# INTERNATIONAL ENERGY AGENCY BUILDING SIMULATION COMPARISON AND VALIDATION STUDY

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ABSTRACT - A heavily monitored unoccupied test building is modeled using the BLAST-3.0, DOE-2.1A, and SERIRES-1.0 building energy analysis simulations. The calculated results are compared with the measured performance data and with the performance calculated with a number of other computer programs run in Europe. Differences between the American codes are analyzed using a procedure to systematically compare inputs and intermediate component and mechanism level outputs. Through this process the algorithmic and input sources of the differences are identified.

## INTRODUCTION

For the past two years the Solar Energy Research Institute (SERI) has participated in a comparison and validation study of building energy simulation computer programs sponsored by the International Energy Agency and the U.S. Department of Energy. In the initial portion of the study a direct gain test building monitored by the National Research Council of Canada in Ottawa was simulated at SERI using three domestic public domain computer programs. The building was also modeled by several European researchers using computer programs developed in their respective countries. All participants modeled the building using two weeks of measured Ottawa weather data taken at the test site, and using Denver and Copenhagen typical annual hourly weather data. In the Ottawa case, calculated temperature and auxiliary energy were compared with values measured in the test building. In the Denver and Copenhagen cases calculated output quantities were compared with each other since no empirical standard existed.

The initial phase of the study revealed large disagreement among the American codes. A procedure was then developed and implemented to isolate the sources of those differences. The differences were primarily attributable to an air mixing algorithm in BLAST-3.0 that can violate the building heat balance under certain conditions. Several input nonequivalencies also contributed to the differences. Once these problems were corrected the American codes agreed within about 12% of auxiliary heating energy. This was about the same range of disagreement observed between the European codes. The percentage disagreement in cooling energy predictions were much larger for both the American and European codes. However, the quantities of energy were relatively small in these predominantly underheated climates.

## DESCRIPTION OF THE TEST BUILDING

The test case was based on a building in Ottawa, Canada. This building is part of a passive test facility supported by the Division of Building Research, National Research Council of Canada(1). The facility contains three buildings each divided into two units. The specific case modeled in this study was unit 3, a direct gain heavy mass module with a north and south zone. As seen in Fig. 1, unit 3 is the western half of the building.

Figure 2 shows a section through the building. The building is a one-story stud wall structure with a basement and an attic. The exterior walls and the corridor wall (E wall) consist of 89-mm batt insulation (R-2.1 $m^2$-K/W), 12.7-mm gypsum board and 100-mm cement brick (outside to inside). The wall between the south and north zone is 100-mm cement brick. The floor consists of carpet, 19-mm plywood, and R-7 $m^2$-K/W insulation. The ceiling is made of R-3.5 insulation, and 12.7-mm gypsum board. Table 1 summarizes the building characteristics. The complete data package is found in Judkoff(2).

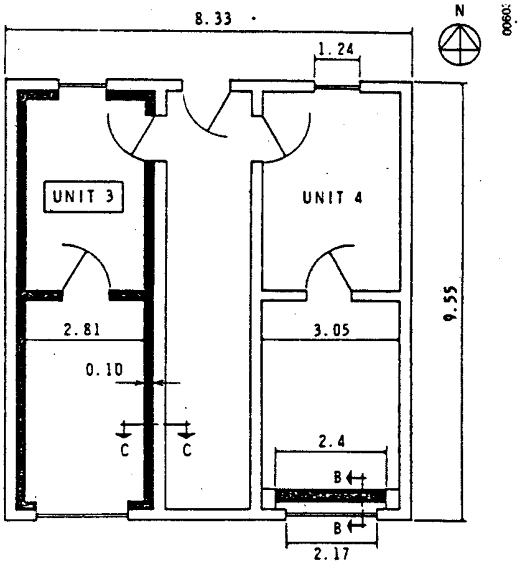
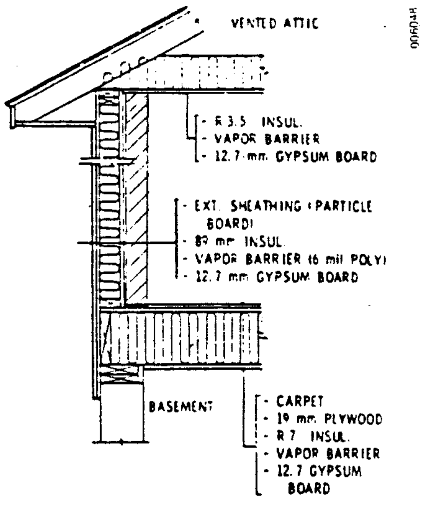


**Fig. 1.** Plan of Canadian direct gain test building.

The operating conditions for the building included a fan in the open doorway between the south and north zone. The fan was rated at 168 $m^3$/h and was always on. The north and south zones were heated by electric resistance heaters set to turn on when the zone temperature was ≤20°C. An exhaust fan was provided to vent at temperatures ≥27°C. The basement and corridor were independently heated to match closely the average unit 3 temperature. Therefore, very little net energy passed through the floor and east wall. The building was carefully sealed with a 6-mil polyethylene vapor and infiltration barrier. Additionally, the independently heated corridor was kept slightly pressurized so infiltration heat losses could be disregarded according to the researcher in charge of the facility.

