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GAIN TEST CELL MEASUREMENTS

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November 1980

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LBL-10619 C.2

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ABSTRACT

Comparisons between temperatures measured in a direct solar gain test cell and temperatures predicted by the building energy analysis computer program BLAST* are reported. The comparisons were performed for three distinct climate periods; the simulations were driven by weather data collected at the test cell site in Los Alamos, New Mexico. The test cell configurations and weather data manipulations are described; quantitative evaluations of the comparisons between measured and predicted interior temperatures are presented; limitations of the comparisons are discussed; and sensitivities of the simulation results to uncertainties in the measured parameters are examined.

I. INTRODUCTION

BLAST is a state-of-the-art, user-oriented, public domain building energy analysis computer program. It has extensive capabilities for analyzing the energy consumption impacts of both the architectural and engineering design features of conventional buildings. The program utilizes thermal balance techniques to calculate dynamic hourly sensible and latent thermal loads for the building being simulated. BLAST also allows hourly simulation of the air handling system performance and of the central energy plant equipment operation; these features permit the program to be used for analyzing the thermal performance of commercial buildings as well as residences.

BLAST is currently being modified to allow performance analysis of passive solar systems. Models which describe the thermal processes occurring in passive solar structures are being developed and incorporated into the program. These activities will (1) provide

[†]This work has been supported by the Research and Development Branch, Passive and Hybrid Division, of the Office of Solar Applications for Buildings, U.S. Department of Energy, under Contract No. W-7405-ENG-48.

*Building Loads Analysis and System Thermodynamics. BLAST is copyrighted by the Construction Engineering Research Laboratory, U. S. Department of the Army, Champaign, Illinois.

a documented passive solar analysis program which is available to the building research and design professions and (2) produce an analysis tool which can be used specifically to evaluate the applicability of passive solar design concepts to commercial-scale buildings. In order to demonstrate the technical viability of the resulting program, comparisons between simulation results and measured data must be performed. This report summarizes the comparisons which have been made to date for direct-gain passive solar systems.

II. VERIFICATION METHODOLOGY

All building energy analysis computer programs use algorithms and models which provide approximate representations of the heat transfer mechanisms coupling the physical elements of the building to one another, to the environment, and to the internal energy sources and/or sinks. Many of the approximations are different from program to program; even within a single program, the significance of a particular approximation to the simulation result may change from building to building and/or from one climate or time period to another. In some applications of a program, the particular algorithms used might provide adequately accurate results but, if the program is used in another context, these same approximations might fail to faithfully predict performance. Additionally, the limitations and/or inadequacies in one algorithm can be disguised by inaccuracies in other algorithms. In order to provide full validation of a building energy analysis computer program, and to fully understand its limitations, the individual models and algorithms must be compared to experimental data for the full range of boundary conditions and excitations that might be encountered in practice; unfortunately, such validation is beyond the scope of currently available experimental data.

The computer program BLAST utilizes state-of-the-art algorithms, many of which are based on first principles of heat transfer and are thoroughly documented. The purpose of the work reported here is to provide a general verification of the program as a whole for a particular passive solar configuration within a specific range of climatic conditions. For the passive system examined, BLAST is shown to provide very accurate analyses; however, because the verification data base is limited in size and variable in quality, this conclusion is necessarily based on subjective evaluations of the net influence of many algorithms on the overall simulation results, rather than on quantitative comparisons between data and predictions from individual algorithms. For this reason, extrapolation of the program to substantially different climates or different types of structures must be accompanied by further verifications under the new use conditions.

The work reported here consists of comparisons between thermal data measured in a small test cell located at Los Alamos Scientific Laboratory and simulated results derived from BLAST. The weather data used to drive the BLAST simulations was accumulated simultaneously with the test cell data. Input to the computer program consisted of the measured geometry and materials data for the test cell, and included engineering estimates for those parameters which have not been measured. Section III of this report describes (1) the input variables and (2) the weather data manipulations necessary to convert measured information into BLAST compatible formats. Section IV presents the results of direct comparisons between measured and simulated results, and several statistical figures of merit derived from the comparisons.

In order to provide a basis for the subjective conclusions regarding the extrapolation of the results of this verification, several sensitivity studies have been performed. These studies examine the sensitivity of the simulation results to many of the estimated input parameters and to the dominant climatic variables. The results are presented in Section V. Section VI contains a discussion of the limitations of the verification and suggestions for further measurements which would eliminate many of the current uncertainties in the verification. Section VII summarizes the conclusions that have been reached during the verification.

III. VERIFICATION PROCEDURE

A. Blast Direct-Gain Model

Direct-gain analysis capabilities are inherent in BLAST; no changes to the basic program were necessary to perform the verifications reported here. A research version of the program called BLAST/MRT was used in this project; on completion of current software development tasks, the program will be released in the public domain as BLAST-3.0. A new thermal balance solution technique which has the capability to simultaneously analyze multizone configurations, has been incorporated into this version of the program.

BLAST utilizes the user-defined building geometry, materials properties, and construction details in the thermal balance solution. Solar transmission, reflectivity, and absorptivity of the user-defined glazing materials and assemblies are calculated as functions of the incident angle. Thermal conduction through the transparent and opaque surfaces of the building envelope and thermal storage within the building materials are calculated using response factor techniques [1] which are limited to one-dimensional heat flow.

Solar and infrared absorptivity of external and internal surfaces is accounted for and shading of external surfaces is analyzed dynamically [2]. No further description of the direct gain space or system is necessary.

