

BASESIMP: A RESIDENTIAL-FOUNDATION HEAT-LOSS ALGORITHM FOR INCORPORATING INTO WHOLE-BUILDING ENERGY-ANALYSIS PROGRAMS

Ian Beausoleil-Morrison
CANMET Energy Technology Centre
Natural Resources Canada
Ottawa, K1A 0E4, Canada
beausoleil-morrison@etb.mets.nrcan.gc.ca

Gintas Mitalas
Retired from the
Institute for Research in Construction
National Research Council of Canada
Ottawa, K1A 0R6, Canada

ABSTRACT

Heat losses from foundations are poorly considered in many whole-building energy programs which are used to model houses. This despite the fact that foundations contribute significantly to residential heating requirements.

A regression-based algorithm known as BASESIMP has been developed to improve the state of foundation heat-loss modelling in whole-building energy programs. The algorithm, developed from 33 000 parametric finite-element-based simulations, covers a broad range of foundation configurations, has minimal processing requirements, and is extensible.

The algorithm, which has been extensively tested and validated against the Mitalas method, has been incorporated into the HOT2000 program and is available for use in other applications.

INTRODUCTION

Heat losses from foundations contribute significantly to residential heating requirements. For example, in a sampling of 33 energy-efficient houses (ongoing study; see, for example Gusdorf and Hamlin 1995) it was found that 16GJ to 52GJ were lost annually through foundations. This represents (on average) 24% of the total heating load for these houses. Foundation losses can be even higher with conventional (non energy-efficient) construction. As such, there is a definite need for accurate foundation heat-loss algorithms that can be implemented into whole-building energy-analysis programs.

In the IEA BESTEST final report, Judkoff and Neymark (1995) correctly observed that foundation heat losses were poorly handled in many whole-building programs: "The state-of-the-art in ground modelling is not very good even in detailed building energy simulation programs". This fact seems surprising given the number foundation heat-loss models that have been developed over the past three decades: the Boileau and Latta method (Boileau and Latta 1968), also known as the ASHRAE method

(ASHRAE 1993); the Labs method (Labs 1979); the Decremental Average Ground Temperature method (Akridge and Poulos 1983); the Hagentoft method (Hagentoft 1988); the ESHD model (Meixel and Bligh 1983); the Shipp model (1983); the Bahnfleth and Pedersen method (1990); the Mitalas method (Mitalas 1982, Mitalas 1987); the Interzone Temperature Profile Estimation (ITPE) technique (see, for example Krarti et al 1988); etc.

It seems the developers of whole-building programs have a myriad of foundation heat-loss models from which to choose, yet most whole-building programs are lacking in this regard. Reasons will vary from case to case but the following factors must surely figure prominently: some models have great computational requirements; some are difficult to implement; some are restricted to few and simple configurations; and some are of questionable accuracy.

Significant advances have been made recently in the field of foundation heat-loss modelling within whole-building programs: Krarti (1996) calculated z-transfer functions for crawlspaces and integrated these into DOE-2 to perform whole-building simulations and Nakhi (1995) developed a three-dimensional ground-contact model and integrated this into the ESP-r whole-building simulation system.

However, most programs still have a need for a foundation heat-loss algorithm that is computationally fast, accurate, can model the relevant configurations, is extensible, and (perhaps most importantly) can be easily implemented. The BASESIMP (*simplified basement model*) algorithm described in this paper has been developed to meet these requirements.

BASESIMP is a regression-based algorithm which expresses both above-grade and below-grade time-dependent heat losses. 33 000 parametric runs were performed with BASECALC (Beausoleil-Morrison et al 1995a and Beausoleil-Morrison 1996a)—a finite-element-based program for analyzing foundation heat losses—to generate the data base for the BASESIMP regressions. BASECALC is a computationally

intensive program, performing a series of two-dimensional finite-element analyses for each foundation. These 33 000 parametric runs required about 1.5 CPU-years to process. BASESIMP represents the results of these 33 000 BASECALC runs with a handful of simple algebraic equations. This means BASESIMP has minimal (negligible) processing requirements which makes its use viable in whole-building programs with short-run-time requirements. The cost of this drastic processing savings is a slight loss in accuracy and restrictions on the configurations that can be modelled. However, as this paper documents, BASESIMP can accurately model most relevant configurations and can be easily extended to new configurations.

