A COMPARATIVE VALIDATION OF THE LONG TERM ENERGY CONSUMPTION PREDICTIONS OF FIVE RESIDENTIAL BUILDING ENERGY SIMULATION PROGRAMS IN A HEATING CLIMATE

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ABSTRACT - Four micro-computer and one mainframe computer scale building energy simulation programs have been evaluated in terms of experimental long-term and transient energy usage data for two energy-efficient houses in the context of a Minnesota cold-climate environment. The test houses which have both been extensively, monitored over at least one calendar year are representative of houses defining the design boundaries within which the Minnesota housing stock is built. The two-phase validation methodology employed which utilizes a constrained optimisation approach involving primarily the parametric variation of the envelope mass flux is described and demonstrated. The results produced illustrate the viability of the parametric validation methodology and portray the importance of earth-contact heat transfer modelling in heating climates. The applicability of the programs tested to various classes of housing is annunciated in terms of the validation results produced.

INTRODUCTION

In view of the increasing popularity of small-scale building energy simulation programs as design and analysis tools in the residential building sector, a need exists for providing impartial guidelines upon which the suitability of various programs may be assessed. Within the context of a Minnesota cold climate environment in which heating space-conditioning loads predominate, the program suitability applies not only to the palette of energy-efficient and inefficient house designs comprising the residential building stock, but also to the vagaries of micro-climatic conditions.

A series of focus group surveys conducted amongst the Minnesota building community (1) indicates that the three major criteria in analyzing the energy performance of houses are absolute accuracy, objectivity and credibility. Hence a research project was initiated in order to meet the need for generating evaluation guidelines for energy simulation programs within these determined criteria. The basic objective for this project was to evaluate the accuracy of a representative range of commercially available and widely used building energy simulation programs when applied to energy-efficient houses in Minnesota climatic conditions.

VALIDATION APPROACH

The primary quantitative evaluation criterion is the degree to which the results produced by the various simulation programs are validated by experimental data. This validation process may be carried out on two levels, namely, a comparison of long-term auxiliary heating and cooling energy consumption and, a comparison of transient performance parameters such as hourly temperature variations and the like.

A quantitative validation based on long-term energy use comparisons only can be extremely deceptive even if acceptable agreement between experimental and simulated data is obtained. The results of such a validation are difficult to interpret because all possible error sources operate simultaneously (2). This implies that even in the presence of good agreement between experimental and simulation results, the possibility of offsetting errors prevents the algorithmic accuracy from being determined objectively. This suggests a two phase validation process based on the postulate that agreement between long-term energy usage experimental and simulated data is a necessary although insufficient condition for quantitative simulation program validation. This implies that if the long-term energy usage predictions of a program cannot be validated with experimental data, then the detailed performance data will also not be validated. Thus the first phase of the validation process consists of evaluating the long-term energy usage data. The programs are then subjected to a second phase in which more detailed transient performance predictions are compared with their experimental counterparts.

RESIDENTIAL BUILDING SELECTION

In terms of the stated objective and the two phase validation process described, the requirements for selecting houses to be used as test cases may be stipulated as:

- the availability of detailed transient energy performance experimental data for a period of at least one calendar year.
- the availability of high quality, high frequency, long-term auxiliary heating and cooling energy use data for at least one and preferably more calendar years (this excludes the use of utility meter readings, particularly if they are estimated).
- the existence of detailed building plans and specifications as well as knowledge of the actual constructed building and the occupants' behavior patterns.

Disregarding these somewhat severe requirements, the selection of houses to be used for validating simulation programs is a contentious issue. It is clear that there is always at least one class of buildings for which any particular program may be validated, the building class which the program author used as the mold for the program algorithm. This is particularly relevant for small-scale building simulations and becomes increasingly less applicable as the size and sophistication of the programs increase. Hence, in order to effectively probe the capabilities of the simulation programs as objective predictors of the energy performance of the Minnesota housing stock as a whole, the use of houses which do not conform to the program bounds yields a wealth of information on the ngths and weaknesses of the programs which would not otherwise be apparent. Furthermore, by selecting houses which define the design boundaries within which the residential building stock is built, the program evaluation exercise yields an added confidence that if the programs may be validated on the design boundaries, then there is a much higher probability that they may also be validated over the entire design surface.

