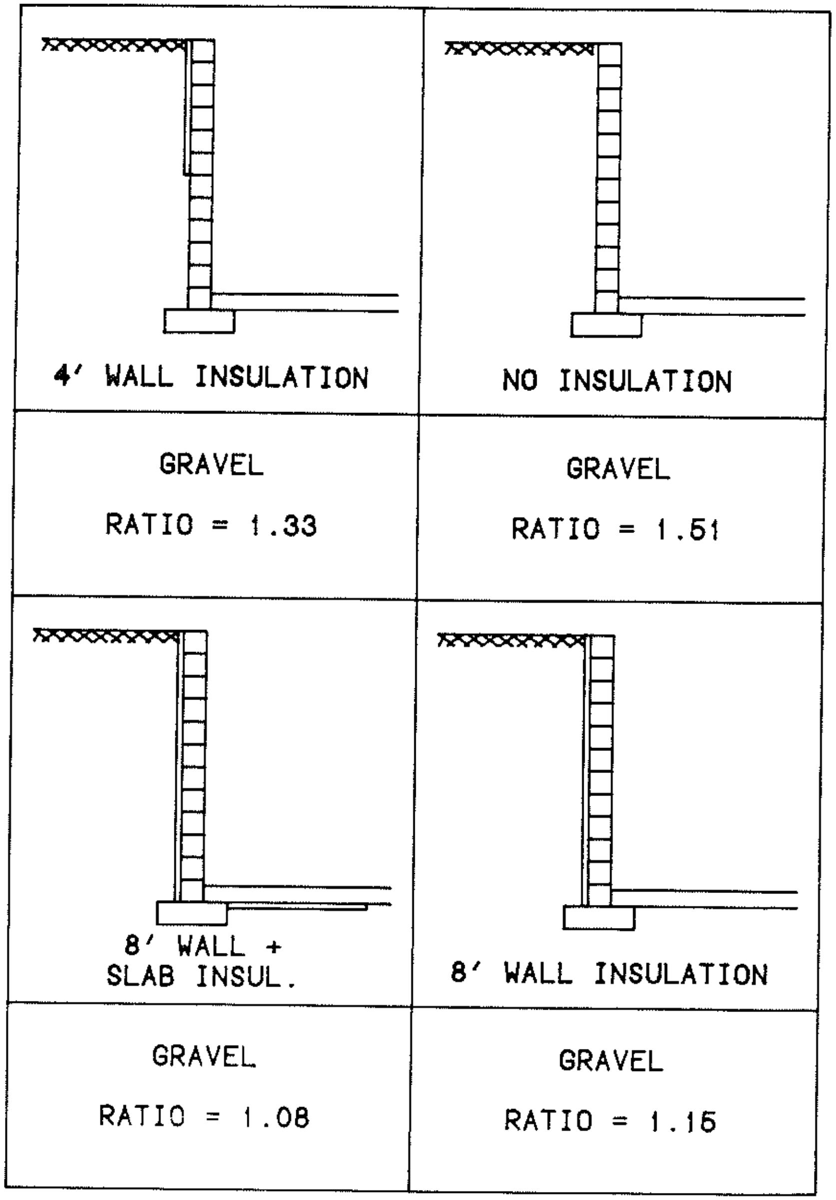

Figure 9. Anchorage, ratio = heat loss/ uninsulated heat loss in silt

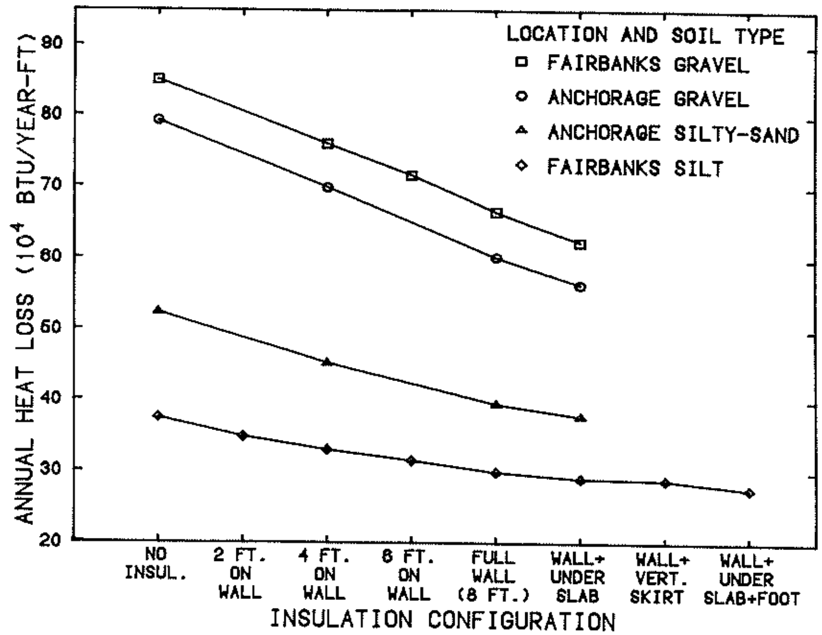

Figure 10. Basement annual heat loss for various insulation configurations

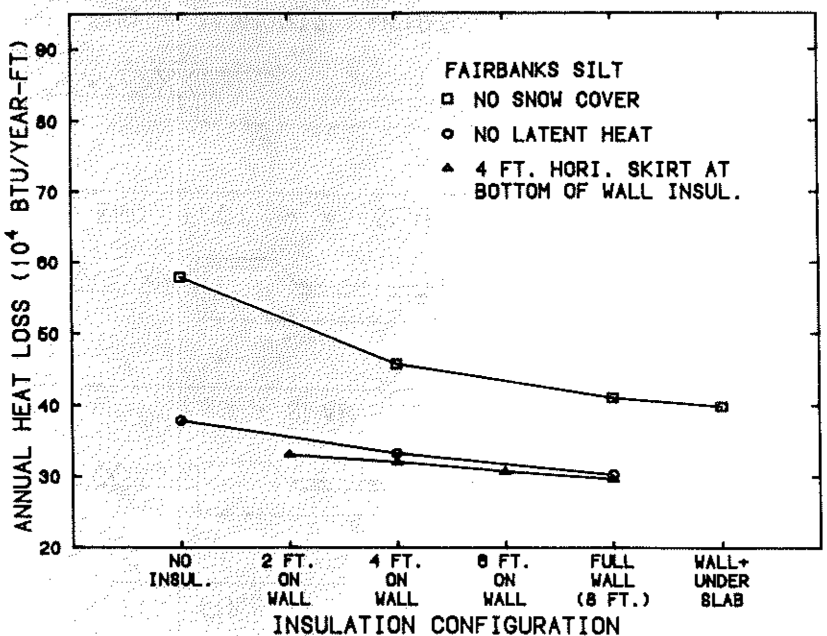