This paper describes the structure, derivation, and validity of the BASESIMP algorithm and discusses how it has been implemented into HOT2000 (Natural Resources Canada 1995), a bin-based whole-building program.

ALGORITHM STRUCTURE

The current version of BASESIMP has the capability to model 27 basement¹ and 40 slab-on-grade² systems. The location of the insulation, the structural material (concrete or wood), and thermal connection to main-floor walls define the BASESIMP system.

An example of a basement system is shown in Figure 1: it has concrete walls and floor and the interior surfaces of the walls are insulated over their full-height.

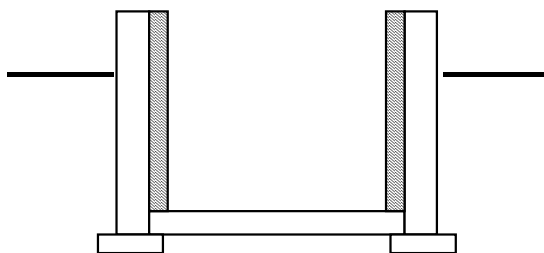


Figure 1 sample basement system

An example of a slab-on-grade system is shown in Figure 2: it has a concrete slab, insulation is placed below the perimeter and around the edge of the slab,

and the brick veneer of the main floor walls rests on top of the slab.

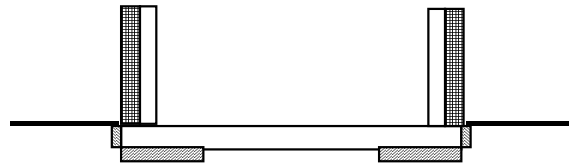


Figure 2 sample slab-on-grade system

For a given system, the BASESIMP algorithm calculates the heat loss as a function of the foundation's thermal and geometrical properties (insulation resistance, height, depth, width, length) and site conditions (soil conductivity, water-table depth, and weather).

BASESIMP uses a single set of correlation equations for all systems while each system has a unique set of correlation coefficients. This makes BASESIMP both easy to implement (one set of equations minimizes coding and debugging) and extensible. In the future, new systems can be analyzed and their correlation coefficients added to a database of coefficients without necessitating coding changes to the algorithm.

As such, BASESIMP can be considered a replacement for the commonly applied Mitalas method (Mitalas 1982 and 1987). There are a number of important differences between BASESIMP and the Mitalas method (Mitalas 1982 and 1987), which forms the basis of the current HOT2000 below-grade heat-loss model and which has been implemented in a number of whole-building programs:

- BASESIMP encompasses a much larger number of foundation systems.
- BASESIMP treats the foundation as a whole rather than breaking it into four segments.
- BASESIMP treats above-grade heat losses, including the effects of thermal bridging from below-grade components to above-grade components.
- BASESIMP accounts for thermal bridging to the main-storey walls (eg. thermal bridging between concrete basement wall and brickwork placed on top of wall).
- No interpolation is required in BASESIMP for the depth of the floor slab and the soil conductivity: these are variables in the correlations.

¹ A *basement* is defined as a foundation whose floor slab is located 0.65m to 2.4m below-grade.

² A *slab-on-grade* is defined as a foundation whose floor slab is located within 0.1m of grade.

- In BASESIMP, the water-table depth is a variable.
- BASESIMP allows the importation of BASECALC output for the modelling of “custom” foundations.

DERIVATION

Mitalas (1982) performed a Fourier-series analysis on ground-surface temperatures and found that the variation could be adequately represented using only the first harmonic of the annual cycle. Invoking the principle of superpositioning, Mitalas expressed the instantaneous below-grade heat loss (ie. heat loss from foundation to soil) in sinusoidal form with an annual angle:

$$Q_{bg}(t) = A + B \cdot \sin(\omega t) \quad (1)$$

A represents the mean-annual value of $Q_{bg}(t)$, B is the amplitude of the annual harmonic of $Q_{bg}(t)$, t is time, and ω is the angular velocity (2π rads/year).