The weather data supplied were actual measurements at the test site in Ottawa, Canada, including



(a) WALL CONSTRUCTION, UNIT

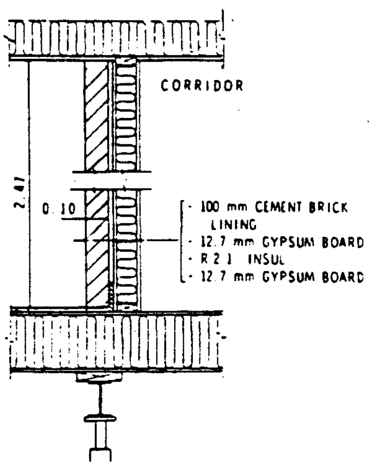


**Fig. 2.** **Construction details of test facility (thermal resistance values—m² °C/W).**

**Table 1. IEA Canada Direct Gain Building Summary Characteristics**

| | | |
|---|---|---|
| Floor area | 27 $m^2$ | 300 $ft^2$ |
| S. window area | 2.6 $m^2$ | 28 $ft^2$ |
| N. window area | 1 $m^2$ | 11 $ft^2$ |
| Wall resistance | 2.1 $m^2$-K/W | R12 |
| Ceiling resistance | 3.5 | R20 |
| Floor resistance | 7.3 | R40 |
| UA overall | 34 W/K | 64 Btu/h °F |
| Thermal storage Mass | 13,565 kg | 29,912 lb |
| Heat capacity | 11.55 mJ/K | 6082 Btu/°F |

hourly values (averages or totals interpreted over the hour) for 14 days (Dec. 29, 1980 to Jan. 11, 1981).

The hourly weather parameters supplied were:

- Average outdoor air temperature, °C
- Total global horizontal radiation, $W/m^2$
- Total vertical south radiation, $W/m^2$
Total vertical north radiation, $W/m^2$
Average wind speed, km/h

## RESULTS FROM THE ORIGINAL RUNS

Figure 3 shows the heating energy results for the original Ottawa run. These results appear quite good in terms of both the calculated-to-measured comparison and the code-to-code comparison. Figure 4 shows the annual heating energy predictions for the Copenhagen climate. These results show significant differences between SERIRES, BLAST, and DOE. SERIRES predicts the highest heating loads of the three U.S. codes and agrees best with the other independently run European codes. BLAST predicts the lowest heating loads of the set. Figure 5 shows the annual heating and cooling results for the Denver climate. These results show the same trends as in the previous data set, but with even more pronounced differences observed. In the Denver climate the heating loads predicted by BLAST are less than half those predicted by SERIRES. The remainder of this paper will describe what was done to identify the causes of these differences.

## STRATEGY

Previous studies at SERI had shown differences between these codes(3,4,5). However, the magnitude of

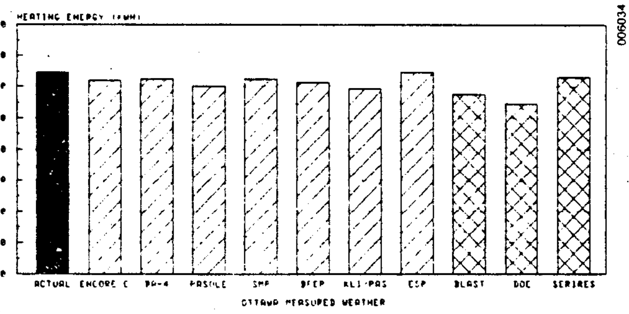


**Fig. 3.** **IEA Canada direct gain original results—Ottawa.**

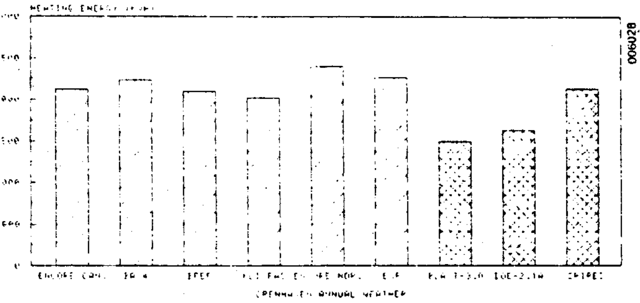


**Fig. 4.** **Original heating results—Copenhagen.**

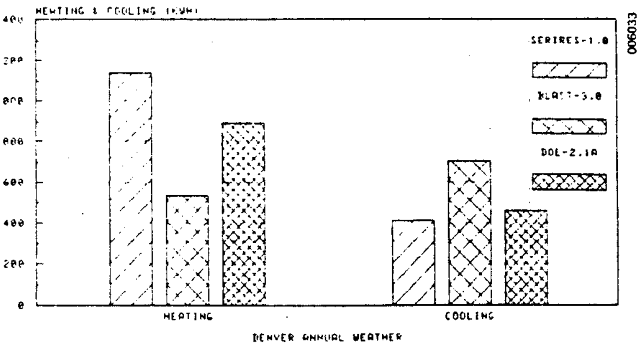


**Fig. 5.** **Original heating and cooling results—Denver.**

the differences exhibited in this case was disturbing. At the same time this case provided a favorable opportunity to isolate the algorithmic source or sources of the differences due to their very magnitude. It was decided to conduct a detailed analysis of this case concentrating primarily on the SERIRES and BLAST programs in the Denver climate.

The Denver climate was chosen because the differences were most pronounced in the Denver runs and because the Denver ersatz typical meteorological year (DENVER ETMY) weather tape was considered the most reliable of all the weather data sets. Weather tapes must be preprocessed to be read by the BLAST and DOE programs. The Copenhagen weather tape was not in a format readily usable by the weather tape preprocessing programs. Also the Copenhagen weather tape did not contain all the fields of data expected by the BLAST and DOE programs. To solve these problems the weather preprocessing programs had to be modified. It was preferable, therefore, to use the DENVER ETMY weather tape to eliminate the possibility of faulty and nonequivalent weather data contaminating the results. Little difference was observed in the Ottawa case, so it was not used for the detailed analysis procedure. Both the Ottawa and Copenhagen cases were rerun at the end of the detailed analysis procedure as a check that any reduction in difference obtained in the Denver case was because of legitimate improvements or corrections and not because of compensating errors.