With this philosophical perspective, the house selection requirements may be fully met by two houses forming part of the Underground Space Center's energy efficient housing data base (3). These houses also match the description of defining segments of the Minnesota housing stock design boundary. The first of these houses is a single story, earth-sheltered unit which is covered and bermed on all sides except the south. The house has only 6 occupant controlled openings, one of which, the main entry, has an airlock vestibule. This, together with the earth-sheltering makes the house extremely tight with regard to infiltration. Furthermore, the house includes passive solar heating by means of the solar radiation incident on the southern living room windows being stored in an insulated portion of the floor slab. These windows are fitted with an automatically controlled shutter. There is also an active solar hot water heating system.

The Camden house, for purposes of argument, may be viewed as a large, insulated and heated basement with windows. It thus provides an excellent test of the capability of the programs to simulate buildings with significant earth-contact components. Since a large proportion of Minnesota housing stock incorporates heated basements, the capability of any program to accurately include the effects of earth contact is mandatory in terms of a Minnesota building design and analysis tool.

In contradistinction, the second house selected is an entirely above-grade, wood frame structure with minimal earth-contact. The east, north and west walls have a nominal R26 of insulation while the ceiling has R50 insulation. The inclusion of two small triple glazed windows in the north facade as well as the provision of an airlock entry qualify all but the southern facade of the house for the "superinsulated" label. The southern facade is entirely glazed thus allowing the incident solar radiation to be collected in a sunspace and actively transferred to a rockbed for storage. The rockbed is located under the wood joist floor to which it is radiatively coupled. Thus the Lynn Park house tests the active solar space heating modelling capabilities of the programs. It furthermore enables an assessment of how the delicate balance between solar gain and conduction and convection losses through the expanse of southern glazing is predicted. This balance is critical to the design of passive and active solar houses and is the cause of much contention amongst the Minnesota building community.

The overall accuracy of the combined transient and long-term experimental energy performance data has been assessed to be typically of the order of ±5% (3). This is enhanced by both houses using electricity only as the energy source for all requirements with no auxiliary space cooling being supplied.

SIMULATION PROGRAM SELECTION AND VALIDATION METHODOLOGY

The simulation programs selected for evaluation are listed in table 1. The selection process was based on a set of criteria geared towards assessing the expected accuracy of the programs for houses in Minnesota climatic conditions (4). These criteria include sophistication of the simulation algorithm; suitability for residential application; number of

TABLE 1. Simulation Program Selection

Program Name	Vendor	Cost	Hardware
3D Scribe	McGraw-Hill Book Co. GREGG Division - 29th Floor 1221 Avenue of the Americas New York, NY 10020	$2,550.00 (high res. graphics version)	Apple II Plus with 64 kBytes of RAM
EEDO^{TM} Version 1.0 (IBM^{TM} PC version of CIRA^{TM})	Burt Hill Kosar Rittleman Assoc. 400 Morgan Center Butler, PA 16001	$495.00	IBM^{TM} PC with 128 kBytes RAM and 2 DS/DD Disk Drives
HOTCAN Version 2.0	National Research Council of Canada Publications Section Division of Building Research Ottawa, Ontario - CANADA KIA OR6	$50.00	Apple II with 48 kBytes RAM
SERIRES Version 1.0	National Energy Software Center Argonne National Laboratory 9700 South Cas Avenue Argonne, IL 60439	$906.00	Control Data Corporation Cyber 170 (as delivered)
4 MN TMY Weather Files	NOAA Data Information Service National Climatic Center Federal Building Asheville, NC 28801	$135.00	1600 BPI 9 track Tape Drive
CALPAS3 Version 3.11	Berkeley Solar Group 3140 Martin Luther King Jr. Way Berkeley, CA 94703	$795.00	IBM^{TM} PC with 256 kBytes RAM 2 DS/DD Disk Drives

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zones simulated; number of nodes or components within each zone; and, current usage popularity. All the programs chosen with the exception of SERIRES may be described as small scale simulations which may be implemented on microcomputers. The SERIRES program is designed for mainframe use although it may be ported onto smaller machines. This small-scale bias reflects the stipulated criterion that the programs selected must be widely used.