In BASECALC equation 1 is extended to include above-grade heat loss (ie. heat loss from foundation to ambient air). Each of the three components of heat loss is related to its thermal boundary conditions and a three-dimensional shape factor. In this form, the shape factors are independent of the absolute values of the thermal boundary conditions (ie. temperatures):

$$\begin{aligned} Q_{basement}(t) = & Q_{above - grade}(t) \\ & + Q_{below - grade, average} \\ & + Q_{below - grade, harmonic}(t) \end{aligned} \quad (2)$$

where

$$Q_{above - grade}(t) = S_{ag}(T_{basement} - T_a) \quad (3)$$

$$Q_{below - grade, average} = S_{bg, avg} \cdot (T_{basement} - T_{g, avg}) \quad (4)$$

$$\begin{aligned} Q_{below - grade, harmonic}(t) = & S_{bg, var} \cdot T_{g, amp} \\ & \cdot \sin(\omega t + PHASE - \pi / 2 - P_s) \end{aligned} \quad (5)$$

S_{ag} is the three-dimensional shape factor for the above-grade component {W/K}; $S_{bg, avg}$ is three-dimensional shape factor for the mean below-grade component {W/K}; $S_{bg, var}$ is the three-dimensional shape factor for the harmonic below-grade component {W/K}; PHASE is the thermal-response factor {radians}; $T_{basement}$ is the temperature of the space contained by the foundation {K}, which is time-

invariant; $T_{g, avg}$ is the annual-average ground-surface temperature {K}; $T_{g, amp}$ is the amplitude of the annual harmonic of the ground-surface temperature {K}; T_a is the exterior dry-bulb temperature {K}, which varies with time; and P_s is the phase lag of the ground-surface temperature cosine wave, equal to the length of time between January 1 and the time of the coldest ground-surface temperature {radians}.

Beausoleil-Morrison et al (1995b) introduced the *corner-correction method* to determine the three-dimensional shape factors using two-dimensional calculations:

$$S_{ag} = SUMUO \cdot 2(length + width) \quad (6)$$

$$S_{bg, avg} = SUMUR \cdot \{2(length - width) + 4 \cdot width \cdot F_{cs}\} \quad (7)$$

$$S_{bg, var} = ATTEN \cdot \{2(length - width) + 4 \cdot width \cdot F_{cv}\} \quad (8)$$

F_{cs} and F_{cv} are the scalar corner-correction factors, a function of foundation and site thermophysical properties. For a given set of foundation and ground thermophysical properties, BASECALC performs three two-dimensional finite-element calculations using unit-temperature-excitation boundary conditions to calculate SUMUO, SUMUR, ATTEN, and PHASE.

With this approach, once a given configuration has been analyzed with BASECALC the resulting shape factors can be combined with any boundary conditions (ie. ground temperature, outdoor temperatures, indoor temperature) to determine the heat loss at any point in time.

BASESIMP performs the identical calculations to determine the three-dimensional shape factors, the three components of the heat loss, and the total foundation heat loss, namely equations 2 through 8. However, unlike BASECALC it does not determine SUMUO, SUMUR, ATTEN, and PHASE through finite-element calculations. Rather, BASESIMP applies simple algebraic correlation equations which have been determined through a regression analysis of BASECALC data.

1 080 BASECALC parametric simulations were performed for the first basement system, a concrete basement with interior full-height insulation (Figure 1). The geometry (depth, width, and height), insulation level, and ground properties (soil conductivity and water-table depth) were varied

systematically to span the expected range of inputs. The density and specific heat of the soil were held constant at 1490 kg/m³ and 1.8 kJ/kgK, respectively. Varying these properties along with soil conductivity would have drastically increased the number of BASECALC simulations and thus CPU requirements, with modest improvement in accuracy: the density and specific heat only influence the harmonic below-grade component of the heat loss.