## DETAILED ANALYSIS PROCEDURE

The detailed analysis procedure consisted of the following steps:

1. Input equivalency comparison
2. Weather variable comparison
   a. Ambient dry bulb temperature
   b. Ambient wind speed
   c. Direct normal solar radiation
3. Intermediate output variable comparison
   a. Incident solar radiation on the south wall
   b. Transmitted solar radiation through the south window
4. Parametric sensitivity studies
   a. BLAST "mixing"
   b. SERIRES window exterior surface coefficients
   c. SERIRES wall exterior surface coefficients
   d. BLAST and SERIRES wall exterior solar absorptance.

### Input Equivalency Comparison

To facilitate a detailed examination of input equivalency between the codes, an input equivalency form was developed. This form was then completed for each of the three codes (these forms were also adopted by the IEA Code Evaluation Task and filled out by the task members for their respective programs). Figure 6 shows a sample page from the four forms required to complete an input equivalency comparison. Completion of these forms revealed two kinds of nonequivalencies: objective nonequivalencies and interpretive nonequivalencies. In the first category only one minor nonequivalency was found. This consisted of differences in the wall external surface solar absorptance specified in SERIRES and DOE (0.86) and in the default value in BLAST (0.7) and that specified in the European codes (0.4). The confusion arose because this parameter was not specified in the data package. Once discovered, however, this was easily corrected according to the Canadian recommendation (0.4). The input comparison did highlight several interpretive nonequivalencies. These consisted of modeling the interzone fan coupling and choosing a value for the constant exterior surface coefficients in SERIRES. The importance of these nonequivalencies was investigated by running parametric sensitivity studies. The selection of the final input values is discussed later in this paper.

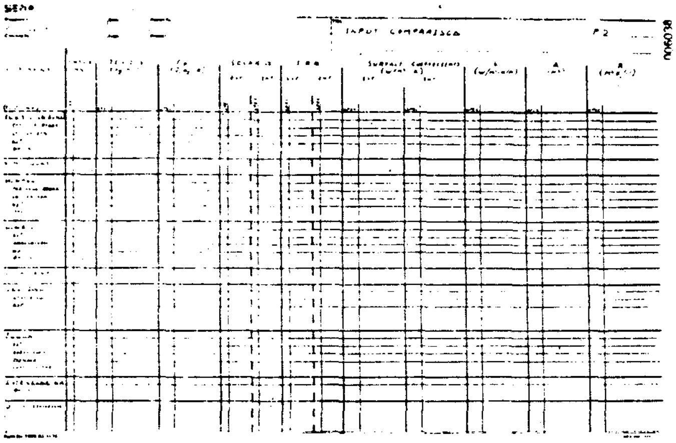


**Fig. 6.** Sample input equivalency form.

### Weather Variable Comparison

Each of the computer programs preprocesses the data from the source weather tape in a different way. Thus, each program produces its own weather input file. These were checked for equivalence by printing the most important weather variables from the programs. Hourly ambient dry bulb temperatures were identical for all three programs. Hourly ambient wind speeds were close to identical for BLAST and DOE. The slight difference is because of an overlapping triangular smoothing function in the DOE weather preprocessor(6). Wind speed was not checked in SERIRES because it was not used by the program in this case.

Figure 7 shows hourly direct normal radiation for a partly cloudy day in December from the Denver ETMY. BLAST and SERIRES yield identical plots; however, the DOE beam radiation plot lags the others by one hour and has a slightly different shape. The one-hour time lag is caused by a bug in the DOE-2.1A weather processor for TMY tapes. This has been corrected in some versions of DOE-2.1B and in DOE-2.1C, according to the DOE-2 support office at the Lawrence Berkeley Laboratory. The

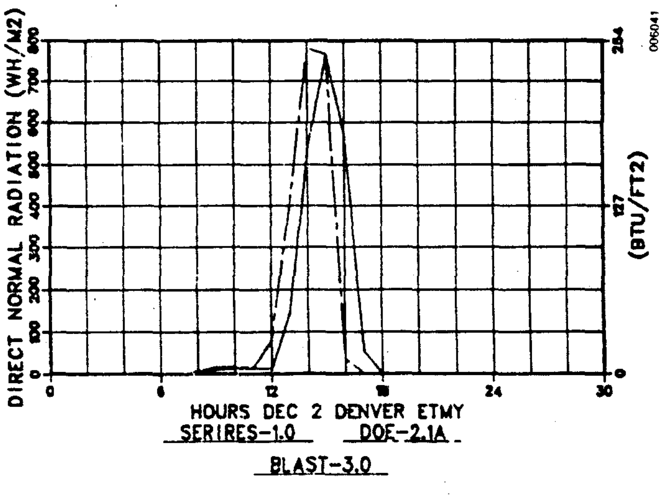


**Fig. 7.** Direct normal radiation.

different shape is because of the overlapping triangular smoothing function used in the DOE weather processor. The effect of this difference is negligible since the time integrated direct normal radiation is essentially identical for all three codes as shown in Table 2. Global horizontal radiation was not checked because any problem in this variable would have also shown up in the checks on incident radiation.

## Intermediate Output Variable Comparison

Figure 8 shows the hourly solar radiation intensity incident on the south wall of the building for an overcast and a partly cloudy day in December. The plots are practically identical for SERIRES and BLAST and somewhat different for DOE. The difference is primarily because of the anisotropic sky model used in DOE versus the isotropic model used in SERIRES and BLAST. For a south-facing surface the difference in these models is the greatest under overcast conditions and least under clear sky conditions. Table 3 shows the time integrated values for incident south solar radiation for two clear days and two partly cloudy days. The anisotropic sky model predicts about 25% greater radiation incident on south surfaces under overcast skies and 8% greater under clear skies.