The quantitative bounds used for establishing the long-term validation accuracy of the programs selected are based on the results of the SERI Class A validation study (2). In view of the quality of the available input data which conforms to the description of "known measured values plus unknown values taken from a handbook", validation accuracy limits of ±20% were selected to be consistent with the SERI Class A results. However, the test houses differ from the laboratory environment of the SERI test modules in that the houses were occupied by residents with unmodified lifestyles during the entire period for which they were monitored. This necessarily predicates that occupant lifestyle dependent effects which cannot be precisely monitored need to be accounted for parametrically. The principal parametric variable in this context is the net envelope mass flux (EMF) consisting of forced and natural ventilation as well as infiltration. Thus, the validation results are primarily expressed parametrically in terms of the EMF, which is also one of the critical parameters in building energy simulation. Furthermore, the EMF may only be analytically or experimentally determined with low accuracy (5), particularly in the presence of occupant lifestyle induced effects.

In addition to the primary parametric variation of the EMF, a constrained optimization technique is used to investigate the effect of varying other parameters regarded as being critical, examples being earth-contact thermal conductivity, internal air movement and shutter thermal resistance. The basis of the constrained optimization technique used is to incorporate in the validation sequence those parameter variations which yield the maximum reduction in validation error. Hence if a number of parameters are changed at a particular point in the sequence then the change producing the greatest error reduction is selected to advance the sequence to the next level.

RESULTS

The results presented concentrate on giving an overview of the long-term energy usage validation process while providing an insight to the transient validation process. This synopsis exemplifies the validation process while achieving the necessary condensation of the voluminous amount of data generated.

A pair of comparative long-term heating energy validation simulation run sequences for the HOTCAN and 3D SCRIBE programs are given in figures 1 and 2 for the Lynn Park and Camden houses respectively. These two programs are contrasted since they produce validation accuracies at the high (3D SCRIBE) and low (HOTCAN) ends of the spectrum. The simulation run number abcissae in figures 1 and 2 are indexed to the parametric changes described in tables 2 and 3 respectively.

Figure 1 and table 2 show that the major parametric variation necessary to coverage to the +20% error bound is a reduction of the envelope mass flux from the baseline case of 1.3 air changes per hour (ach) to .4 ach in run 3. As this effective EMF is physically a lower limit for the Lynn Park house, closer convergence to the upper accuracy bound was achieved through an increase of the shutter thermal resistance on the large expanse of south facing glazing from R2 to a fictitious value of R8 in runs 4 and 5. Thereafter, errors less than 20% could be achieved by either reducing the EMF further to .25 ach (run 6) or by effectively isolating the house from earth contact heat transfer in run 7. Either of these approaches is an unrealistic description of the Lynn Park house envelope.

The simulation run sequence for the 3D SCRIBE program (figure 1), by contrast, shows a marked lack of sensitivity to the EMF. The +20% error bound is achieved and superceded for a baseline EMF of 1.3 ach, radically different from the very strong dependence on the EMF shown by HOTCAN. The major parameter varied in order to reduce the validation error is the solar gain absorptance factor which when set at .85 results in the lowest validation error of 2.7% being achieved in run 6. Run 5 demonstrates the effect of reducing the number of zones used to model the house from 10 to 4. The validation accuracy is reduced by 5.8% while the program run time for an annual simulation period is decreased by 63% from 8.93 hours to 3.35 hours. Another factor varied was

TABLE 2. Lynn Park Validation Sequence using HOTCAN and 3D SCRIBE

Run No.	HOTCAN	3D SCRIBE
1	Baseline parameters	Baseline parameters
2	Basement floor insulation increased to R20.	Inclusion of unidirectional forced convection heat transfer between sunspace and rockbed
3	Run 1 with envelope mass flux reduced from 1.3 ach to .4 ach.	Run 1 with absorptance behind glazing increased from .5 to .7 and internal gain factor corrected to .3836 .
4	Run 3 with shutter insulation on south facing fenestration increased from R2 to R5.	Run 3 with absorptance increased to 1.
5	Run 4 with shutter insulation on south facing fenestration increased to R8. increased to R8.	Run 4 with 10 interior zones consolidated into 4 zones.
6	Run 5 with envelope mass flux reduced to .25 ach.	Run 5 with absorptance decreased to .85 .
7	Run 5 with basement floor insulation increased to R20.	