Algebraic equations of various functional forms were assessed for their ability to relate each dependent variable (SUMUO, SUMUR, ATTEN, PHASE) to the independent variables (depth, width, height, insulation level, soil conductivity, water-table depth). The equations were developed from the basis of physical meaning. As SUMUO expresses the above-grade component of the heat loss, for example, it should be proportional to the area exposed to the outdoor air (height-depth), inversely proportional to the insulation's resistance, and, perhaps less intuitive, inversely proportional to soil conductivity. The following four formulations for SUMUO were assessed:

$$SUMUO = \left\{ a_1 + \frac{b_1(\text{height} - \text{depth})}{rsi^{c_1}} \right\} \quad (9)$$

$$SUMUO = \left\{ \frac{a_1 + b_1(\text{height} - \text{depth})}{(\text{soilk})(rsi)^{c_1}} \right\} \quad (10)$$

$$SUMUO = \left\{ \frac{a_1 + b_1(\text{height} - \text{depth}) + \frac{c_1}{\text{soilk}}}{rsi^{d_1}} \right\} \quad (11)$$

$$SUMUO = \left\{ \frac{a_1(\text{depth}) + b_1(\text{height}) + \frac{c_1}{\text{soilk}}}{rsi^{d_1}} \right\} \quad (12)$$

Each equation was assessed for its ability to fit the set of 1 080 data points. Six criteria were used to assess the fits: the mean of the absolute errors, the

maximum of the absolute errors, the root-mean square of the absolute errors, the mean of the relative errors, the maximum of the relative errors, the root-mean square of the relative errors. Based on these criteria, equation (11) proved to be the superior formulation.

This process was repeated for SUMUR, ATTEN, and PHASE, producing the following formulations:

$$SUMUR = \left[\frac{\{q_2 + r_2(\text{width})\} \cdot \{u_2 + v_2(\text{soilk})\} \cdot \{w_2 + x_2(\text{depth})\}}{(\text{wtable})^{s_2+t_2(\text{width})+y_2(\text{depth})}} \right] + \left[\frac{a_2(\text{depth})^{b_2}(\text{soilk})^{c_2}}{(\text{wtable})^{d_2}(rsi)^{e_2+f_2(\text{soilk})+g_2(\text{depth})}} \right] \quad (13)$$

$$ATTEN = \{a_3 + b_3(\text{soilk}) + c_3(\text{depth})\} + \left\{ \frac{e_3 + f_3(\text{soilk}) + g_3(\text{depth})}{(rsi)^{h_3}} \right\} \quad (14)$$

$$PHASE = a_4 + \frac{b_4}{(rsi)^{c_4}} \quad (15)$$

This completed the correlation development for the first BASESIMP system. Similar BASECALC parametric simulations were performed for the remaining 26 basement systems and 40 slab-on-grade systems. To simplify code development, testing, and maintenance and to ensure extensibility, it was desired to maintain the same functional forms for the remaining 66 systems. To this end, a regression analysis of the other 66 sets of data were performed using equations (11), (13), (14) and (15). It was found that with some minor modifications these equations could accurately represent all data sets. Modifications were necessary to account for phenomena not present in the first case, namely: a term to account for thermal bridging which results when the foundation walls are insulated on the exterior (see Figure 3); and a term to account for thermal bridging that occurs when interior and exterior walls are both partially insulated (see Figure 4). The final form of the correlation equations are given below:

$$\begin{aligned}
SUMUO = & \left\{ \frac{a_1 + b_1(\text{height} - \text{depth}) + \frac{c_1}{\text{soilk}}}{rsi^{d_1}} \right\} \\
& \bullet \left\{ \frac{1}{e_1 + (i_1)(\text{overlap})^{f_1} (rsi)^{g_1} (\text{height} - \text{depth})^{h_1}} \right\} \\
& + \{j_1\}
\end{aligned}
\tag{16}$$