In a BLAST/MRT simulation, the user can select either of two options for allocating internal solar gains among the surfaces of the zone being analyzed. In the normal simulation, eighty percent of the total transmitted solar radiation is presumed to fall on the surface(s) which define the floor. If there is more than one user-defined floor surface, the solar radiation is weighted among the surfaces according to their areas and solar absorptivities. The remaining twenty percent of the solar radiation transmitted through the transparent surfaces is distributed to all other surfaces defining the zone; again, the surface area and solar absorptivities are used to weight the distributions among surfaces. The second option consists of distributing all of the solar gains to all surfaces according to solar absorptivity and surface area weighting. Under either option, the solar energy is distributed uniformly over each surface. The hourly solution consists of performing simultaneous energy balances on all surfaces and the zone air, resulting in temperatures for each surface and the zone air. The energy balance on each surface considers:

- Convection to the room air;
- Dynamic one-dimensional conduction through the surface and, therefore, thermal storage within the materials;
- Thermal radiation to all other surfaces;
- Solar gains;
- Radiative gains from occupants, equipment, and lights.

The energy balance on the zone air considers:

- Convective gains from each surface;
- Convective gains from occupants, equipment, and lights;
- Infiltration of outside air;
- Convective gains from auxiliary heating and cooling equipment.

The version of BLAST to be released in 1980 will have two major improvements over this model. First, the solar radiation distribution on the internal surfaces of the zone will be dynamically calculated for each hour in the simulation. Second, the user will be able to specify movable insulation over any surface of the zone. This new model will provide both expanded and more precise direct gain analysis capabilities.

B. Test Room Description

The building used for the BLAST verification was one of a number of small passive solar test rooms built at the Los Alamos Scientific Laboratory in 1976-77. Appendix 1 provides a detailed description of the test room. These structures are well-insulated, and measure six feet wide by eight feet deep by ten feet high; the entire south-facing vertical surface is double-glazed with plexiglas sheeting. The simple standard design of the test rooms and careful monitoring of weather and temperatures make them very useful for research purposes. Data from this facility has been used for comparisons with several other computer codes (SUNSPOT [3,4], DOE-1 [5,6], DEROB [7]) as well as hand calculation techniques [8]. LASL has outfitted the test cells to investigate various passive solar concepts ranging from direct gain to convective loop configurations. In the direct gain test cell simulated by BLAST, a 14.6 cm (5-3/4") layer of solid concrete blocks lined the floor and the bottom portions of both side walls and of the back wall. All incoming direct sunlight fell on a concrete surface. A schematic section of the test room showing the location of storage mass on the floor and walls is included in Appendix 1.

Extensive thermocouple instrumentation allowed temperature measurements to be made on most surfaces, at various locations within the thermal storage material. In addition the mean radiant (globe) temperature and radiation shielded room air temperature were monitored. The measured air temperatures provide the basic verification information as described in Section D below.

C. Climatic Data

Hourly weather data collected at the test cell site by LASL included total solar radiation on a vertical surface, wind velocity, and outside dry bulb temperature. The temperature and wind speed data were provided in directly usable form. It was necessary to estimate corresponding wet bulb and sky temperatures, wind direction, and barometric pressure in order to complete the weather file input for BLAST. These estimates were made by observing and comparing Albuquerque Typical Meteorological Year (TMY) weather tapes for similar time periods and dry bulb temperatures. The solar data on these tapes is developed from measurements of solar radiation. Though this method is approximate, the sensitivity of the BLAST simulation results to these three parameters was shown to be small.

Incident solar radiation in the plane of the vertical south facing window was measured and reported by LASL but considerable manipulation was necessary in order to make the data compatible with the BLAST input requirements. The computer program input consists of hourly values for the horizontal diffuse solar radiation, direct normal radiation, and ground reflected radiation on a vertical surface. These figures are internally translated to the plane of each opaque and transparent surface defining the structure. Since only total vertical surface radiation was available, considerable difficulty was experienced in establishing an accurate and internally consistent direct/ diffuse breakdown. In particular, the component of solar radiation normal to a south-facing wall will inevitably include a ground reflected component which can, at times, be significantly larger than the diffuse sky radiation. In addition, during partially clear days, actual direct and diffuse radiation values can vary rather dramatically from the corresponding clear day values. The solar data utilized in the BLAST verifications reported here were calculated using the procedure described below.

In order to account for the variations in direct and diffuse radiation on both clear and cloudy days, a method was developed to convert the solar data reported by LASL to the necessary direct normal, diffuse horizontal, and ground reflected components based on a measure of "clearness" for each hour. Albuquerque TMY weather tapes were used as the best available information on which to base predictions of representative direct and diffuse radiation values at Los Alamos. The test cell site and Albuquerque are approximately 100 kilometers (65 miles) apart and have a 750 meter (2500 ft) altitude difference. TMY solar data recorded during the same periods of the year as those used in the verification simulations was reviewed, and typical direct normal and diffuse horizontal radiation values were established as a function of hour and clearness (0-100 percent of the clear day total). Using a 20 percent ground reflection factor, a corresponding ground reflected component (on a vertical south surface) was also calculated. All three radiation components were converted to percentages of the total solar radiation striking a south-facing vertical surface. These percentages were then applied to the total south facing vertical radiation data reported by LASL.

D. BLAST Input

Input to BLAST was prepared as specifically and as accurately as possible. The construction details, materials properties, geometry, and weather data were obtained from LASL personnel;* the weather data was manipulated as described in Section C above and the BLAST

*This and other necessary information concerning the test rooms and the site were obtained from Jim Hedstrom and John Moore of LASL.

input coding was carried out. Two features of the simulations---internal heat sources and infiltration---are discussed in this section.

Internal heat sources, such as people, lights, and equipment, are normally described by defining appropriate schedules. Thermostat control parameters for the heating and cooling systems, including linear throttling ranges and dead bands, are normally specified as input to BLAST. In the simple case of the direct gain test cell whose internal thermal activity responds only to environmental excitations, none of these schedules or controls were relevant and therefore no thermal loads were calculated.

No infiltration measurements were made in the test cells during the period simulated, nor have measurements been made to determine the dependence of infiltration on temperature or wind. Knowing the importance that infiltration can have, especially in a small building, it was important to understand both the calculations performed by BLAST to determine the air exchange rate, and the sensitivity of the calculation to changes in the specified infiltration rates.