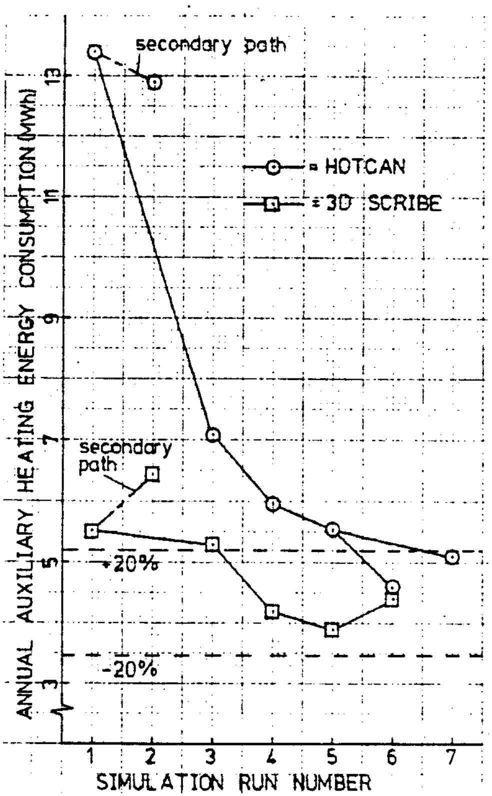

Figure 1. Lynn Park Simulation Run Sequence Using HOTCAN and 3D SCRIBE.

the method of describing the internal air movement. Run 2 demonstrates the effect of attempting to accurately reflect the mode of forced convective heat transfer between the space and the thermal storage rockbed. As this ge resulted in an increase in the validation error it was included on a secondary validation path in conformity with the rules of the constrained optimization validation methodology employed. The change in run 3 was necessary to account for an error discovered in the algorithm by which the 3D SCRIBE program converts an internal gain factor into an equivalent base energy consumption resultant from occupants, lights and appliances.

The simulation run sequences for the Camden house depicted in figure 2 and table 3 are similar to those for the Lynn Park house. The validation accuracy of the HOTCAN program approaches the +20% error bound for a reduction in the EMF from the baseline case of 3.154 ach to .5 ach in run 5. The minor reduction in error achieved in run 6 for an arbitrary increase in living room shutter thermal resistance from R5 to R8 resulted in this parametric change being rejected. A further reduction in EMF to a physically implausible level of .25 ach results in an accuracy of better than 20%. Run 8 demonstrates the effect of manipulating the HOTCAN input parameter set so as to describe the Camden house artificially as consisting solely of a basement. This manipulation results in a 23.6% change in the validation error from 11.3% to -12.3%. Doubling the EMF to .5 ach for this artificial configuration results in the upper error bound being exceeded by .9%, again demonstrating the predominant parametric effect of the EMF for the HOTCAN program.

As for the Lynn Park house, the 3D SCRIBE program reveals an almost complete indifference to the EMF. Over the 5 run simulation sequence, the validation error ranges from a high of 7.1 % (run 3) to a low of .9% (run 5). A reduction in the EMF of .5 ach between runs 1 and 5 produces an approximate 5% overall reduction in validation error compared with an 84% reduction in error for the same EMF reduction produced by the HOTCAN program. Decreasing the solar absorptance factor by .15 in run 3 results in a 5.4% increase in error compared with run 2. The computation time for an annual simulation period is reduced from 7.25 hours for 10 zones to 2.78 hours for 4 zones in run 5, a 62% decrease.

Viewing the HOTCAN/3D SCRIBE run sequences as a whole reveals the anomalous behavior of the 3D SCRIBE program The strong dependence of validation accuracy on the EMF shown by the HOTCAN program is duplicated by the CALPAS3, EEDO^{TM} and SERIRES programs thus substantiating the probability of an algorithmic error in the 3D SCRIBE program.

TABLE 3. Camden Validation Sequence using HOTCAN and 3D SCRIBE

Run No.	HOTCAN	3D SCRIBE
1	Baseline parameters	Baseline parameters
2	Envelope mass flux reduced from 3.154 ach to 1.952 ach	Envelope mass flux reduced from 1.5 ach to 1.2 ach
3	Envelope mass flux reduced to 1.351 ach.	Absorptance behind glazing decreased from 1 to .85 .
4	Envelope mass flux reduced to 1.101 ach.	Run 2 with 10 zones consolidated into 4 zones.
5	Envelope mass flux reduced to .5 ach.	Run 4 with envelope mass flux reduced to 1 ach.
6	Shutter insulation on south facing living room fenestration increased from R5 to R8.	
7	Run 5 with envelope mass flux reduced to .25 ach.	
8	Change of configuration such that entire space treated as basement as opposed to a main floor/basement split.	
9	Envelope mass flux increased to .5 ach.	