$$\begin{aligned}
SUMUR = & \left[\frac{\{q_2 + r_2(\text{width})\} \cdot \{u_2 + v_2(\text{soilk})\} \cdot \{w_2 + x_2(\text{depth})\}}{(wtable)^{s_2 + t_2(\text{width}) + y_2(\text{depth})}} \right] \\
& + \left[\frac{a_2(\text{depth})^{b_2} (\text{soilk})^{c_2}}{(wtable)^{d_2} (rsi)^{e_2 + f_2(\text{soilk}) + g_2(\text{depth}) + h_2(\text{overlap})}} \right]
\end{aligned}
\tag{17}$$

$$\begin{aligned}
ATTEN = & \{a_3 + b_3(\text{soilk}) + c_3(\text{depth})\} \\
& + \left\{ \frac{e_3 + f_3(\text{soilk}) + g_3(\text{depth})}{(rsi)^{h_3 + i_3 \cdot \text{overlap}}} \right\}
\end{aligned}
\tag{18}$$

$$PHASE = a_4 + \frac{b_4}{(rsi)^{c_4}}
\tag{19}$$

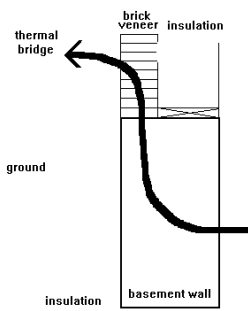


Figure 3 Thermal bridge due to exterior insulation

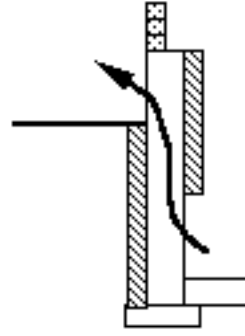


Figure 4 Thermal bridge due to combination insulation

Therefore, BASESIMP uses a single set of correlation equations—equations (16) through (19)—for all 67 systems while each system has a unique set of correlation coefficients (the coefficients are given in Beausoleil-Morrison 1996b). This makes BASESIMP both easy to implement (one set of equations minimizes coding, testing, and debugging) and extensible. In the future, new systems can be analyzed and their correlation coefficients added to a database of coefficients without necessitating coding changes to the algorithm.

VALIDITY

Any regression-based algorithm inherently sacrifices some accuracy: no correlation equation can perfectly represent a data set. Although each correlation was assessed for its ability to fit each set of data using the six criteria outlined in the previous section, the possibility exists that the errors could propagate when SUMUO, SUMUR, ATTEN, and PHASE are combined in equations (2) through (8) to predict the heat losses.

To assess whether the algorithm propagates errors and to assess the ability to represent data not used to generate the regressions, a test data set was assembled. 228 BASECALC files were created using randomly generated values for the independent variables. The BASECALC-derived SUMUO, SUMUR, ATTEN, and PHASE were used to predict the heating-season (October 1 through April 30) heating load for Edmonton (Canada) using equations (2) through (8). Equations (16) through (19) and equations (2) through (8) were then used to determine the BASESIMP-predicted heating load. Figure 5 compares the BASESIMP predictions against the BASECALC (reference) for the 228 test points.

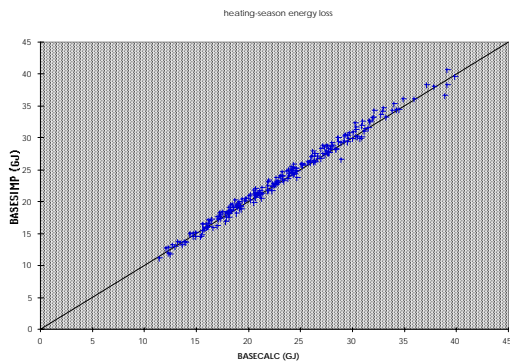


Figure 5 BASESIMP versus BASECALC

BASESIMP's average error for the 228 points in predicting the heating-season heat load was 0.55GJ. Its greatest error for a single point was 3.4GJ. This demonstrates BASESIMP's ability to accurately predict the absolute value of heat loss.