Figure 11. Basement annual heat loss for various insulation configurations

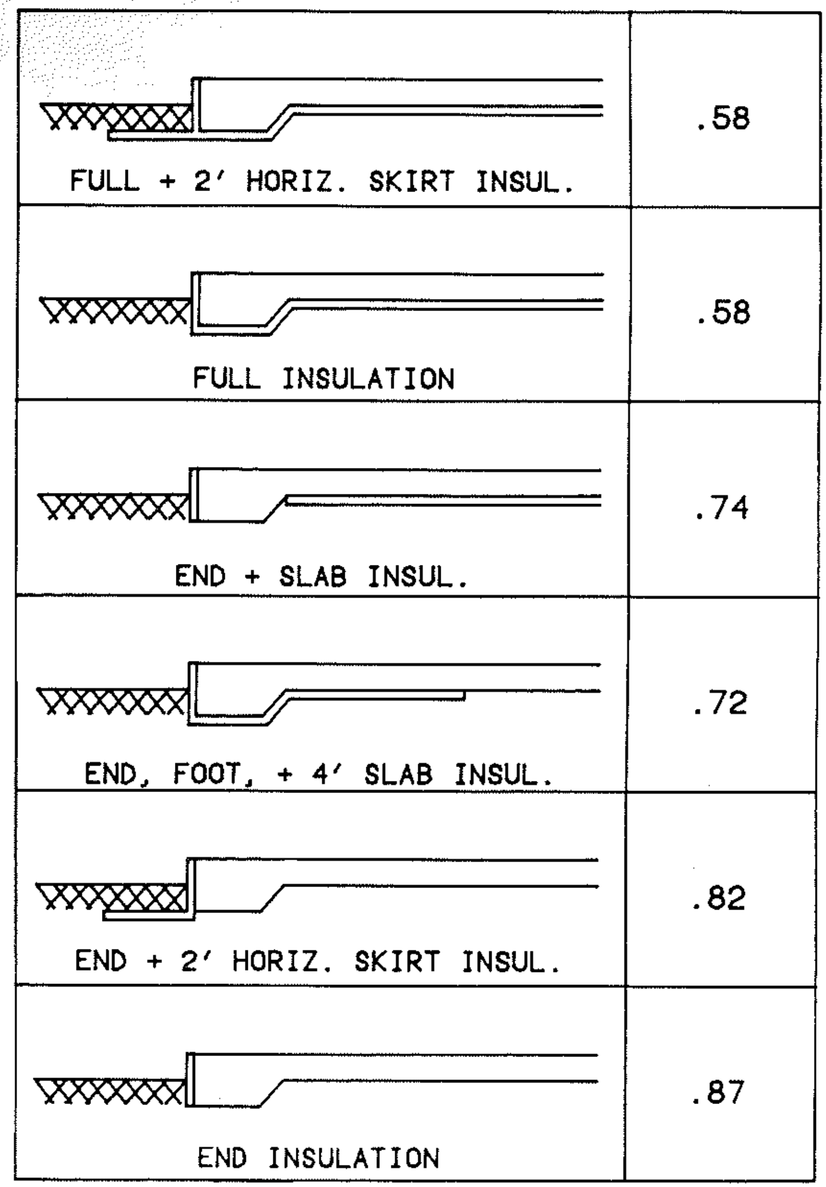

Figure 12. Fairbanks transient heat loss/ uninsulated heat loss

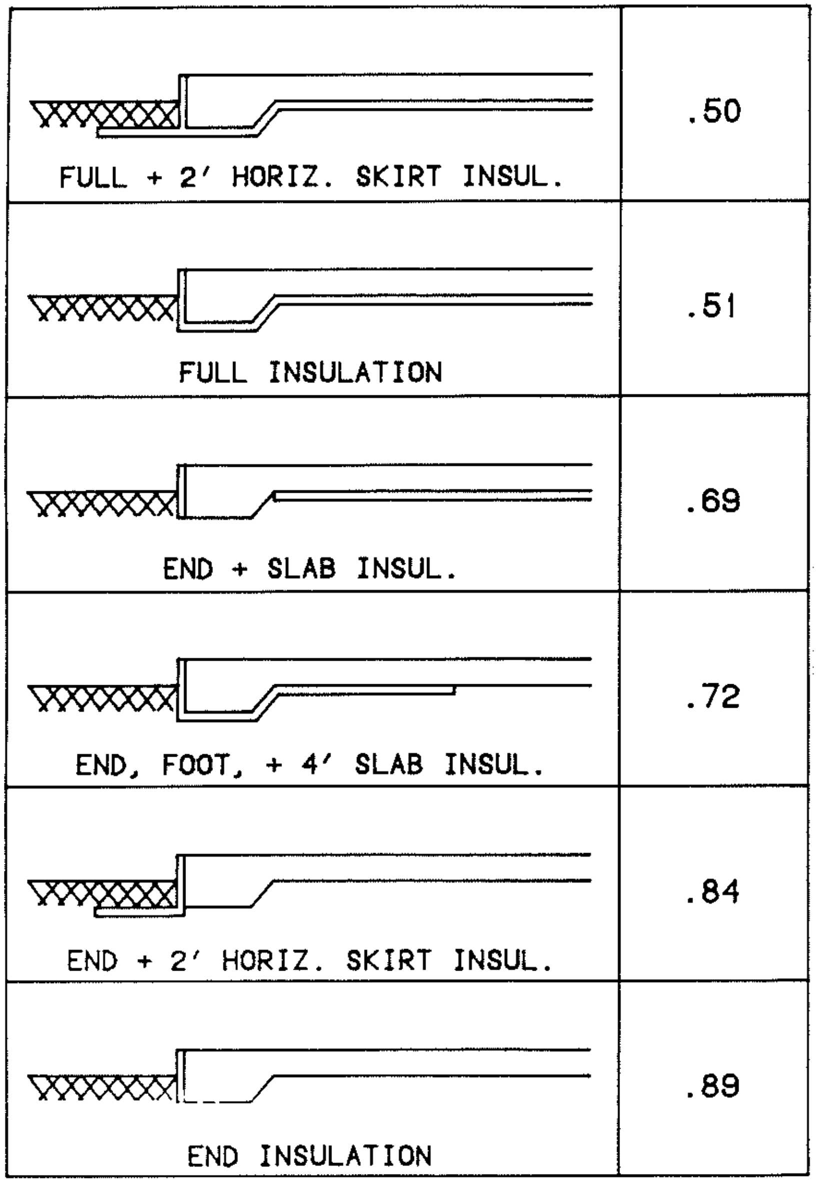

Figure 13. Anchorage transient heat loss/ uninsulated heat loss