BLAST infiltration calculations take the base rate defined by the user and modify it according to changes in wind speed (WS) and inside-outside temperature differential (ΔT). The base rate corresponds to an arbitrarily chosen design condition with a wind speed of 7.5 mph (3.35 m/sec) and a ΔT of 0. The infiltration rate varies as those parameters rise and fall, according to the formula:

$$\begin{aligned} \text{Infiltration Rate} &= \text{Base Rate} * (.606 + .0525 * \text{WS (mph)} + .0202 * \Delta T (^{\circ}\text{F})) \\ &= \text{Base Rate} * (.606 + .1177 * \text{WS (m/s)} + .036 * \Delta T (^{\circ}\text{C})) \end{aligned}$$

For a given user-specified base infiltration rate, the effects of windspeed and temperature difference can be substantial; factors of two or three in the infiltration rate are common during periods of low ambient temperatures.

The complete BLAST input is included in Appendix 2.

E. Quantification of the Verification

The actual verification consists of comparing the hourly test cell air temperature measurements and the air temperatures predicted by the BLAST simulation. As will be shown in Section IV below, excellent qualitative agreement was obtained. In order to quantify this comparison, the following figures of merit have been calculated for each verification period:

- Maximum temperature difference;
- Average difference in diurnal temperature swing;
- Average of the absolute temperature difference;
- Time-integrated RMS temperature difference.

Use of these quantitative figures of merit permits more discriminating comparisons of the predictions of the various models which are currently in use to simulate passive systems.

IV. VERIFICATION RESULTS

A. February

The verification simulations were performed for three time periods with different weather and solar conditions. No complete summer measurements were available at the start of the verification. Figure 1 shows the results of the BLAST simulation in comparison to the measured data from Los Alamos for the February-March period. The general shape of the curve matches the measured data reasonably well, and responds in a similar manner to sudden environmental changes. The accuracy of the nighttime prediction is especially good. The important discrepancy is the evaluation of the daytime peaks, for which the prediction consistently falls short of the measured temperature. Despite this, by sundown each day the simulation is again highly accurate. Furthermore, no cumulative differences are observed during over the seven-day simulation period.

The absence of systematically increasing deviations between the measured and simulated test room parameters implies that the simulation is accounting properly for the solar gains and thermal losses from the test cell; however, the consistent deviations during the mid-day period indicates that BLAST may be overestimating the effectiveness of the thermal mass, overestimating the coupling of the solar excitations to the thermal storage, or underestimating the convective coupling of the air to the storage mass.* This question is discussed in Section VI (sensitivities). The quantitative figures of merit (Fig. 4a) reflect the situation described. Although the largest temperature differentials are significant [$6-7^{\circ}\text{C}$ ($10-12^{\circ}\text{F}$)] these occur in only a few hours; the average, and even the RMS temperature differentials

*Goldstein [8] has calculated the thermal capacity from measurements made on the concrete in the test cells. He finds the specific heat to be only 64 percent of the standard value assumed by LASL and used in the BLAST simulation. This effect was investigated and results are presented in Section V.

XBL 806-7123

FIGURE 1

[1.4°C (2.5°F) and 2.0°C (3.6°F), respectively], are creditable. Naturally the differences in diurnal temperature swings are similar to the maximum temperature differentials, because the predicted minimum night temperatures are nearly identical to the measured values. The bias toward measured values higher than the BLAST prediction results from the day-long effects of BLAST'S underestimation of the peaks.

B. September

The BLAST simulation for the September period is plotted with the measured data in Fig. 2. It is clear that the data is tracked with considerable accuracy throughout all ten days. No systematic discrepancies are visible over the entire period.

The figures of merit shown in Fig. 4b indicate how well BLAST performs in this instance. More than two-thirds of the hours are predicted within less than 0.5°C (0.9°F), the average being only 0.4°C (0.7°F). When one considers that rounding errors for the measured data average 0.14°C (0.25°F), the accomplishment becomes even more apparent. No hour has a temperature differential of more than 1.8°C (3.3°F). Even the diurnal temperature swings show a maximum of 1.1°C (2.0°F) and an average of 0.5°C (0.9°F) difference between predicted and measured values.

C. December

The qualitative comments applied to the September comparison (Fig. 2) are also appropriate for the December data displayed in Fig. 3. The accuracy is somewhat lower; the figures of merit in Fig. 4c are all about twice those of the September comparison, with the exception of the maximum temperature difference, which is only about 35 percent higher. More specifically, the predictions for almost two-thirds of the hours are within 1.0°C (1.8°F) or less, and in only three hours does the difference exceed 2.0°C (3.6°F). Again, there appears to be no long-term divergence. As in the February comparisons (Fig. 1), the curves suggest an overestimation of effectiveness of thermal storage. This would account for the consistent 1-2°C (2.3°F) underprediction during the warmup and peak temperature periods, and the delayed temperature degradation during the final three days of diminished solar radiation.

V. VERIFICATION SENSITIVITIES

Since a few of the BLAST input parameters were based on subjective estimates, and since some of the internal parameters and procedures used in BLAST are approximations, especially when applied to a test cell, several sensitivity studies were performed. It is by such

XBL 806-7121

FIGURE 2

XBL 806-7128

FIGURE 3

FIGURES OF MERIT:

- AVE. ABSOLUTE TEMP DIFFERENCE
- ⊙ AVE. TEMP DIFFERENCE
- TIME INTEGRATED ROOT-MEAN-SQUARE OF TEMP DIFFERENCE
- ◇ MAXIMUM TEMP DIFFERENCE
- DIURNAL TEMP SWING DIFFERENCE
- ▽ AVE. ABSOLUTE DIURNAL TEMP SWING DIFFERENCE
- △ AVE. DIURNAL TEMP SWING DIFFERENCE

DISTRIBUTION OF HOURLY TEMPERATURE DIFFERENCES

HOURLY TEMPERATURE DIFFERENCES

DIURNAL TEMPERATURE SWING DIFFERENCE

POSITIVE VALUES INDICATE MEASURED DATA GREATER THAN BLAST SIMULATION PREDICTION

FIGURE 4

studies that the reliability of the verification and efficacy of extrapolations of the model to full scale buildings can be judged.