However, in many applications the algorithm will be used not to predict absolute heat loss, but rather to predict the relative performance of one foundation to another. This would be done, for example, to assess the energy impact of changing an insulation level or placement.

To assess the algorithm's ability to predict the reduction in heating load due to increasing insulation resistance, each *system* was assessed with two levels of insulation: RSI 1.5 and RSI 3.5. In all cases BASESIMP predicted the energy savings over the heating season in Ottawa (Canada) to within 0.8GJ of BASECALC. Most cases were predicted to within 0.5GJ.

To assess the algorithm's ability to predict the impact of changing an insulation placement, each *system* was compared to another (similar) *system*. In all cases BASESIMP predicted the heating-load impact of the insulation-placement change over the heating season in Ottawa (Canada) to within 1.1GJ of BASECALC. Most cases were predicted to within 0.5GJ.

Judkoff and Neymark (1995) stated the following concerning validation: "Each comparison between measured and calculated performance represents a small region in an immense N-dimensional space. We are constrained to exploring relatively few regions within this space...". Due to the large number of variables and the high cost of empirical validation, it would be impossible to fully validate any foundation heat-loss method. Notwithstanding, some validation against accepted standards is necessary for any new method.

To this end, a number of inter-program comparisons were made between BASESIMP and the Mitalas method (Mitalas 1982 and 1987). The Mitalas method was chosen because it is one of the most tested and validated foundation heat-loss models. Mitalas monitored 14 foundations across Canada to develop and validate his method. The Mitalas method has been analyzed and tested by others as well. For example, Krarti et al (1990) found good agreement between the ITPE method, the Walton method, and the Mitalas method. Krarti (1993) found that the ITPE method compared well to the Mitalas method for predicting yearly average basement heat loss. Sobotka et al (1994) compared monitored data from a test house in Japan to four heat-loss methods, including the Mitalas method. They found that the Mitalas method gave the best agreement with the measured data. Sobotka et al state that "The most often cited method for calculation of residential basement heat loss is probably that of Mitalas".

A basement corresponding to the Mitalas system 3 was selected and the time varying heat losses predicted by both methods. Agreement between the two methods was close, as can be seen in Figure 6.

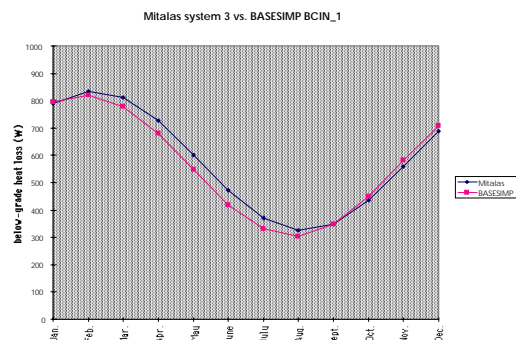


Figure 6 BASESIMP vs. Mitalas (basement)

A number of the independent variables, such as temperature boundary conditions, soil conductivity, dimensions, and the resistance of the insulation were altered one-by-one. Both methods responded similarly to each perturbation, although BASESIMP showed greater sensitivity. A similar comparison was made for a slab-on-grade foundation (see Figure 7).

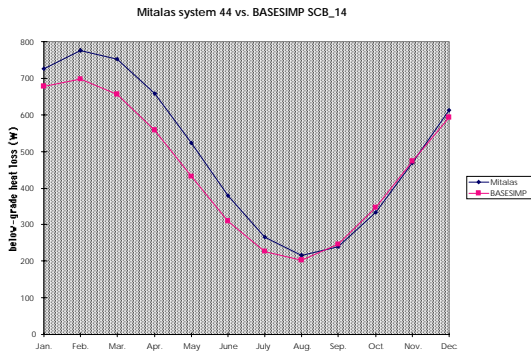


Figure 7 BASESIMP vs. Mitalas (slab-on-grade)

IMPLEMENTATION

For maximum portability, a stand-alone version of the BASESIMP algorithm, including the corner-correction method, has been coded in FORTRAN77. All correlation coefficients reside in ASCII files, which allows the algorithm to be easily extended to new systems without coding changes. The stand-alone program can be easily customized for individual applications. For example, it has been incorporated as a subroutine into HOT2000.