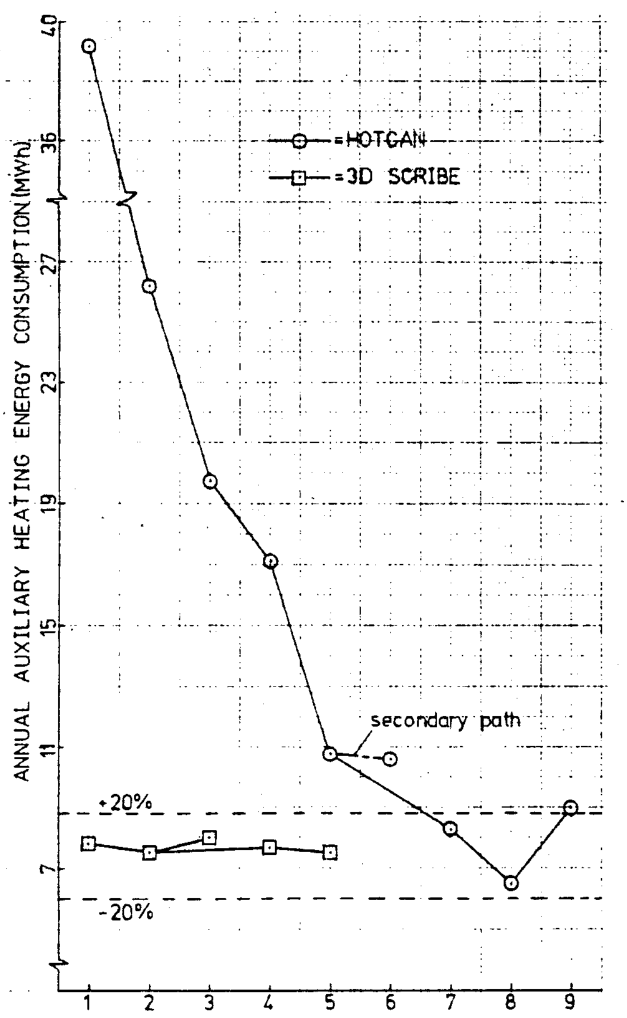

Figure 2. Camden Simulation Run Sequence Using HOTCAN and 3D SCRIBE.

The effect of various methods of describing earth-contact heat transfer on the long-term energy usage validation accuracy is depicted in figure 3. The figure describes a series of parametric runs performed with the CALPAS3 simulation program for the earth-sheltered Camden house. The baseline case is established by presenting the entire earth-contact surface using the CALPAS3 "slab" input parameters. The single monthly ground temperature provided in the input parameter set is used to describe an area weighted average over the earth-contact surface, the average ground temperature adjacent to each surface being determined from a damped sinusoidal ground temperature profile (6). These conditions result in a 57.7% validation error. The earth-contact envelope description is refined in run 2 by using the "rockbed slab/rockbed" input parameters to model the uninsulated portion of the floor slab (66% of the total slab area) as a discrete entity. Furthermore, the average ground temperatures used for each discrete earth-contact surface in the area weighting process are derived from experimental data monitored in the ground adjacent to an earth-sheltered building on the University of Minnesota campus (6). These changes result in the validation error being reduced to 13.2%, a 44.5% decrease. Run 3 is included for completeness as the change in furnace fan power described (figure 3) was included in the earth-contact parametric sequence and produced a 9.2% reduction in validation error independent of the effect of any earth-contact configuration changes.

The effect of using ground temperature and wall/earth coupling thermal conductances produced by a two-dimensional finite difference, earth-contact simulation program (6) is demonstrated by run 4. This reduces the error ascribable to earth-contact configuration changes by 11.7% compared with run 2. The "rockbed" in this run is assigned a depth of about 32 ft with zero conductance coupling to the ground temperature. This results in compliance with the simulation results which portray an adiabatic boundary at that depth. Reducing the rockbed depth to 2 ft with approximately 0.59 thermal conductance between the rockbed and the average ground temperature increases the validation error by 28.3%. Doubling the coupling thermal conductance decreases the error by a relatively minor 2.5%. These changes demonstrate the inpact of earth-contact configuration changes on the auxiliary energy usage predictions.