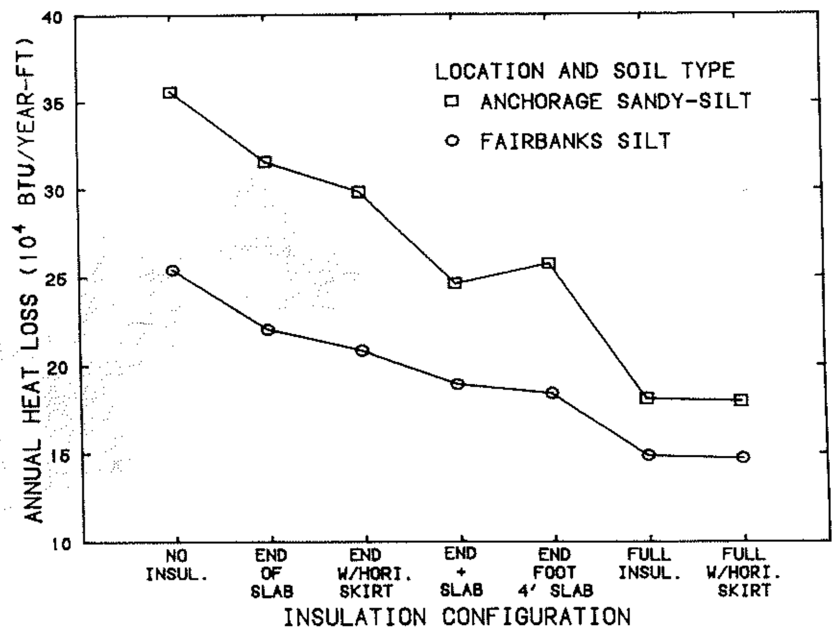

Figure 14. Slab-on-grade annual heat loss for various insulation configurations

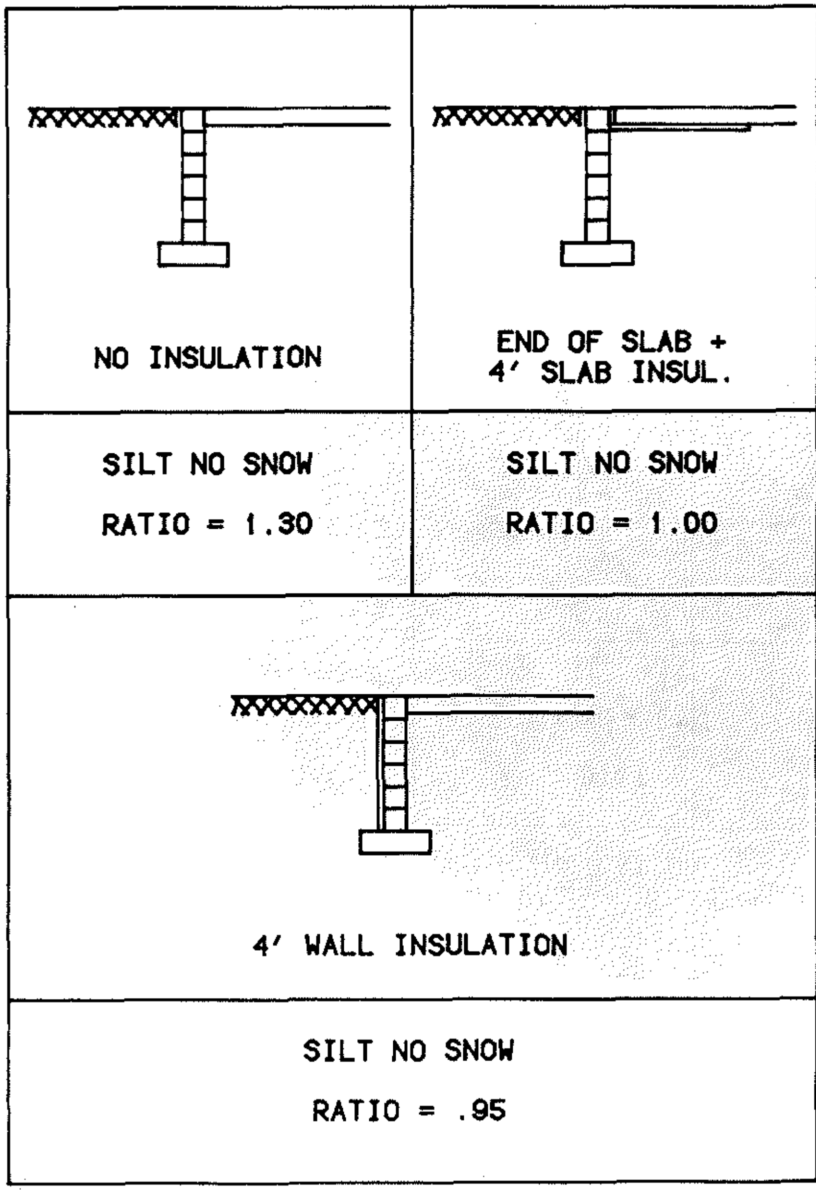

Figure 15. Slab with grade beam. Fairbanks; ratio = heat loss/uninsulated heat loss in silt