**Table 2. Direct Normal Radiations ($W\ h/m^2$)**

| | Clear June 1,2 | Cloudy Dec. 2 |
|---|---|---|
| SERIRES-1.0 | 14,320 | 2121 |
| DOE-2.1A | 14,340 | 2120 |
| BLAST-3.0 | 14,308 | 2120 |

**Table 3. Total Incident South Solar Radiation ($W\ h/m^2$)**

| | Clear June 1,2 | Cloudy Dec. 1,2 |
|---|---|---|
| SERIRES-1.0 | 5903 | 2736 |
| DOE-2.1A | 6403 | 3570 |
| BLAST-3.0 | 5905 | 2679 |

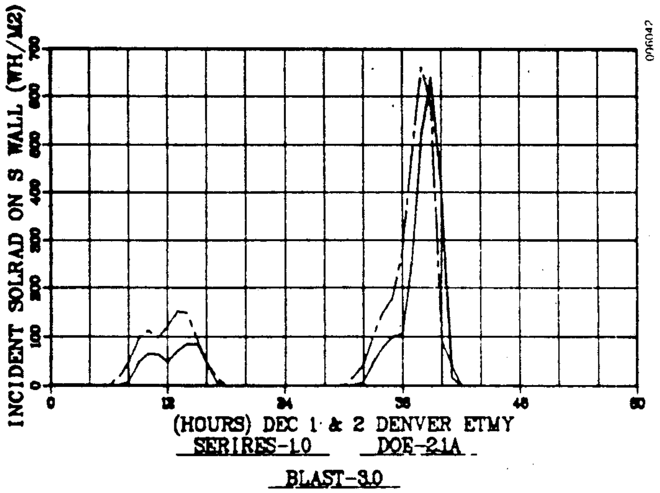


Fig. 8. Solar radiation incident on south vertical surface.

Figure 9 shows the hourly transmitted solar radiation through the south window for June 1 and 2. BLAST predicts 24% higher total solar radiation for this time period than SERIRES. Since the window is not shaded, this could have been caused by either a faulty optical transmission algorithm or nonequivalent optical properties for the window. BLAST and SERIRES require different inputs to describe glazing optical characteristics. SERIRES calculates transmittance, absorptance, and reflectance for each hourly incidence angle given index of refraction, extinction coefficient, glazing thickness, and number of lites(7). BLAST calculates the extinction coefficient, off-normal transmittance, absorptance, and reflectance given the index of refraction, normal transmittance of a single pane in air, thickness, and number of lites(8). This makes direct comparison of the glass optical properties difficult.

To determine input equivalency for the window for BLAST and SERIRES, the index of refraction, extinction coefficient, glass thickness, and number of panes assigned as inputs in SERIRES were used with the Fresnell equations, Snell's law, Bouger's law, and the SERIRES equations to manually calculate the normal transmittance input value for BLAST(9). As a cross check, this normal transmittance value was then used with the equations in BLAST to manually calculate the extinction coefficient. This extinction coefficient was then compared with the extinction coefficient initially input to the SERIRES program.

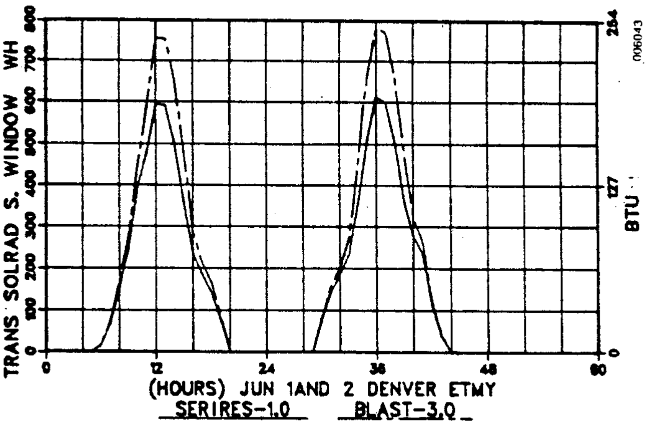


Fig. 9. Original transmitted solar radiation through south windows.

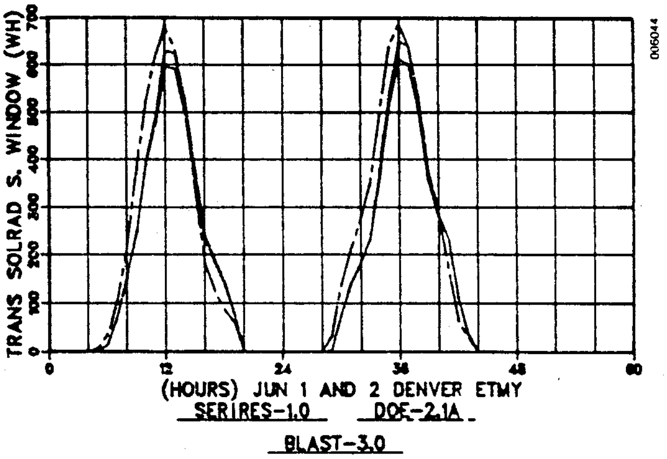


Fig. 10. Final transmitted solar radiation through south windows.

This process revealed nonequivalencies caused by (1) the default index of refraction in BLAST versus the index of refraction input in SERIRES, and (2) the normal transmittance for a single pane in air input in BLAST versus the normal transmittance for a single pane in air calculated with the Fresnell equations and the SERIRES subroutine "TRANS." Table 4 shows the results of the calculations leading to the correction of these values. A complete description of the equations and calculations is presented in the full length report on which this paper is based(2).