The parameters chosen for sensitivity examination were those which:

- (1) Were most uncertain as BLAST input:
 - infiltration level
 - direct/diffuse split of the solar flux
- (2) Test the correctness of the approximations in the direct gain model of BLAST:
 - distribution of transmitted solar radiation on internal surfaces
 - values of the internal surface convection coefficients
- (3) test the response of the model to variations in the environmental excitations of the direct gain space:
 - solar absorptivity of external surfaces
 - total solar flux
 - steady state U-values of the opaque envelope surfaces
 - exposed area, thickness, and specific heat of the thermal storage mass.

A high degree of sensitivity of the simulation to these individual parameters would indicate areas where extrapolation of the model to other climates, buildings, and/or building scales should be accompanied by careful measurements of the parameters as part of additional verification activities. Results from each of these sensitivity studies are presented below.

A. Infiltration

Infiltration sensitivity runs were made at 0.0, 0.0021, and 0.0064 CMS (0.0, 4.5, and 13.5 CFM respectively). These correspond to no infiltration, 0.5 times, and 1.5 times the base rate of 0.0042 CMS (9 CFM) used in the verification simulations (where 1 air change = 0.0026 CMS = 5.5 CFM). Although this base rate may seem high for a well constructed building, it may be reasonable when one considers the very high surface-to-volume ratio of the small test cell and the very large temperature differentials encountered. The results of the infiltration sensitivity studies are summarized in Fig. 5.

FIGURE 5

As shown, the BLAST temperature predictions were very sensitive to the infiltration rate, shifting by three to four degrees Celsius for a 50 percent change. Such a change in infiltration rate increased the average temperature differences from 0.4 to 1.3°C (0.7 to 2.3°F) in September and from 0.8 to 2.8°C (1.4 to 5.0°F) in December. Even an accurate "best guess" for the actual infiltration cannot be made in the absence of detailed information on construction tightness and microclimatic effects at the test cell site. However, the simulation's lack of any systematic drift away from the measured temperatures, even over 5-10 day simulation periods, tends to increase confidence in the infiltration levels used. The sensitivity runs showed that the same base infiltration rate (9 CFM) gave the best results for each time period, further substantiating the input estimates. Of course, there is always the possibility of offsetting discrepancies in U-values, especially for the glazing, but the materials properties are far less prone to large errors.

B. Direct/Diffuse Split

Due to the uncertainty in the breakdown of total radiation into direct and diffuse components, the sensitivity of the simulation to different proportions was tested, as shown in Fig. 6. The effect of this change during September days is seen to be rather insignificant and only evident during peak solar hours (the average absolute temperature difference increased only imperceptibly). This effect can be attributed to similar values of direct and diffuse solar transmittance through the plexiglas window due to the sun angles at this time of year. The shift of direct radiation to diffuse radiation has a more dramatic influence during December, when the direct solar transmittance is noticeably larger. The average temperature difference in December was doubled.

C. Solar Radiation Distribution

Redistribution of the solar gains among the internal surfaces produced little change. In the previous simulations, 80 percent of the transmitted radiation was distributed evenly over the floor surface—the other 20 percent was uniformly distributed on the concrete surfaces of the walls. In Fig. 7, the effect of reversing the allocation is shown. In all the sensitivity runs, this redistribution produces larger diurnal temperature swings. This may be partly responsible for the consistent under-prediction by the BLAST simulation of the peaks in the February time period. In an additional test, the 20 percent of the total radiation originally distributed to the inside surfaces of the walls was concentrated entirely on the concrete portion of the back (north) wall. The change in prediction was extremely small.

FIGURE 6

XBL 806-7131

FIGURE 7

D. Convection Coefficients

The effects of changing the convection heat transfer coefficient between the air and the concrete floor of the test cell was studied in two sensitivity runs; values of $2.02 \text{ W/m}^2\text{C}$ and $8.08 \text{ W/m}^2\text{C}$ were used. These correspond respectively to 0.5 and 2.0 times the value of $4.04 \text{ W/m}^2\text{C}$, which is the standard BLAST assumption* (see Fig. 8). As expected, changes in the predicted temperatures are most evident during peak solar hours when heat flow rates within the test cell are at a maximum. During September, despite underpredicting the peaks by 1°C or more, halving the convection coefficient left the average and RMS temperature differences virtually unchanged; temperature predictions during nighttime loss mode hours had actually improved slightly. Doubling the convection coefficient led to higher predictions and nearly doubled the average RMS temperature differences. On the other hand, during December days, doubling the convection coefficient improved the BLAST temperature predictions during peak solar hours. Also during December, doubling the convection coefficient resulted in slightly lower average and RMS temperature differences than those obtained by halving the convection coefficient.

Initial results from these sensitivity runs lead one to question the assumption presently made by all building energy analysis programs that surface convection heat transfer coefficients are constant over time. This suspicion has been voiced earlier by Bauman et al. [9] and Gadgil et al. [10]. Particularly during those periods when solar gains provide surface temperatures much higher than the air, use of a higher convective coefficient during peak solar hours may be necessary in order to properly represent the thermal behavior of a building. However, as shown in Fig. 8, increasing the convection coefficient during December caused poorer prediction of nighttime conditions when the surface/air temperature differences are smaller. Indications are that during the September period, the higher convection coefficient ($8.08 \text{ W/m}^2\text{C}$) is not required for accurate prediction of the test cell temperature during peak solar hours, and, in fact, a lower coefficient may be appropriate during nighttime hours. These results imply that the convection coefficients may be quite sensitive to the temperature difference between the surface and air and that accurate simulations may require calculation of the convection coefficients based on current conditions. This too is consistent with the results of references [9] and [10].