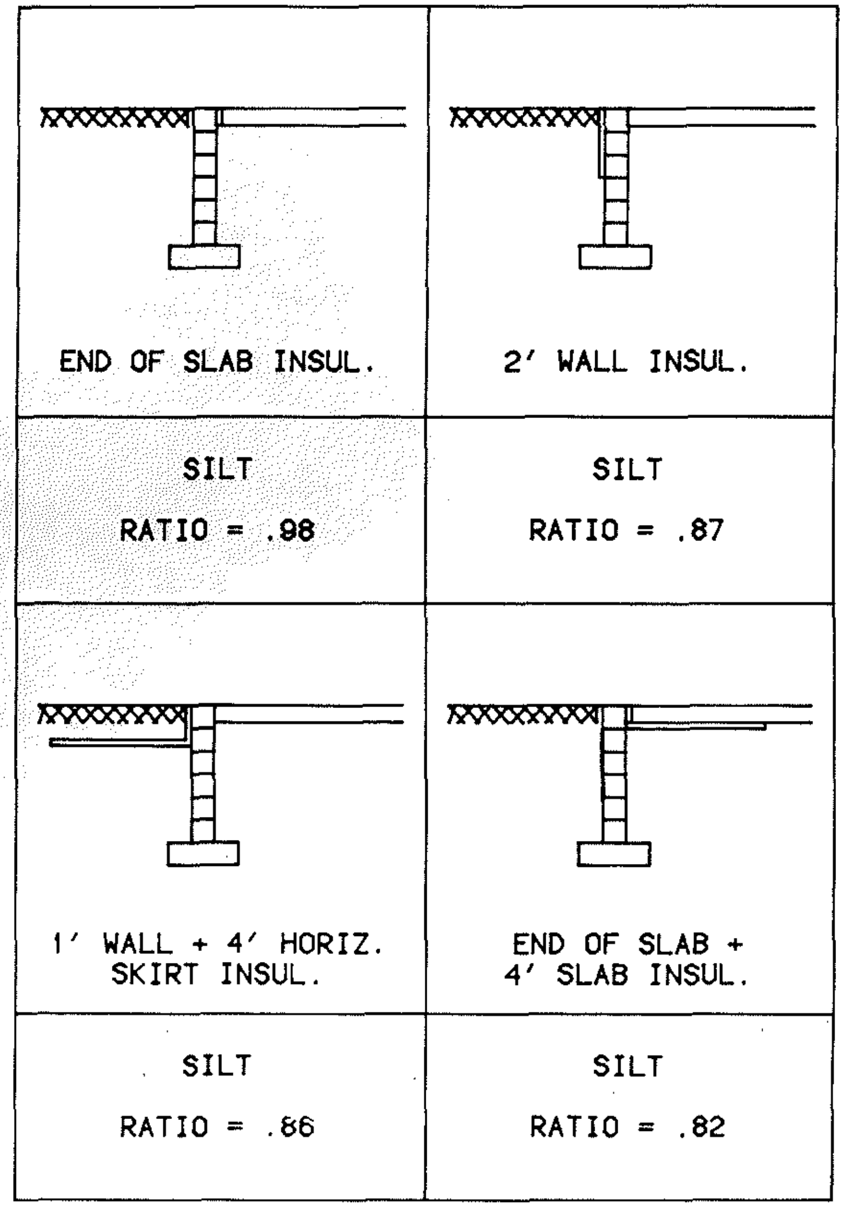

Figure 16. Slab with grade beam. Fairbanks; ratio = heat loss/uninsulated heat loss in silt