Figure 10 shows the hourly solar radiation transmitted through the south window on June 1 and 2 as calculated by the three codes after correction of the BLAST transmittance and index of refraction inputs. It is apparent that the BLAST curve has moved much closer to the SERIRES curve. The time integrated totals are within 4% for SERIRES and BLAST. The small difference observed near the noon hours is not understood at this time. The difference between DOE and the other codes is partly because of the difference in incident radiation and partly because of non-user-adjustable differences in window optical properties. Unlike SERIRES and BLAST, DOE-2.1A limits the glazing types to those that exist in a prescribed library. The user must pick the glazing code type that most closely approximates the window to be modeled. This limitation has been improved in DOE-2.1C according to the DOE-2 support office at LBL.

## Parametric Sensitivities

The checks that were done in the first three steps of the analysis procedure revealed several objective input nonequivalencies that were corrected by appropriately modifying the code input files. These checks also revealed several interpretive modeling problems that indicated the need for sensitivity studies. These included (1) different ways of modeling the interzone fan coupling, and (2) SERIRES sensitivity to the values chosen for the constant combined exterior surface coefficients.

### Interzone Fan Coupling

BLAST-3.0 contained two poorly documented algorithms referred to as "MIXING" and "CROSS MIXING" that appeared appropriate for modeling the interzone fan coupling(10). To clarify the meaning of these modeling alternatives four parametric runs were made. These included no mixing, mixing = 0.047 $m^3/s$, cross mixing = 0.0235 $m^3/s$, and cross mixing = 0.047 $m^3/s$.

Figure 11 shows north zone temperature profiles for 48 hours in summer and 48 hours in winter with the auxiliary heating and cooling systems deactivated to allow free-floating temperatures in the north and south zones. It was expected that the no mixing case would show the lowest temperatures in the north zone and that the various mixing/cross-mixing options would show higher temperatures according to how much heat they were transferring from the south zone, respectively. In fact we observe the expected pattern. Temperatures are coolest in the no mixing case because no heat is being supplied from the south zone other than what conducts across the interzone wall. Temperatures are next warmest for cross mixing = 0.0235 $m^3/s$ because the added airflow effectively supplies additional heat from the south zone. Temperatures are only slightly warmer for cross mixing = 0.047 $m^3/s$ because we are approaching the saturation limit for this strategy; i.e., for a given rate of mixing the limit occurs when the north and south zone temperatures become equal. The airflow rate of 0.0235 $m^3/s$ is already sufficient to maintain a relatively isothermal temperature distribution between the two zones. The increase in heat transfer to the north zone is therefore slight when the cross-mixing airflow rate is doubled to 0.047 $m^3/s$. The large increase in temperature seen when mixing = 0.047 $m^3/s$ is used in place of cross mixing is suspicious.

Figure 12 shows the south zone temperature profiles for the same time periods. The no mixing and cross-mixing profiles show the expected reversal in position with respect to Fig. 11; i.e., the no mixing profile is warmer than cross mixing = 0.0235 $m^3/s$ and cross mixing = 0.047 $m^3/s$, respectively. The mixing temperature profile; however, was warmest in the north zone and is again warmest in the south zone. Mixing appears to be adding heat to both zones, thereby violating the building heat balance. This contributes to the underprediction of heating loads and overprediction of cooling loads seen in Figs. 4 and 5.

Subsequent to these results the BLAST support office issued a newsletter addendum to the MIXING documentation indicating that it was the responsibility of the user to specify an appropriate airflow rate from another zone or from the exterior to maintain the building energy balance(11). This confirmed that the code will not automatically maintain a heat balance under the conditions of this case.

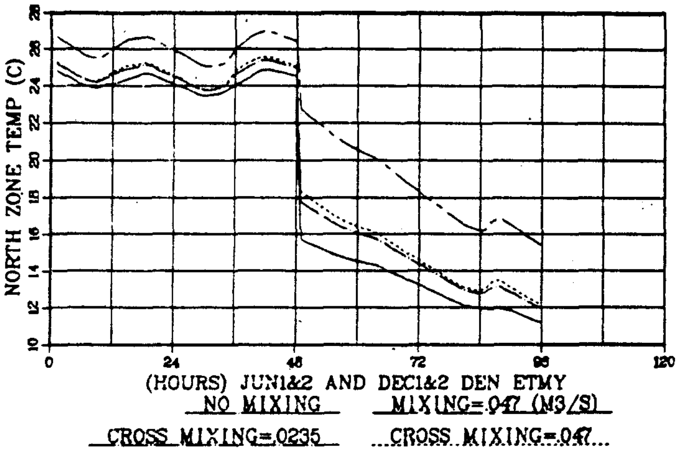


Fig. 11. BLAST3 sensitivity to mixing: north zone.

Table 4. Check for Window Input Equivalency

| | Extinc. Coef. | 1 Pane Norm. Trans. | 2 Pane Norm. Trans. | 2 Pane 60 Deg. Trans. | Dif. Trans. |
|---|---|---|---|---|---|
| BLAST | 0.01952 | 0.8615 | 0.7467 | 0.6479 | 0.6589 |
| SERIRES | 0.0196 | 0.8615 | 0.747 | 0.65 | 0.65 |
| Snell, Fresnell & Bouger | 0.0196 | 0.8615 | 0.747 | 0.65 | 0.65 |
| DOE | | | 0.75 | | |

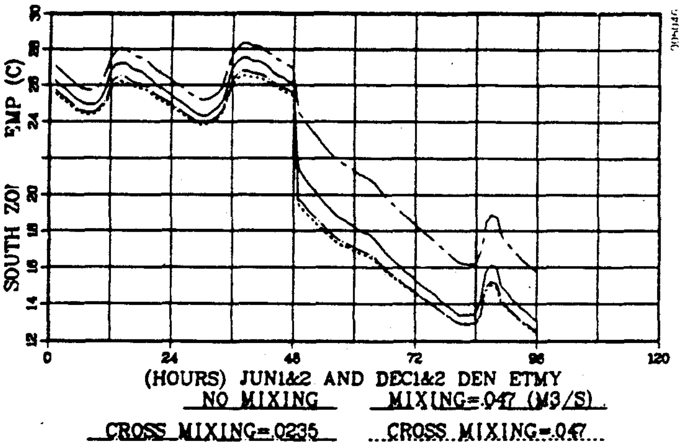


Fig. 12. BLAST3 sensitivity to mixing: south zone.