*For nonvertical surfaces, BLAST assumes a convection heat transfer coefficient which is dependent on the temperature difference between the surface and the adjacent air. The temperature difference dependence is limited, however; the convection coefficient changes from hour to hour during the simulation only in response to the direction of heat flow. For horizontal surfaces with heat flow vertically upward (downward), a value of $4.04 \text{ W/m}^2\text{C}$ ($0.97 \text{ W/m}^2\text{C}$) is used. For the time period during which this sensitivity was examined, the test cell floor was always warmer than the test cell air.

FIGURE 8

E. External Surface Absorptivity

The effect of solar absorptance on the opaque exterior surfaces was tested with two simulations spanning the range of possible surface absorptivities (External Absorptivity = 0.0–1.0). As shown in Fig. 9, a change from the default solar absorptance value of 0.75 to 0.0 or 1.0 resulted in shifts in the temperature predictions of up to 1 degree Celsius, particularly during the afternoon peaks. Although solar absorptivity on the external surfaces is not a dominant excitation of the test room, it is non-negligible when compared to the differences between the predictions and measurements. There is only a slight change in the temperature profile when the absorptivity is changed; the freedom one has in selecting an infiltration rate can mask the effects of this excitation.

F. Total Solar Flux

The sensitivity of the prediction to the total amount of solar energy entering through the window was examined. Figure 10 shows that when the transmitted solar energy was increased or decreased by 20 percent, substantial changes in the test cell temperatures were observed—an increase produced average absolute temperature differences which were 2.6 and 3.3°C (4.7 and 5.9°F) higher than the base runs for September and December, respectively. Again, the qualitative shape of the inside temperature profiles were not substantially altered so uncertainties can be masked by infiltration adjustments. By comparing the results from the September and December time periods, it is apparent that the effect of a given increment of solar gain diminishes rapidly as the inside temperature rises and the heat losses increase. The case with no solar gain is predictably close to the average outside temperature, indicating the degree to which the test cell is dominated by solar.

No reflection back through the window is accounted for in BLAST. This is expected to reduce the solar effect 2–5 percent, which, judging from Fig. 10, would cause a small but noticeable downward shift of the curve.

G. Thermal Resistance of Opaque External Surfaces

Figure 11 shows the sensitivity to the steady-state U-value of the insulated wall surfaces. Here, too, the shape of the temperature profile is relatively insensitive to the value of the parameter. As could be expected for the structure being simulated, thermal losses are obviously dominated by conduction through the glazing and/or infiltration losses.

FIGURE 9

XBL 806-7120

FIGURE 10

FIGURE 11

H. Thermal Storage Mass

Measurements in the test cell indicated that the exposed edges of the 5.5 inch (0.14 m) thick concrete walls added 18.5 percent to the surface exposure between the thermal mass and the room air. This additional area was not taken into account in the original BLAST simulations. Two sensitivity runs were made to investigate the effect of this difference. Figure 12a shows results when the total thermal mass of the test cell was kept constant by reducing the thickness of the concrete walls by 18.5 percent. In Fig. 12b the thermal storage capacity of the test cell was kept constant by reducing the specific heat of the concrete by 18.5 percent. The simulations are surprisingly insensitive to substantial changes in these parameters. This implies that the test cell is substantially over-massed; relatively little of the concrete thickness is participating in diurnal storage.

The effect of altering the thermal storage capacity of the mass in the test cell was studied by changing the specific heat of the concrete by ± 25 percent (Fig. 13). The most noticeable result was the moderating influence of the mass on diurnal temperature swings; during most days the diurnal swings are reduced $1\text{--}2^{\circ}\text{C}$ ($1.8\text{--}3.6^{\circ}\text{F}$) when the thermal capacity is increased. In general, the value of the specific heat of the storage materials should be known within the limits used in the sensitivity study. However, where the value is in doubt (variable moisture content of materials or unknown properties of concrete aggregate), appreciable errors in prediction performance could be experienced, especially in terms of temperature swings. The small magnitude of the changes in this case can be explained by the proportionately large quantity of mass in the test cell to begin with.

If the amount of mass is more carefully sized than in the test cell, the total exposed area of the thermal mass in a solar structure or its total thermal capacity could potentially play an important role in changing the effectiveness of the mass.

The effect of lowering the concrete specific heat to 64 percent of its standard assumed value, as suggested by Goldstein [8], was investigated for all three test periods. Although little effect was seen during the September and December periods, results for February are shown in Fig. 14. As expected, the difference between the BLAST predictions of average absolute diurnal temperature swings and the LASL measurements was reduced, from 3.8°C (6.8°F) to 1.8°C (3.2°F); however, the effectiveness of the thermal mass in moderating the test cell air temperature during nighttime heat loss periods was reduced. The net result was a poorer overall agreement between the BLAST and LASL test cell air temperatures. The average absolute temperature difference is 2.1°C (3.8°F), and the time-integrated RMS temperature difference is 2.5°C (4.8°F); the previous values were 1.5°C (2.7°F) and 2.0°C (3.6°F), respectively.