Based on user input, the HOT2000 interface selects the most appropriate of the 67 BASESIMP systems. Before initiating the simulation, HOT2000 calls the BASESIMP routine, passing the independent variables, which returns the values of S_{ag} , $S_{bg,avg}$, $S_{bg,var}$, and PHASE. HOT2000 then applies equations (2) through (5) each time it needs to evaluate the foundation heat loss.

HOT2000 also contains a facility to allow users to model "custom" foundations in their houses. This facility is used when none of the 67 systems closely matches the configuration at hand. The user performs a BASECALC simulation of the custom foundation then imports the BASECALC-derived values of S_{ag} , $S_{bg,avg}$, $S_{bg,var}$, and PHASE into HOT2000. In this case the BASESIMP subroutine would not be called to apply equations (16) through (19).

BASESIMP could be implemented in a similar fashion into other whole-building programs. For simple applications, developers may choose to limit the number of systems to a subset of the current 67. Other developers may wish to derive correlations coefficients for new systems, as appropriate for their user base.

CONCLUSIONS

A regression-based algorithm has been developed for estimating residential-foundation heat losses. The algorithm, known as BASESIMP, can accurately

model most foundation configurations of interest. The algorithm is extensible: it has been structured to allow new foundation configurations to be easily incorporated. As its processing requirements are low, BASESIMP is ideally suited for use in whole-building programs, particularly those with short run times.

The accuracy of the algorithm to predict heat losses, and perhaps more importantly, the energy impact of insulation placement and resistance changes, has been demonstrated. In addition, the algorithm has been compared against the well-tested Mitalas method.

ACKNOWLEDGMENTS

We would like to thank Harry Chin, Simon Sansregret, Carlo Mortello, Alain Belzile, and Marc Ouellette for their assistance in developing and testing the BASESIMP correlations.

REFERENCES

- Ackridge J.M. and Poulos J.F., "The decremented average ground temperature method for predicting the thermal performance of underground walls, *ASHRAE Transactions* (1983) 89 (2A).
- ASHRAE, Fundamentals Handbook (SI)*, (1993) 25.10-25.15.
- Bahnfleth W.P. and Pedersen C.O., "A Three-Dimensional Numerical Study of Slab-on-Grade Heat Transfer", *ASHRAE Transactions*, (1990) 96(2) 61-72.
- Beausoleil-Morrison I., "BASECALC™: A Software Tool for Modelling Residential-Foundation Heat Losses", *Proc. Third Canadian Conference on Computing in Civil and Building Engineering*, Montréal Canada (1996a) 117-126.
- Beausoleil-Morrison I., *BASESIMP: A Simplified Foundation Energy-Loss Model Derived from BASECALC Simulations*, Natural Resources Canada internal report (1996b).
- Beausoleil-Morrison I., Mitalas G.P., McLarnon C., "BASECALC: New Software for Modelling Basement and Slab-on-Grade Heat Losses", *Proc. Building Simulation '95*, International Building Performance Simulation Association, Madison USA, (1995a) 698-700.
- Beausoleil-Morrison I., Mitalas G.P., Chin H., "Estimating Three-Dimensional Below-Grade Heat Losses from Houses Using Two-Dimensional Calculations", *Proc. Thermal Performance of the Exterior Envelopes of Buildings VI*, ASHRAE, Clearwater Beach USA, p.95-99 (1995b).

Boileau G.G. and Latta J.K., "Calculation of Basement Heat Losses", Technical Paper No. 292 of

Div. Bldg. Res., National Research Council of Canada, December (1968).

Gusdorf J. and Hamlin T., *Indoor Air Quality and Ventilation Rates in R-2000 Houses*, Natural Resources Canada final report, (1995).