### External Surface Coefficients

Both BLAST and DOE calculate the exterior combined convective and radiative surface coefficients hourly based on second order polynominal equations in wind speed. SERIRES requires the user to input a constant combined exterior surface coefficient. The data package issued for the test site specified the ASHRAE Handbook of Fundamentals' winter value for this constant. The handbook value was rather arbitrary since it was not based on measured wind speed for the two week period in Ottawa, nor was it representative of annual conditions in Denver or Copenhagen. Table 5 shows the sensitivity of the SERIRES heating and cooling energy predictions to the constant combined exterior surface coefficient. The polynomial equations in BLAST and DOE ere used to calculate the coefficients for several wind speeds. A similar set of runs showed comparable sensitivity for the wall external surface coefficient. From these results it was decided to calculate the SERIRES constant combined surface coefficients based on the average wind speed for each location. [A complete description of the equations and calculations is in Judkoff(2).]

### RUNS

Starting with the initial run for each code, a series of simulations was performed leading to the final run. Some of the runs resulted from input improvements and some represented sensitivity studies. Different criteria apply to input file changes for the two different kinds of runs. In a sensitivity study any change to an input file that helps to understand the parameter under investigation is legitimate. Concerning input improvements, strict rules must be observed. An input change is allowable only if it models the actual building more realistically, or if it achieves greater input equivalence with another code. A result moved in a desirable or undesirable direction is never by itself a legitimate reason for making or not making a change to an input.

Table 5. Window External Surface Coefficient Sensitivity: SERIRES

| Wind Speed (m/s) | Ext Surf-U ($W/m^2$ K) | Heating (kWh) | Cooling (kWh) |
|---|---|---|---|
| 0.0 | 10.2 | 976 | 457 |
| 3.13 | 21.27 | 1093 | 425 |
| 7.85 | 33.33 | 1142 | 413 |

### Blast Runs Summary

BRUN1: The initial run.
BRUN2: Same as BRUN1 except window optical characteristics are made equivalent to those in SERIRES.
BRUN3,4,5: Same as BRUN2 except these were sensitivity runs to investigate the mixing and cross-mixing algorithms. These runs showed mixing violating the building heat balance; therefore, cross mixing (BRUN4) was used.
BRUN6: Same as BRUN4 except wall external solar spectrum absorptance was changed from 0.7 to 0.86 to be equivalent to SERIRES and DOE.
BRUN7: Same as BRUN6 except wall external solar absorptance was changed to 0.4 to be equivalent with the European codes.

### SERIRES Runs Summary

SRUN1: Initial run.
SRUN2,3: Same as SRUN1 except these runs investigated the sensitivity of the window constant combined exterior surface coefficient. These runs showed the effect to be significant.
SRUN4: Same as SRUN1 except (1) the window exterior surface coefficient was calculated from the average windspeed, (2) the interzone fan coupling algorithm was replaced with an equivalent interzone conductance.
SRUN5: Same as SRUN4 except the wall exterior surface coefficient was calculated from the average wind speed.
SRUN6: Same as SRUN5 except the wall external solar absorptance was changed to 0.4 to match the value used in the European codes.

### DOE Runs Summary

DRUN1: Initial run.
DRUN2: Same as DRUN1 except (1) wall exterior solar absorptance set to 0.4 to match European codes, (2) floor heat transfer to ground modeled by using the U-effective algorithm in DOE (this was to allow dynamic modeling of the floor mass in the zone while decoupling the floor from the ground. This run indicated that the U-Effective algorithm was not working properly.), (3) the interzone fan equivalent parallel conductance was adjusted to correspond to the volumetric heat capacity of air at 1600-m altitude (Denver).
DRUN3: Same as DRUN2 except an additional pure resistance layer = R999 was added under the floor to assure decoupling from the ground and correct the problem in the U-effective alogrithm.

## RESULTS/INTERPRETATION

### BLAST Results

Figures 13 and 14 show the annual heating and cooling energy predicted by BLAST and SERIRES in the Denver climate for the series of runs leading to the BLAST final run. The original BLAST run (BRUN1) predicted 608-kWh less heating energy than the original SERIRES run (SRUN1) and 192-kWh more cooling energy.

The change in the BLAST window inputs from the original run to BRUN2 reduced the quantity of solar energy entering the building. As expected this increased

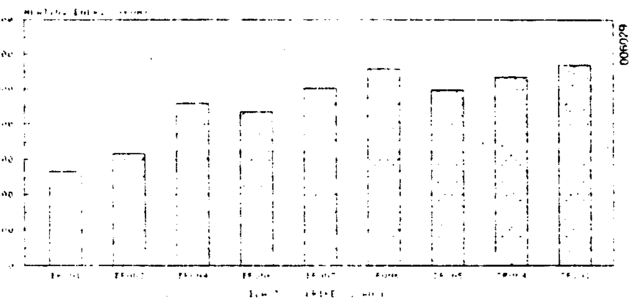


**Fig. 13.** **BLAST runs 1,2,4,6,7 and SERIRES runs 1,4,5,6 (heating energy).**

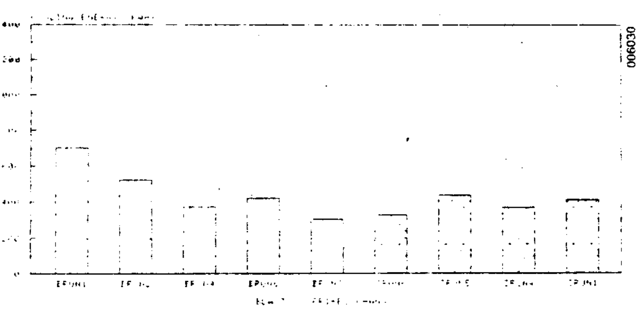


**Fig. 14.** **BLAST runs 1,2,4,6,7 and SERIRES runs 1,4,5,6 (cooling energy).**

the heating load and decreased the cooling load. The heating load increased by 98 kWh and the cooling load decreased by 181 kWh. The change in the window transmissivity, therefore, accounted for about 16% of the difference in predicted heating load between BLAST and SERIRES, and about 60% of the difference in predicted cooling load.