FIGURE 12A

FIGURE 12B

FIGURE 13

FIGURE 14

VI. LIMITATIONS OF THE VERIFICATION

The BLAST simulation results provide a high degree of confidence in the ability of the program to analyze direct gain structures; however, several limiting features of the verification should be noted:

A. Infiltration

The question of infiltration rate is very important when viewed in the context of other attempts to verify programs. As noted earlier, the verification reported here used a best estimate value of approximately 1.6 air changes per hour; in order to get good agreement with the test cell data, rates of 0.25–2.5 air changes have been used* by different researchers. The magnitude of such differences can be seen in Fig. 5; adjustments to the infiltration rate can obscure uncertainties in several other simulation parameters. The range of these estimates completely masks many more subtle differences, and inhibits useful comparisons. In the present case, having used the same base infiltration rate for three seasons, in which its effect would be very different, and having maintained accuracy in the results, some confidence is felt in the infiltration estimate. Some physical measurements of the test cell in question are clearly required in order to remove the uncertainty of the infiltration estimates. LBL has recently begun experimentally measuring the infiltration rate of the Los Alamos direct-gain test room.

B. Solar Radiation

Most important to the proper simulation of the test cell is a specific set of solar radiation data, particularly a distinction in the solar data between direct and diffuse (or ground reflected) radiation. Because of the differences in transmission between these two components of the solar excitation, large discrepancies at certain times of day and year can result from an improper allocation of the

*The SUNSPOT simulation used ~1 air change, based on a crack calculation [4]. DOE-2 simulations have used 1.0 and 2.5 air changes [5,6]. Goldstein used ~1/4 air change with his hand calculation method [8].

total radiation. Figure 6 illustrates the point. Because of the importance of solar gains in the simulation (Figs. 6, 7, 9, and 10), more complete solar data should have high priority for instrumentation of future test buildings.

C. Operating Schedules

No internal loads are treated in the test cells: they are unoccupied, and contain no lights or equipment. This project does not verify BLAST for those load calculations dealing with the internal loads which would occur in a standard building. Since no auxiliary heating or cooling equipment is included in the test cell, no thermal loads are calculated. The verification cannot be extrapolated directly to a direct gain system that includes conventional back-up systems.

D. Solar Domination

The test cell has virtually the entire south face, more than one square foot of glazing for each square foot of floor area, devoted to direct gain glazing. As a result, the test cell is extremely sensitive to solar gains, much more so than conventional passive buildings would be. (Compare temperatures with and without sun, Fig. 10.) Solar dominance will result in high surface temperatures relative to conventional structures, as evidenced by the high interior air temperature encountered during the measurement period. The effects of buoyancy driven convection may be exaggerated and convection coefficients may be artificially large as a result. This, together with the large surface area to volume ratio noted above, results in a very strong convection component in the energy balance.

E. Scale

The size of the test cell in relation to a full scale building has several implications:

- The internal surface area to volume ratio of the test cell is large relative to an occupied building. Convective coupling of the surfaces to the room air is exaggerated in comparison to the other heat transfer processes occurring at the surface.
- As observed in Section D above, the glazing area to total internal surface area is large relative to occupied buildings. The solar gain component of the energy balance at each internal surface will be exaggerated in comparison to other heat transfer mechanisms. Likewise, conductive losses will be dominated by the window considerably more than in a real building. Conductive losses through opaque envelope surfaces are correspondingly small in the test cell.

- The small volume of the test cell implies that multi-dimensional conductive heat flow effects may be exaggerated in comparison to an occupied building where wall, floor, and ceilings are much more expansive.
- The room is empty, so all interior surfaces radiate to each other. There are no light furnishings or partitions to participate in the energy balance on the test cell air.

VII. CONCLUSIONS

Qualitatively, it is clear that the BLAST model provides a creditable representation of a direct-gain test cell, subject to three qualifications—these comparisons do not deal with internal loads, latent loads, or auxiliary mechanical systems. The predictions of BLAST are always very close to the actual measurements. The average differences are 1.4, 0.4 and 0.8°C (2.5, 0.7, 1.4°F) for the three simulated periods. Sudden test cell temperature changes due to sun, outside temperature, and/or wind are invariably reflected in the BLAST simulations. In all three simulation periods, there is no long-term systematic shift away from the measured data points, even over a ten-day period.

The discrepancies observed here between measured thermal parameters and BLAST predictions are consistently within the uncertainties resulting from estimated input parameters. However, the verification presented here cannot be directly transferred to full scale occupied buildings, especially those which have loads influenced to a large degree by internal loads or mechanical systems, or which consist of more than one heating or cooling zone. However, those techniques in BLAST which deal with the dominant characteristics of the test cell (solar gains, thermal storage, materials properties, infiltration) have been shown to work quite well, and buildings where these characteristics play a similar role can be analyzed by BLAST with confidence.

It is clear that further verification is needed. Additional building types, other passive systems, and other simulation programs should be rigorously investigated. Specific building types should be identified, and suitable examples should be found, thoroughly instrumented, and strictly controlled for periods long enough to provide sufficient data for verification.

One by-product of this investigation is worth noting. It became very clear that there are a great many subtle effects within BLAST which can make important differences in the results. (This is also generally true of other comprehensive building energy analysis programs.) Calculation and adjustment methods for solar gains and infiltration are two good examples. Dependence on such programs for information on which to base design decisions should be accompanied by a thorough appreciation of the sensitivity of the results to variations in the assumptions and/or input parameters. To avoid the risk of both misinterpretation and over-reliance, users should ensure that experienced personnel participate in the interpretation of the simulation results in terms of design decisions.

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APPENDIX 1. DIRECT GAIN TEST CELL DESCRIPTION*

I. GENERAL DESCRIPTIONI.A. Description of the Environment

The test cell is located in Los Alamos, New Mexico, at an elevation of 2259 m (7410 ft), a latitude of 35° 52' N, and a longitude of 106° 19' W. The site is situated in a cleared area, thus void of any shading due to trees or neighboring buildings. Ground cover at the site is primarily made up of dirt and gravel beds, with natural grasses and brush beginning to dominate at approximately 20 meters. According to the AIA/RC regional climate classification, the structure is located in climate region 4. The average winter temperature is 0.6°C (33°F), with an average temperature of -1.7°C (29°F) in January. There are approximately 3515°C days (6307°F days) in a typical winter, and the winter design temperature is -15.0°C (5°F).