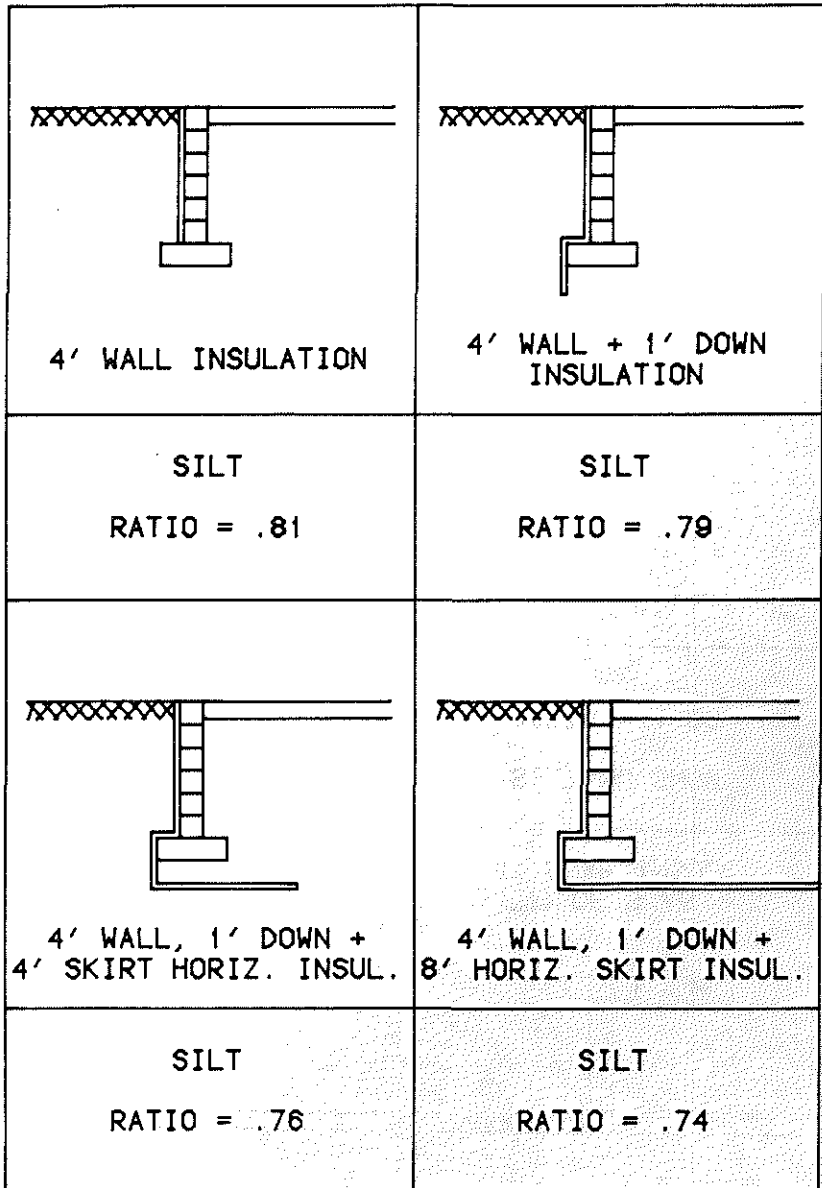

Figure 17. Slab with grade beam, Fairbanks; ratio = heat loss/uninsulated heat loss in silt

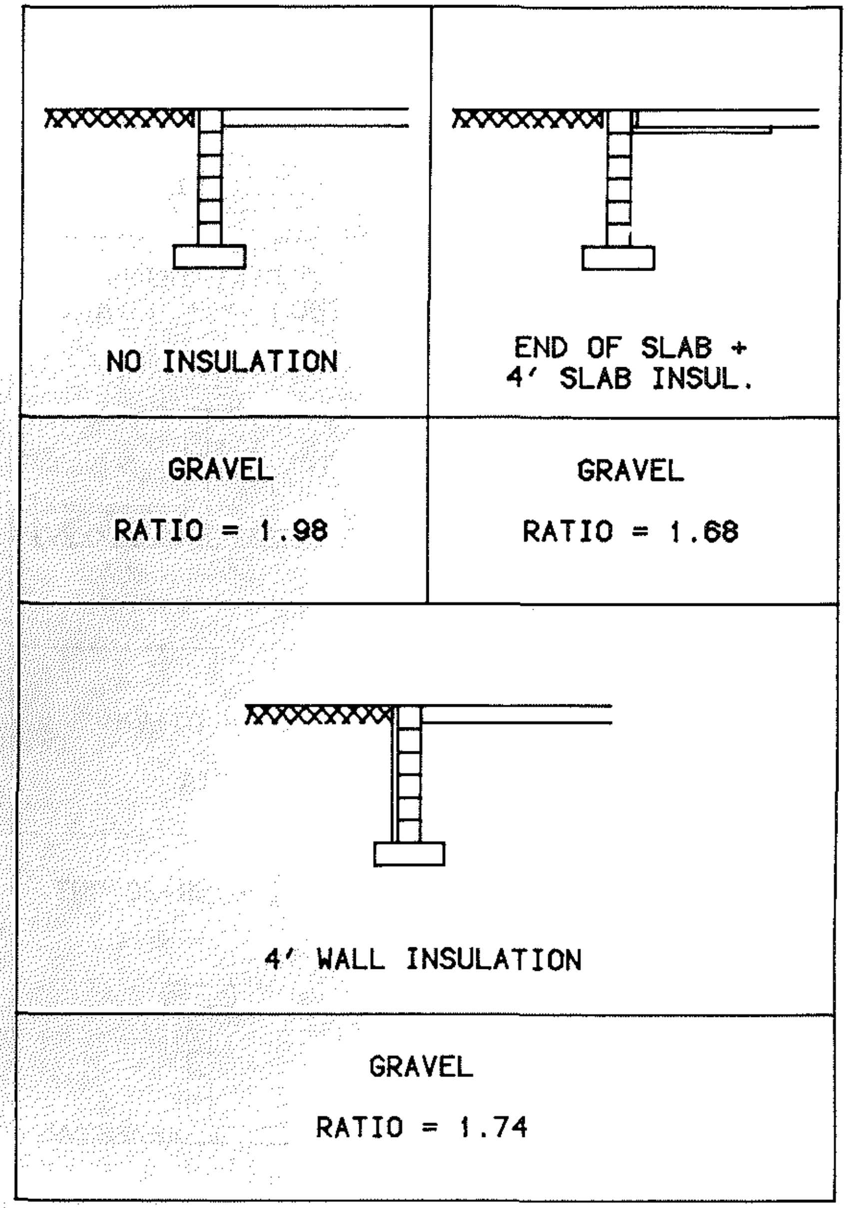

Figure 18. Slab with grade beam, Fairbanks; ratio = heat loss/uninsulated heat loss in silt