Hagentoft C.E., *Heat Loss to the Ground From a Building: Slab on the Ground and Cellar*, PhD thesis, Lund University, Sweden (1988).

HOT2000: A Comprehensive Tool for the Design of Energy Efficient Homes and Buildings, Version 7.10, Natural Resources Canada, (1995).

Judkoff R. and Neymark J., *International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Tool*, National Renewable Energy Laboratory, Colorado, USA, (1995).

Krarti M., Claridge D.E., Kreider J.F., "ITPE Technique Applications to Time Varying Two-Dimensional Ground-Coupling Problems", *Int. J. Heat Mass Transfer*, (1988) 31(9) 1899-1911.

Krarti, M., D.E. Claridge, and J.F. Kreider, "ITPE Technique Applications to Time Varying Three-Dimensional Ground-Coupling Problems", *Journal of Heat Transfer*, (1990) (112) 849-856.

Krarti, M., "Steady-state heat transfer from partially insulated basements", *Energy and Buildings*, (1993) (20) 1-9.

Krarti M. and Choi S., "Effect of Hourly Indoor Temperature Variation on Energy Performance of Building Foundations", *to be published in Energy and Buildings*, (1996).

Labs K., "Underground Building Climate", *Solar Age*, (1979) 4(10) 44-50.

Meixel G.D. and Bligh T.P., *Earth Contact Systems—Final Report*, prepared for the USA DOE, Underground Space Center, University of Minnesota and Massachusetts Institute of Technology, November (1983).

Mitalas G.P., "Basement Heat Loss Studies at DBR/NRC", DBR Paper No. 1045, Ottawa (1982).

Mitalas G.P., "Calculation of Below-Grade Residential Heat Loss: Low-Rise Residential Building", *ASHRAE Transactions*, (1987) NY 87-03-1.

Nakhi A.E., *Adaptive Construction Modelling within Whole-Building Dynamic Simulation*, PhD Thesis, University of Strathclyde, Glasgow, UK, (1995).

Shipp P.H., "Basement, Crawlspace, and Slab-on-Grade Thermal Performance", *Proc. of Thermal Performance of the Exterior Envelopes of Buildings II*, (1983) 160-179.

Sobotka, P., H. Yoshino, and S. Matsumoto, "Thermal performance of three deep basements: a comparison of measurements with ASHRAE Fundamentals and the Mitalas method, the European Standard and the two-dimensional FEM program", *Energy and Buildings*, (1994) (21) 23-24.

NOMENCLATURE

$Q_{\text{basement}}(t)$ = total heat loss from foundation (W)

$Q_{\text{above-grade}}(t)$ = heat loss from foundation to ambient air (W)

$Q_{\text{below-grade,average}}(t)$ = mean-annual heat loss from foundation to soil (W)

$Q_{\text{below-grade,harmonic}}(t)$ = annual harmonic of heat loss from foundation to soil (W)

S_{ag} = 3D shape factor for above-grade heat loss (W/K)

$S_{\text{bg,avg}}$ = 3D shape factor for mean-annual below-grade heat loss (W/K)

$S_{\text{bg,var}}$ = 3D shape factor for annual harmonic below-grade heat loss (W/K)

PHASE = thermal-response factor (radians)

T_{basement} = temperature of the space contained by the foundation (K)

$T_{\text{g,avg}}$ = annual-average ground-surface temperature (K)

$T_{\text{g,amp}}$ = amplitude of the annual harmonic of the ground-surface temperature (K)

T_{a} = exterior dry-bulb temperature (K)

P_{s} = phase lag of the ground-surface temperature cosine wave (radians)

t = time (weeks)

$\bar{\omega} = 2^1$ rad/year

length = length of foundation (m)

width = width of foundation (m)

height = height of foundation wall (m)

depth = depth of foundation wall (m)

soilk = thermal conductivity of soil (W/mK)

rsi = thermal resistance of insulation ($\text{m}^2\text{K/W}$)

wtable = depth of water table below grade (m)

a_1, q_2 , etc = correlation coefficients