I.B. Description of Building

The test cell has interior dimensions of 3.09 m (10.1 ft) high 1.59 m (5.2 ft) wide and 2.24 m (7.3 ft) deep, excluding the mass storage walls. The exterior walls of the cell are constructed of:

- (a) 1 in. polystyrene insulation ($R = 5.4$ in.)
- (b) 2 x 4 stud frame with 3-1/2 in. fiberglass batt insulation
- (c) 5/8 in. exterior plywood painted white.

A breakdown of the ceiling construction is as follows:

- (a) 26 galv. Wheeling Verco Metal (corrugated)
- (b) 2 x 6 ceiling joist with 2 layers, 3-1/2 in. fiberglass insulation
- (c) 2 x 4 roof rafters with air space
- (d) 5/8 in. plywood decking
- (e) one layer 90 percent roll roofing over one layer 30 percent felt.

I.C. Description of Passive Solar System

The passive solar system of the Direct Gain cell utilizes 4.09 m² (44.0 ft²) of double pane 3.2 mm Plexiglas G glazing with 25 mm (1.0 in.) airspace between panes. The glazing is justified by 3808 kg (8736 lb) of mass with an exposed surface area of 13.2 m² (142.6 ft²).

*This description is adapted from R. D. Busch, "Passive Solar Data from the Los Alamos Scientific Laboratory," Bickle/CM, Inc., for the Solar Energy Research Institute.

DIRECT GAIN
TEST CELL

XBL806-7147

FIGURE A-1

The thermal mass is composed of a high density "pea gravel" block, 2164 kg/m^3 (135 lb/ft^3) with dimensions of 0.194 m (0.365 ft) in width by 0.395 m (1.297 ft) in length by 0.143 m (0.469 ft) thick and is untreated on the exposed surface. The amount of mass and exposed surface area by location is as follows:

(1) Floor	997 kg (2288 lb),	2.74 m^2 (29.5 ft^2)
(2) East wall	1088 kg (2496 lb),	3.71 m^2 (39.9 ft^2)
(3) North wall	635 kg (1456 lb),	2.78 m^2 (23.4 ft^2)
(4) West wall	1088 kg (2496 lb),	3.71 m^2 (39.9 ft^2)

There are no vents in the cell and the temperature is allowed to float. The cell is externally shaded by an overhang of length 0.356 m (1.167 ft) located 0.432 m (1.417 ft) above the glazing. This provides some protection against the summer sun while allowing the winter sun to fall on the glazing.

I.D. Description of Data Acquisition System

Temperature Measurements

Temperature sensors are type K (chromel-alumel CR/AL) having a measured repeatability of $\pm 0.3^\circ\text{C}$ ($1/2^\circ\text{F}$). These sensors have continuous unspliced leads and are used in several ways:

- (1) Outside ambient drybulb temperature was obtained using a bare, unshielded thermocouple located on the shaded, north exterior wall.
- (2) Indoor globe temperature was obtained using a black-painted toilet bowl float with thermocouples located at the interior center. The device gives an approximate measure of mean radiant temperature and is located at the center of the cell near ceiling height.
- (3) Storage wall temperature was measured and recorded rather extensively by LASL. Data points taken include: a three-point rake of the North and West wall at mid planes, a three-point rake of the floor at three different locations (front, mid, rear), and a two-point rake (mid, backside) of the East wall. Only the sunside and backside surface temperature of the North, West, and floor storage masses along with the East wall mid point temperature are published in this report. Thermocouples were cemented 3.2 mm ($1/8 \text{ in.}$) beneath the surface of the blocks using an aluminated particle epoxy.

Radiation Measurements

Total solar radiation on a vertical plane was measured using a Eppley PSP pyranometer vertically mounted on a support standard beside the test cells. This device has a reported cosine error of ± 1 percent for 0° – 70° and ± 3 percent for 70° – 80° zenith angles.

Data Recording

All data is recorded at hourly intervals using a Hewlett-Packard HP9830 Data Logger. Sensed voltage samples for each channel are taken at approximately one-second intervals and the accumulated average is printed at scan time.

II. SYSTEM THERMAL PROPERTIES

II.A. Building Variables

(1) Interior Dimensions:	3.09 m (10.1 ft) high 1.59 m (5.2 ft) wide 2.24 m (7.3 ft) deep
(2) Glazing Area:	4.09 m ² (44.0 ft ²)
(3) Glazing Transmittance:	0.85 per pane
(4) Glazing U-value:	2.44 W/m ² °C (0.43 Btuh/ft ² °F) for double pane
(5) Total Mass:	3808 kg (8736 lbs)
(6) Mass Heat Capacity:	920 W-hr/°C (1747 Btu/°F)
(7) Mass Surface Area:	13.2 m ² (143 ft ²)
(8) Solar Absorptance of Mass:	0.65-0.70
(9) Building Heat Load Factor:	18.1 W/°C* (34.3 Btuh/°F)*
(10) Infiltration:	no measurements or control during the simulation period.
(11) Ventilation:	None
(12) System Operating Energy:	None
(13) Internal Heat Sources:	None
(14) Thermostat Setpoint:	No thermostat

*Calculated using standard ASHRAE techniques.