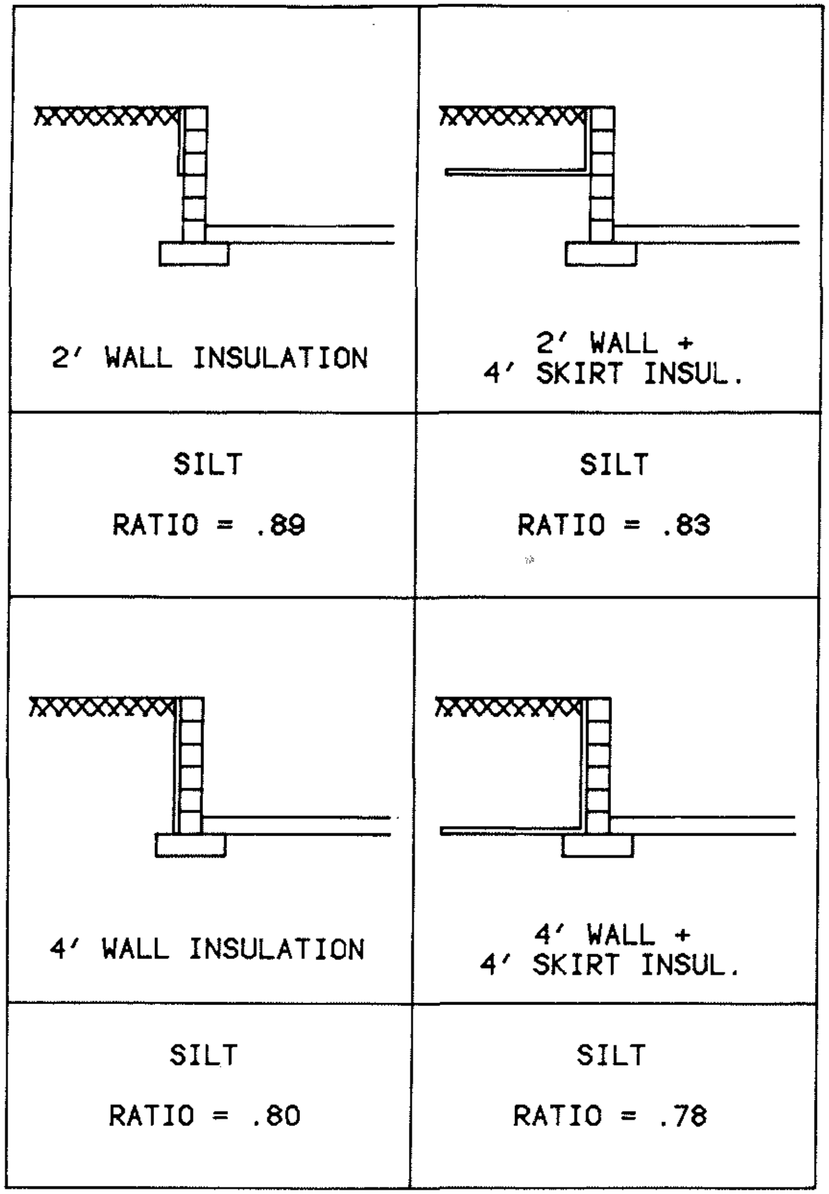

Figure 19. Daylight basement. Fairbanks; ratio = heat loss/uninsulated heat loss in silt

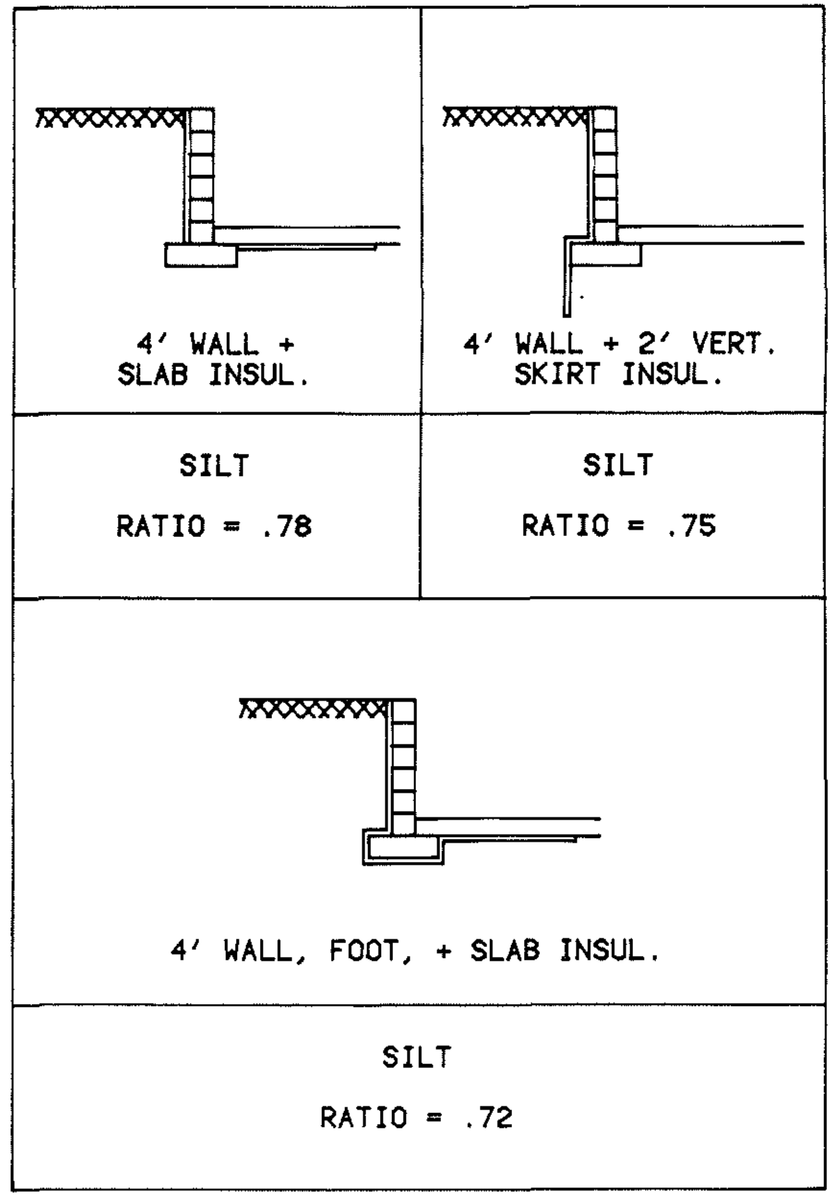

Figure 20. Daylight basement. Fairbanks; ratio = heat loss/uninsulated heat loss in silt