The change from BRUN2 to BRUN4 involved changing from mixing to cross mixing to model the interzone fan. This change increased the predicted heating load by 286 kWh accounting for about 47% of the original difference in predicted heating load between BLAST and SERIRES and about 30% of the difference in cooling load.

BRUN6 set the wall exterior solar absorptances to 0.86 instead of 0.7. This reduced the heating load by about 5% and increased the cooling load by about 10%. At this point BRUN6 and SRUN5 contain equivalent input files. The difference between these two cases is 122-kWh heating energy and 16-kWh cooling energy.

In BRUN7 the wall exterior solar absorptances were set to 0.4. This increased the heating load in BLAST by 134 kWh and decreased the cooling load by 116 kWh. This was also done in SRUN6. The final difference between BLAST and SERIRES is 113-kWh (10%) heating energy and 18-kWh (6%) cooling energy.

## SERIRES Results

Figures 13 and 14 show the effect on the annual heating and cooling energy predictions of each successive change to the SERIRES input files. The first run is displayed at the extreme right of the chart so that the final bar can be seen next to the final BLAST run.

The change from SRUN1 to SRUN4 resulted from two input changes. Change 1 involved adjustment of the window air-to-air conductance so that the constant combined convective and radiative window exterior film coefficients corresponded with those calculated in BLAST and DOE for a 4.02 m/s wind speed, the average annual wind speed in Denver. Change 2 involved substitution of an additional equivalent parallel interzone conductance for the fan model. The fan model was replaced because it constrained the control strategy in a way that was neither representative of the real situation nor comparable to the other codes. The control strategy constraints for the fan model in SERIRES only allow air flow when the source zone temperature is greater than or equal to the sink zone temperature. Additionally, the fan is not allowed to heat the sink zone above the heating set point for that zone. This was quite different from the actual situation where the fan was always on. In the actual situation the fan was both an effective heater of the north zone and an effective cooler of the south zone. In the SERIRES model the fan was an effective heater of the north zone but a very ineffective cooler of the south zone.

The combined change of the window film coefficients and the interzone fan model results in a 70-kWh decrease to the heating load and a 45-kWh decrease to the cooling load.

In SRUN5 the wall-exterior-combined radiative and convective coefficients were adjusted to correspond with those calculated by DOE and BLAST for the average annual Denver wind speed. This decreased heating by 78 kWh and increased cooling by 68 kWh.

SRUN6 changed the wall exterior solar spectrum absorptance from 0.86 to 0.4 to match the value used by the European modelers. This increased heating by 125 kWh and reduced cooling by 114 kWh.

At the outset the initial BLAST and SERIRES energy use predictions differed by about 53% for heating and 41% for cooling. The final BLAST and SERIRES runs (SRUN6 and BRUN7) differed by about 10% for heating and 6% for cooling.

## DOE-2.1A Results

Figure 15 shows the annual heating and cooling results for DOE-2.1A. DRUN1 was the initial run. In DRUN2 the following changes were made: (1) the wall external solar absorptance was changed from 0.86 to 0.4 to match the European codes, (2) the interzone fan equivalent parallel conductance was modified to correspond with the volumetric heat capacity of air at 1600-m altitude, (3) the heat transfer from the floor to the ground was modeled with the U-effective command in DOE. This command supposedly allows for full dynamic modeling of internal floor mass while allowing a user specified heat transfer coefficient to the ground. Since the building was assumed to be decoupled from the ground, U-effective was set at 0.001 Btu/h ft$^2$ °F. In the previous run this had been modeled with an additional 1-ft thick underfloor dynamic layer with negligible conductance, density, and specific heat. The U-effective subroutine appeared to be the preferred way to model this situation according to the users' manual(12). However, a routine inspection of the output file from DRUN2

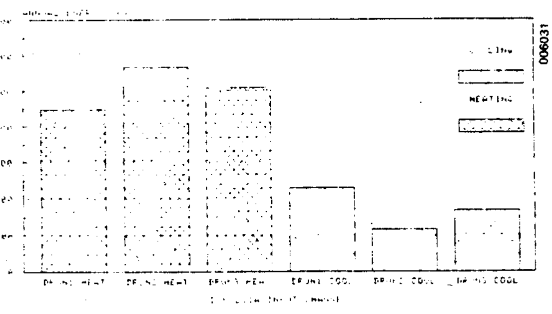


**Fig. 15.** **DOE-2.1A runs 1,2,8.**

revealed too much heat transferring to the ground. This was traced to a bug in the U-effective algorithm that prevents the floor heat transfer coefficient from being reduced beyond a minimum value. This caused too much increase in heating and too much reduction in cooling in DRUN2. In DRUN3, therefore, an additional pure resistance layer with an R-value of 999 was added under the or to prevent ground heat transfer.

Figure 16 shows the initial and final heating and cooling predictions from the three codes in the Denver climate. All three codes agree within 10% for heating and 6% for cooling.