The earth-contact simulation run sequence shows the importance of physically plausible ground temperatures and envelope/ground thermal conductances. Even though the results are produced for the extreme case of an earth-sheltered house, they are indicative of the importance of adequate simulation program earth-contact heat transfer modelling for typical Minnesota houses which have heated or partially heated basements.

The parametric variation of the EMF for the EEDO^{TM} and SERIRES programs are shown for the Lynn Park and Camden houses in figures 4 and 5 respectively. These figures are largely self-explanatory with the exception of the EEDO^{TM} profile in figure 4. In this instance the EMF variation was achieved by altering the overall leakage area of the envelope. The profile evinces a piecewise linearity with a discontinuity

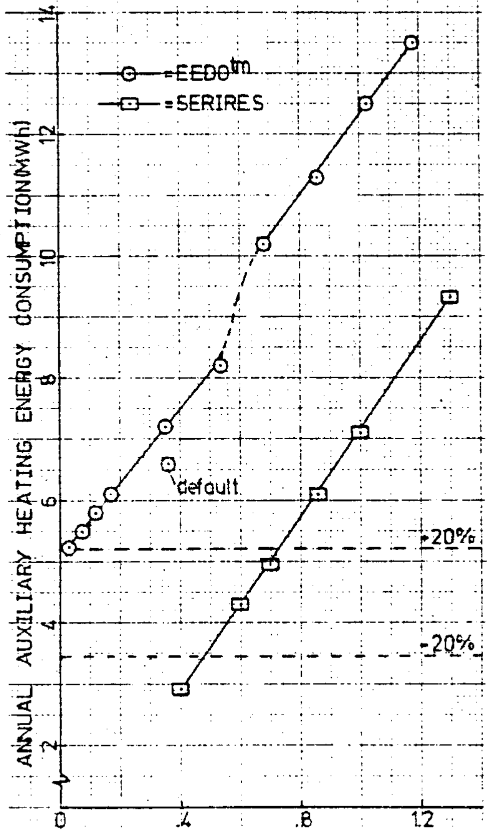

Figure 4. Lynn Park EMF Parametric Variation Using EEDO^{TM} and SERIRES.