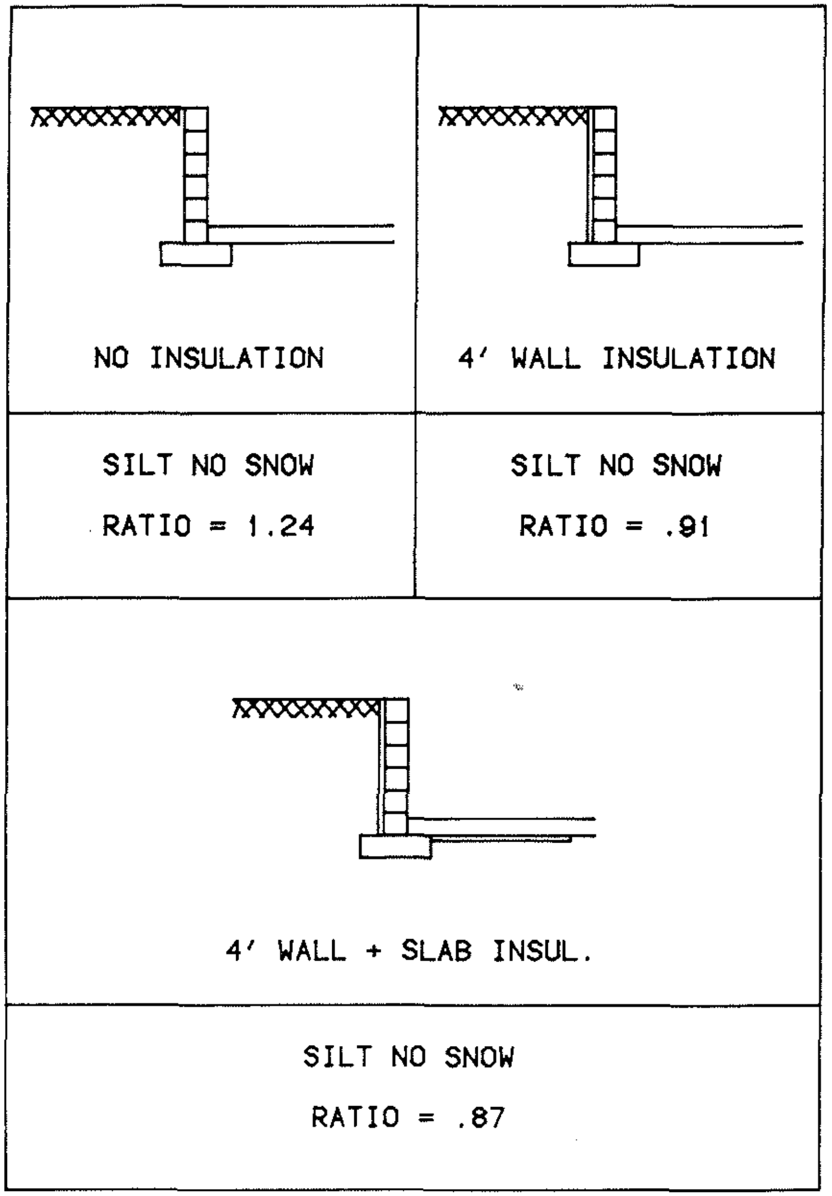

Figure 21. Daylight basement, Fairbanks; ratio = heat loss/uninsulated heat loss in silt

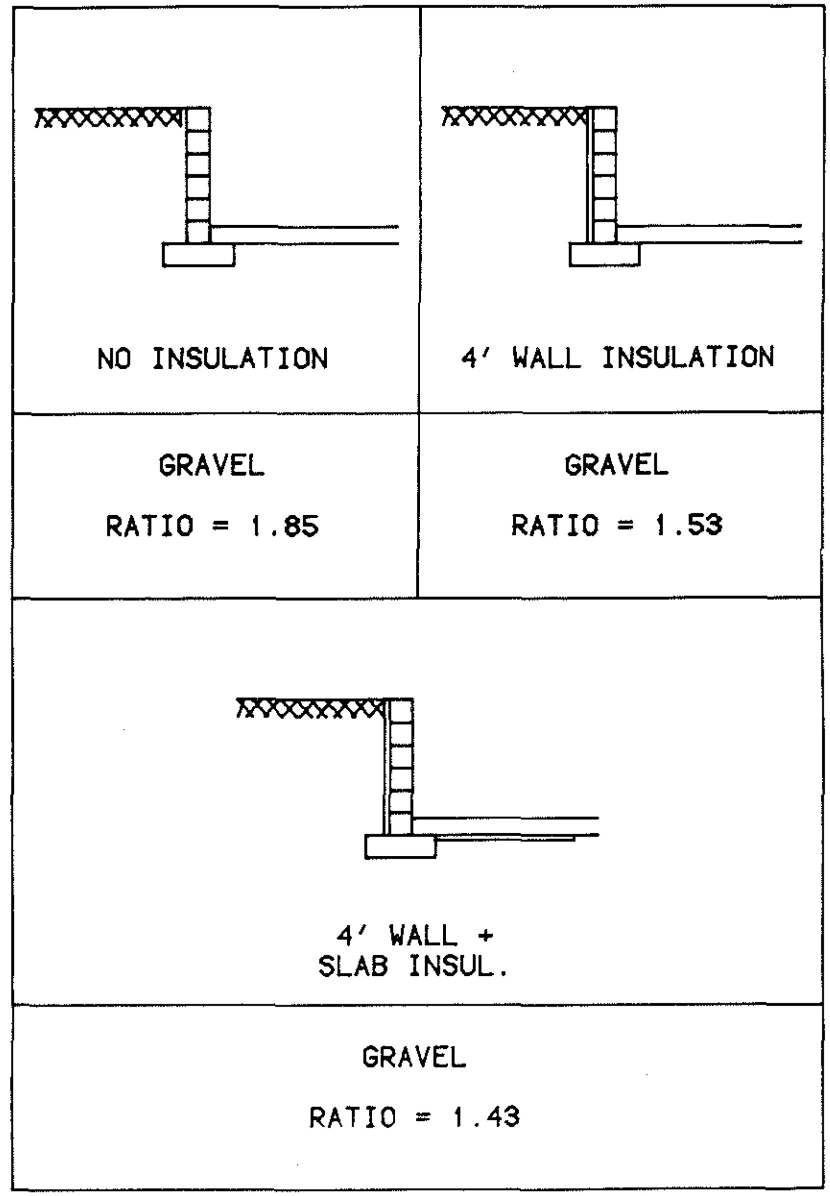

Figure 22. Daylight basement, Fairbanks; ratio = heat loss/uninsulated heat loss in silt