## OTTAWA RESULTS

Figure 17 displays the measured and calculated heating energy from December 29 through January 11 in the Ottawa climate. The input files for BLAST, SERIRES, and DOE are the same as the final Denver input files for BRUN7, SRUN6, and DRUN3 except for the location-dependent variables. Observe that the input changes from the original to the final runs have had little effect on the heating loads predicted by the three codes. This is because the mechanisms affected by the input changes are those driven primarily by the solar forcing function. In the Denver climate these mechanisms were important. In the Ottawa climate these mechanisms were relatively insignificant.

## COPENHAGEN RESULTS

Figure 18 presents the annual heating energy predictions for the final run using Copenhagen weather data. The BLAST, SERIRES, and DOE input files for this run are the same as for the final Denver run except for the location-dependent parameters. The SERIRES prediction has changed little from the original run as was also the case for the Denver and Ottawa climates. The BLAST DOE predictions have increased by 527 and 285 kWh, respectively, and are now both within the range of variability shown by the other codes. All three American codes agree within 11%.

Figure 19 shows the annual cooling predictions for the final run in the Copenhagen climate. The SERIRES cooling prediction has decreased by 43 kWh. The BLAST prediction has decreased by 361 kWh, and the DOE prediction has increased by 130 kWh. The cooling predictions for all three codes are now within the range of variability shown by the other codes. The BLAST and SERIRES predictions agree within 13%. The DOE-2.1A prediction is approximately double that of SERIRES and BLAST; however, the quantity of cooling energy is small in the Copenhagen climate.

The consistency of the results is a strong indicator that the changes made to input files were legitimate and that significant compensating errors are not present. Consistency is observed across climates and parametric changes in all of the output data examined.

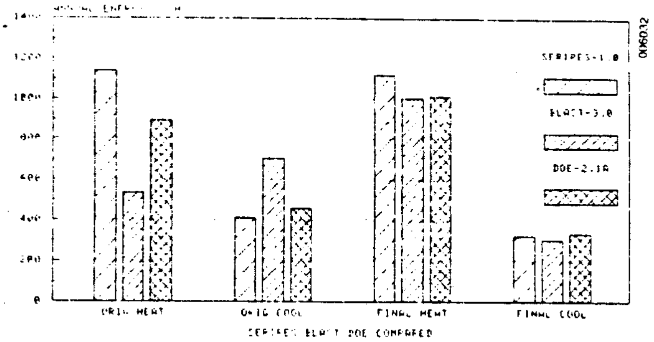


**Fig. 16.** **Original and final results of SERIRES, BLAST, and DOE.**

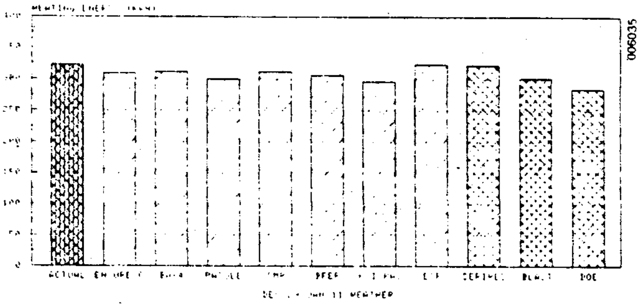


**Fig. 17.** **Final results—Ottawa.**

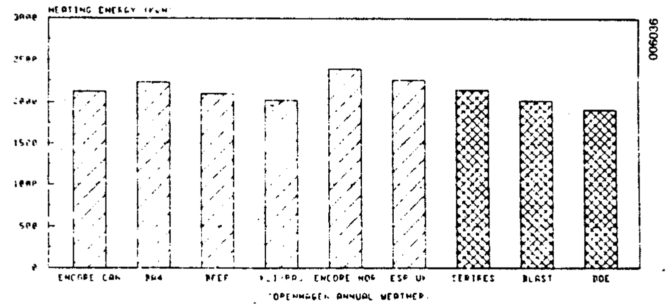


**Fig. 18.** **Final heating results—Copenhagen.**

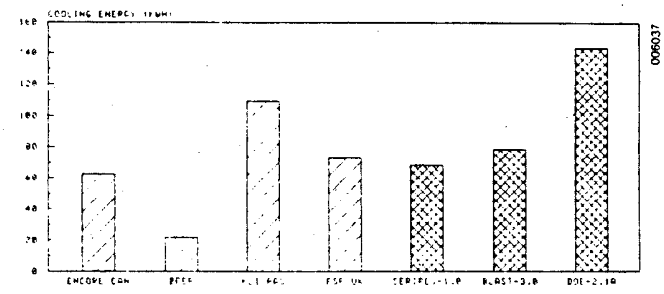


**Fig. 19.** **Final cooling results—Copenhagen.**

## CONCLUSIONS

The purpose of this project was to identify the reasons for the large differences in annual heating and cooling energy predicted by the BLAST-3.0, SERIRES-1.0, and DOE-2.1a building energy analysis simulation programs. To accomplish this a procedure was developed that allowed detailed analysis of input equivalency and important intermediate output quantities associated with specific mechanism and component algorithms.

This analysis procedure revealed several input nonequivalencies and several internal code bugs. The procedure also highlighted the sensitivity of several algorithmic differences between the codes. When these problems were corrected, the three American codes showed reasonable agreement for all locations run and all output quantities inspected. The level of disagreement remaining between the codes was well within the range of what would be expected given the algorithmic differences between the codes. Specific conclusions are summarized below:

- The BLAST "mixing" algorithm does not automatically maintain a heat or mass transfer balance between zones. The user must precalculate interzone or infiltration flows so a balance is maintained.

- The DOE-2.1A "U-effective" alogrithm has undocumented limitations that do not allow zero ground heat flow.
- The American codes agreed within the range of variability shown by all the other codes in the study.
- The procedures developed and implemented in this study were successful in identifying the sources of system level code output differences.

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