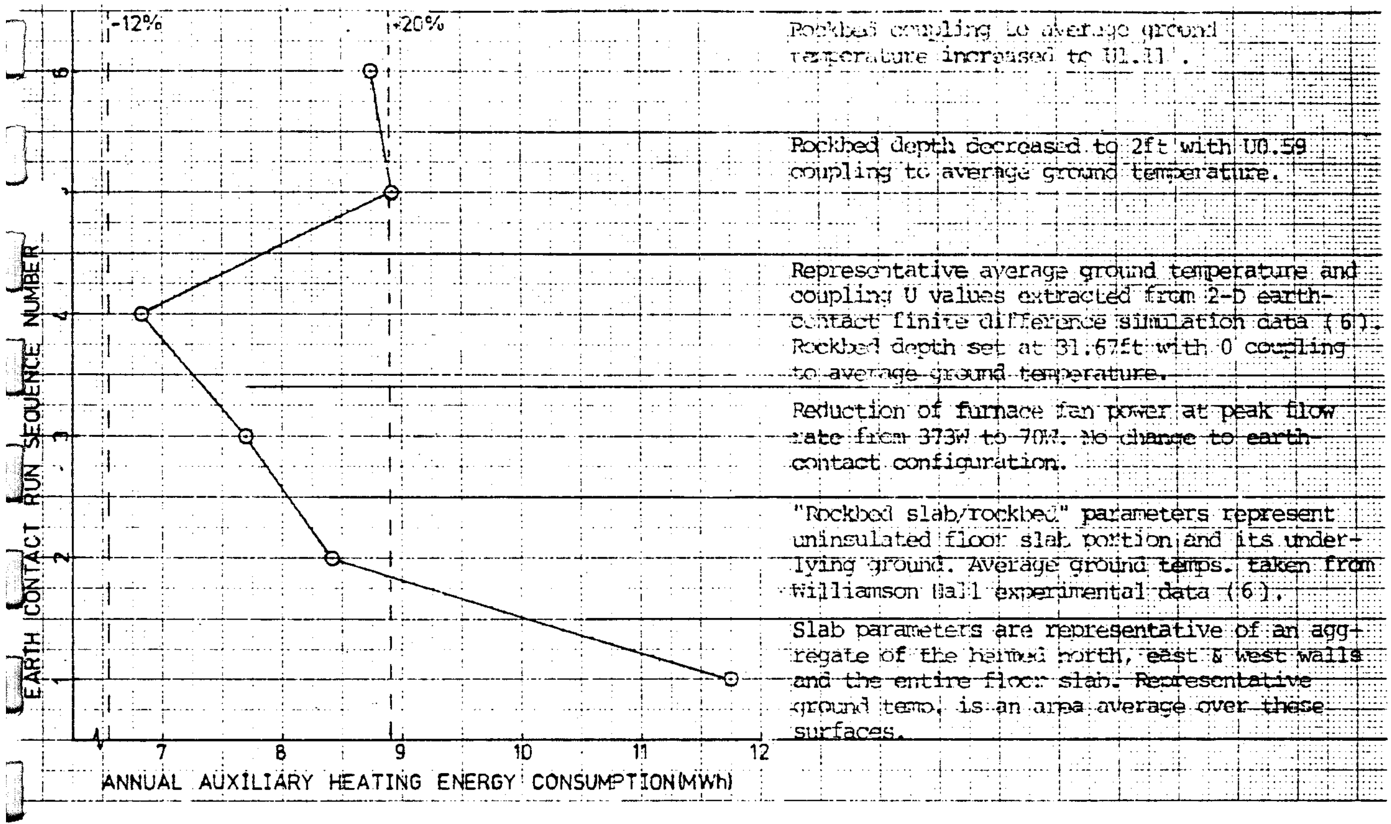

Figure 3. Camden Earth-Contact Parametric Variation Run Sequence Using CALPAS3

occurring between EMFs of .54 and .68 ach while the slopes of both linear segments are nearly identical. The default EMF (that is, using an EEDO™ supplied default leakage area) is isolated from the linear profile. These two phenomena are indicative of a possible error in the infiltration algorithm used by the EEDO™ program, although no attempts at locating this error have been made. Figure 5 shows that for the Camden house in which the EMF variation was achieved by altering the forced ventilation rate, the observed anomalies are absent. In overall perspective, all the profiles show an essentially linear characteristic with the ±20% error band being spanned by the SERIRES program for both houses. The EEDO™ program spans the error band for the Camden house only. This is an entirely fortuitous result in view of the gross and artificial manipulation of the EEDO™ input parameter set necessary to apply the program to an earth-sheltered house. The envelope mass flux range for which the SERIRES program achieves better than 20% accuracy for both houses is consistent with available experimental infiltration and ventilation test data and is believed to be physically credible.

A sample of the results produced by a comparison of the transient energy performance data is shown in table 4. The numbers tabulated correlate the gradients of the EMF/annual auxiliary heating consumption profiles (such as those of figures 4 and 5) produced by the simulation programs with those extracted from the detailed experimental data base (5). With the exception of the 3D SCRIBE program, the agreement between the experimental and simulation values is within 25%, SERIRES achieving errors of 13.4% and 8.8% for the Lynn Park and Camden houses respectively. The order of magnitude difference in gradient produced by the 3D SCRIBE program compared with the experimental value for the Lynn Park house quantifies the effect noted in figures 1 and 2 and highlights the existence of an algorithmic error.

TABLE 4. Energy Consumption/Envelope Mass Flux Profile Gradient Comparison

Data Source	Energy consumption/mass flux gradient (MWh/ach)	
	Lynn Park	Camden
Empirical	8.2	11.4
EEDO™ simulation	6.3/6.7*	9.87
SERIRES simulation	7.1	10.4
3D Scribe simulation	0.8	not avail.

* Note Corresponds to lower/upper gradients of relevant profile in figure 4.

Finally, table 5 gives an overall perspective of the long term validation accuracy results produced for the five programs tested. These results cannot be interpreted as definitively portraying the overall accuracy of any of the programs on a generalized basis, and thus should not be used to rank the programs in any way. The results should only be used to evaluate the applicability of the programs to the housing types tested and, by inference, to the overall classes of housing for which a particular program is clearly inappropriate. Thus only the SERIRES program appears to be useful for earth-sheltered housing and, by extension, for above-grade housing with significant, below-grade components. Similarly, the CALPAS3 and SERIRES programs seem to be appropriate for above-grade, well-insulated houses with active solar heating systems, and by extension, to less complicated slab-on-grade houses in general. The apparent algorithmic error revealed in the 3D SCRIBE program, however, dictates that it should be used with caution in all circumstances.