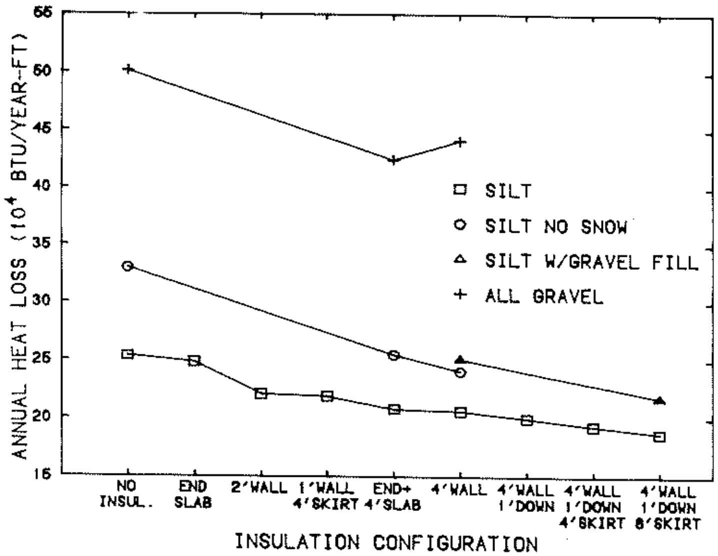

Figure 23. Slab-with-grade-beam annual heat loss for various insulation configurations

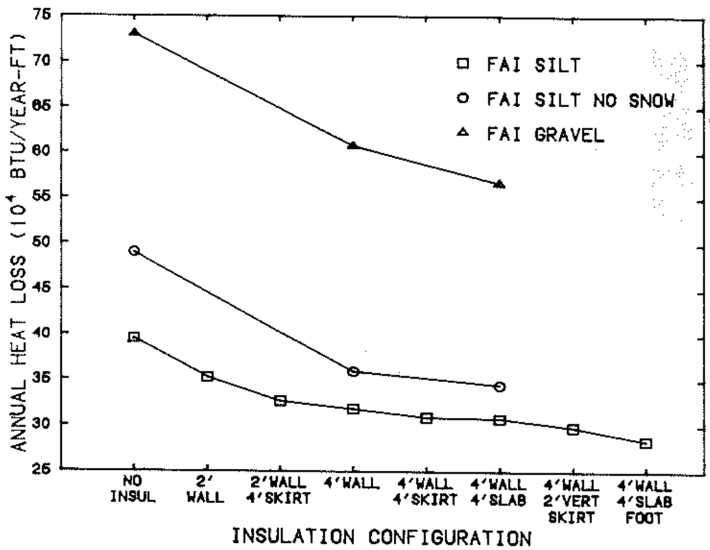

Figure 24. Daylight basement annual heat loss for various insulation configurations

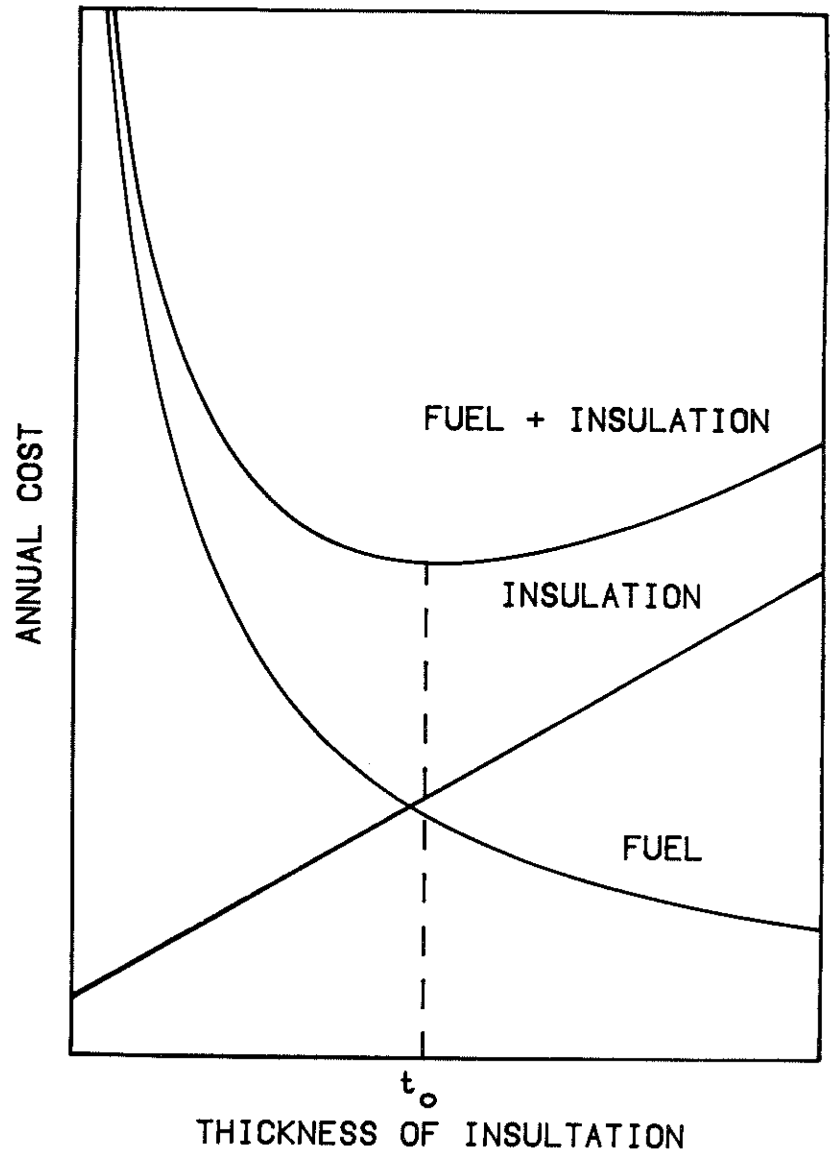

Figure 25. Typical curves of costs vs. insulation thickness