APPENDIX 2:

BLAST INPUT

```

BEGIN INPUT;
RUN CONTROL?
    NEW ZONES,
    REPORTS (CONTINUOUS,WALLS,ZONE,SHADE,23),
    UNITS(IN=ENGLISH,OUT=METRIC);
DEFINE MATERIALS?
DOUGLAS FIR 3 1/2    =(L=.292, K=.0667, CP=.33, D=32);
PLYWOOD 1/4         =(L=.0208, K=.0667, CP=.29, D=34,
    MEDIUM SMOOTH);
PLYWOOD             =(L=.0208, K=.0667, CP=.29, D=34,
    ABS=.00, MEDIUM SMOOTH);
PLYWOOD TAR 1/4     =(L=.0208, K=.0667, CP=.29, D=34,
    ABS=.30, MEDIUM SMOOTH);
STUD INS 3 1/2      =(L=.292, K=.0316, CP=.295, D=8.375);
STYRO INS 1         =(L=.083, K=.0230, CP=.29, D=1.00, ABS=.01);
COR STEEL           =(L=.005, K=26.2, CP=.12, D=489, ABS=.01);
PLEXIGLAS 1/8       =(GLASS, ABS=.01, R=.023, TRANS=.85, VERY SMOOTH);
AIRSPACE 3/4        =(AIR, R=1.10);
AIRSPACE 1          =(AIR, R=2.06);
AIRSPACE 12         =(AIR, R=1.09);
CONCRETE 5 3/4      =(L=.479, K=.7576, CP=.20, D=129);
CONCRETE            =(L=.479, K=.7576, CP=.20, D=129, ABS=.01);
END MATERIALS;
DEFINE ROOFS?
    ROOF 1          =(PLYWOOD TAR 1/4, AIRSPACE 12, STUD INS 3 1/2,
    AIRSPACE 1, COR STEEL);
END ROOFS;
DEFINE WALLS?
    WALL 1          =(PLYWOOD 1/4, DOUGLAS FIR 3 1/2, STYRO INS 1);
    WALL 1A         =(PLYWOOD, DOUGLAS FIR 3 1/2, STYRO INS 1);
    WALL 2          =(PLYWOOD 1/4, STUD INS 3 1/2, STYRO INS 1,
    CONCRETE 5 3/4);
    WALL 2A         =(PLYWOOD, STUD INS 3 1/2, STYRO INS 1,
    CONCRETE 5 3/4);
    WALL 3          =(PLYWOOD 1/4, STUD INS 3 1/2, STYRO INS 1);
    WALL 4          =(STYRO INS 1, STUD INS 3 1/2, STUD INS 3 1/2,
    STYRO INS 1, CONCRETE 5 3/4);
    WALL 5          =(STYRO INS 1, STUD INS 3 1/2, STUD INS 3 1/2,
    STYRO INS 1);
    WALL 6          =(PLYWOOD 1/4, STUD INS 3 1/2, STYRO INS 1,
    CONCRETE);
    WALL 7          =(PLYWOOD, STUD INS 3 1/2, STYRO INS 1);
    WALL 8          =(PLYWOOD, STUD INS 3 1/2, STYRO INS 1,
    CONCRETE);
END WALLS;

```

DEFINE FLOORS?

FLOOR 1 =(PLYWOOD 1/4, STUD INS 3 1/2, STYRO INS 1,
CONCRETE 5 3/4);

FLOOR 2 =(PLYWOOD 1/4, STUD INS 3 1/2, STYRO INS 1,
CONCRETE);

END FLOORS;

DEFINE WINDOWS?

WINDOW 1 =(PLEXIGLAS 1/8, AIRSPACE 3/4, PLEXIGLAS 1/8);

END WINDOWS;

DEFINE CONTROLS (NONE)?

PROFILES?

NOTHING = (1. AT 32.0. AT 32., -0 AT 120,-1 AT 120);

SCHEDULES?

MONDAY THRU SUNDAY = (00 TO 24 - NOTHING),

HOLIDAY = SUNDAY;

END CONTROLS;

DEFINE LOCATION?

LOS ALAMOS =(LAT=35.9, LONG=106.3, TZ=7);

END LOCATION;

PROJECT = #LASLSTC#;

LOCATION = LOS ALAMOS;

WEATHER TAPE FROM 14 SEP 78 THRU 24 SEP 78;

GROUND TEMPERATURES = (67,65,65,68,73,78,82,84,84,81,77,72);

BEGIN BUILDING DESCRIPTION;

DIMENSIONS?

N=0, E=90, S=180, W=270;

ZONE 1 #PASSIVE SOLAR TEST CELL#?

EXTERIOR WALLS?

STARTING AT (0,7.52,0)

WALL 3 (3.51 BY 10.06)

FACING (W),

STARTING AT (0,4.01,0)

WALL 5 (4.01 BY 10.06)

FACING (W),

STARTING AT (0,7.52,10.06)

WALL 3 ((7.52,0),(7.52,0.17))

FACING (W),

STARTING AT (5.25,7.52,0)

WALL 6 (5.25 BY 4.52)

FACING (N),

STARTING AT (5.25,7.52,4.52)

WALL 3 (5.25 BY 5.54)

FACING (N),

STARTING AT (0,0,0)

WALL 1 (5.25 BY 10.23)

FACING (S)

WITH WINDOWS OF TYPE

WINDOW 1 (4.85 BY 9.08)

AT (.20,.48)

WITH OVERHANGS (10.83 BY 1.50)

AT (-.17,11.06);

PARTITIONS?

STARTING AT (5.25,0,0)

WALL 4 (4.09 BY 10.06)

FACING (E),

STARTING AT (5.25,4.09,0)

WALL 5 (3.43 BY 10.06)

FACING (E),

STARTING AT (5.25,0,10.06)

WALL 5 ((7.52,0),(0,0.17))

FACING (E);

ROOF?

STARTING AT (5.25,7.52,10.06)

ROOF 1 (5.25 BY 7.52)

FACING (N) TILTED (1.30);

EXPOSED FLOOR?

STARTING AT (0,7.12,0)

FLOOR 1 (5.25 BY 7.12)

FACING (S);

INFILTRATION = 9,CONSTANT;

CONTROLS = NONE, 0 HEATING, 0 COOLING;

PEOPLE = 0,CONSTANT;

LIGHTS = 0, CONSTANT;

ELECTRIC EQUIPMENT = 0,CONSTANT;

END ZONE;

END BUILDING DESCRIPTION;

END INPJT;

=OR