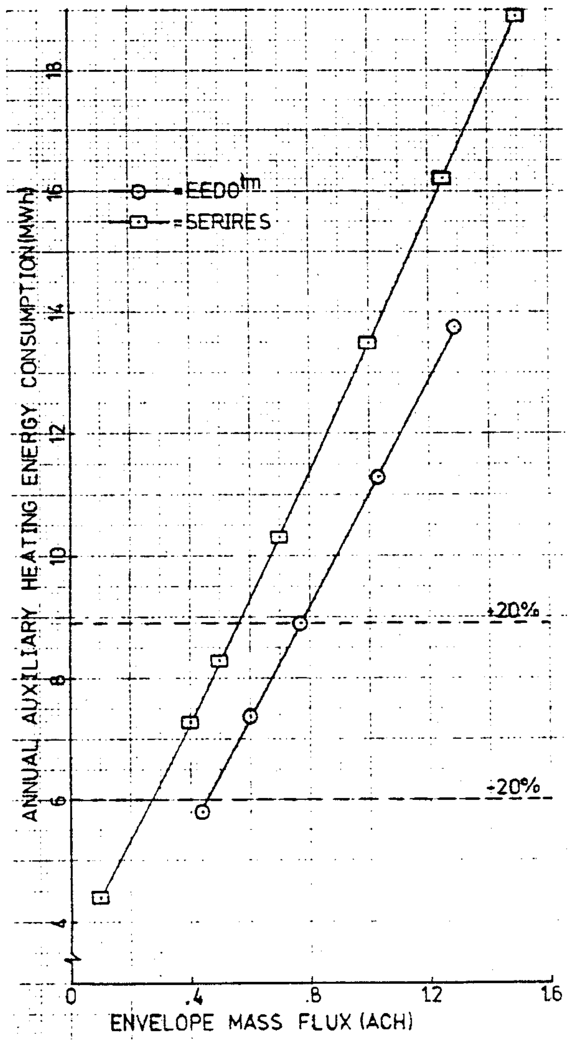

Figure 5. Camden EMF Parametric Variation Using EEDO^{TM} and SERIRES.

CONCLUSIONS

The results produced demonstrate the usefulness of the envelope mass flux parametric approach to validating and using building energy simulation programs. Both long-term energy usage as well as transient comparisons of experimental and simulated data show that physically consistent energy performance predictions which include the effects of occupant behavior may be made by an application of the envelope mass flux parametric variation methodology.

In the context of a predominantly heating climate, the importance of accurate earth-contact heat transfer modelling is demonstrated for houses with significant below-grade envelope components. The SERIRES program seems to be applicable to a broad range of house designs of which the Minnesota housing stock is comprised. The applicability of the CALPAS3 program to a slab-on-grade house configuration with an active solar space heating system has been demonstrated. The program's applicability to simpler slab-on-grade designs may thus be reasonably inferred. The 3D SCRIBE program appears to suffer from an algorithmic error pertaining to the computation of envelope mass flux energy transfers and hence the program should be used with appropriate caution. The HOTCAN and EEDO^{TM} programs evince characteristics which indicate their usefulness for predicting the energy consumption of standard house configurations which closely conform to the specific house types for which they were designed. Their general applicability over the spectrum of energy-efficient housing types found in Minnesota has not been demonstrated.

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TABLE 5. Long Term Auxiliary Heating Energy Usage Validation Comparison

	Program	Error (%)		
		Baseline Parameters	Best Achieved	Physically Credible Estimate
Lynn Park	CALPAS3	283.0	3.0	< 20
	HOTCAN	208.5	6.5	> 60*
	3D SCRIBE (1.3 ach)	27.6	2.7	n/a
	EEDO	32.9	.5	> 100
	SERIRES	31.9	-1.2	≤ ± 20
Camden	CALPAS3	79.3	3.5	> 20
	HOTCAN	426.5	11.3	> 40*
	3D SCRIBE (1.3 ach)	5.1	.9	n/a
	EEDO^{TM}	-18.5	-1.2	fortuitously =0
	SERIRES	159.5	-2.3	≤ ± 20

* Note: Credible estimate cannot be made owing to existance of algorithmic error.

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