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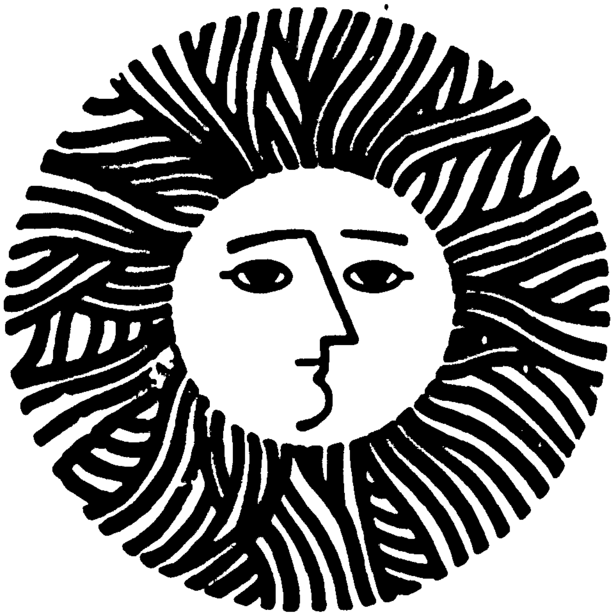

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VERIFICATION OF BLAST BY COMPARISON WITH MEASUREMENTS OF A SOLAR-DOMINATED TEST CELL AND A THERMALLY MASSIVE BUILDING*

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ABSTRACT

As part of an ongoing effort to use empirical data to test the computational accuracy of the building energy analysis computer program BLAST,[+] two verification studies are reported. In the first, comparisons between temperatures measured in a direct solar gain test cell and temperatures predicted by the program have been made. The comparisons were performed for two distinct climate periods; the simulations were driven by weather data collected at the test cell site in Los Alamos, New Mexico. The test cell configuration 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.

In the second study, comparisons of BLAST predictions to temperatures and loads measured in a massive structure have been carried out. These tests represent a first step in verifying the program's ability to (1) calculate full-scale building loads and (2) accurately model hybrid cooling using forced ventilation. The structure, its controlled external environment, and the tests conducted are described; results of completed comparisons and anticipated future simulations are discussed.

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 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 two comparisons which have been made to date. More comprehensive reports of these activities are available on request [1,2].

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 approxima-

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

tions differ 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 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 [3]. The purpose of the work reported here is to provide general verification of the program as a whole, for particular passive solar configurations within specific ranges of climatic conditions. For the passive systems examined, BLAST is shown to provide very accurate analyses. However, extrapolation of the program to different climates or different types of structures must be accompanied by further verifications under the new use conditions.

Two verification efforts are summarized here. In the first, comparisons between thermal data measured in a small test cell located at Los Alamos Scientific Laboratory and simulated results derived from BLAST have been performed. The weather data used to drive the BLAST simulations were 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 input values. Section IV presents the results of direct comparisons between measured and simulated results, and several statistical figures of merit derived from the comparisons. In addition, in order to provide a basis for the extrapolation of the results of the direct gain test cell 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. Results of some sensitivity studies 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.

The results of the test cell verification imply that the program is capable of accurately representing a configuration in which the building's thermal performance is dominated by heat transfer through glazings (solar gains and conductive losses) combined with the redistribution of the resulting thermal energy among internal surfaces. However, the test cell comparisons do not provide a thorough test of thermal storage in massive construction and in particular, conductive losses through a thermally massive building envelope. In addition, the test cell data does not allow testing of the thermal load calculations. For this reason, a second verification has been carried out. In this case comparisons have been made between BLAST predictions and measured data from a massive building located in a controlled environment inside a test chamber at the National Bureau of Standards. Section VII describes the structure, the conditions imposed upon it through the controlled external environment, and initial results of the comparisons.

Section VIII summarizes the conclusions that have been reached during the verification process to date.

III. TEST CELL 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.

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 [4] 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 [4]. No further description of the direct gain space or system is necessary.

In a BLAST/MRT simulation, the user can determine how the solar gain is distributed among the surfaces, although it is distributed uniformly over a given 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;

- 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 near the end of 1981 (BLAST-3.0) will have three 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. Third, convection coefficients will be dynamically calculated, based on hourly air and surface temperatures. 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 [6]. A cross-section of the direct gain test room is shown in Fig. 1. This structure is well-insulated, and measures 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.

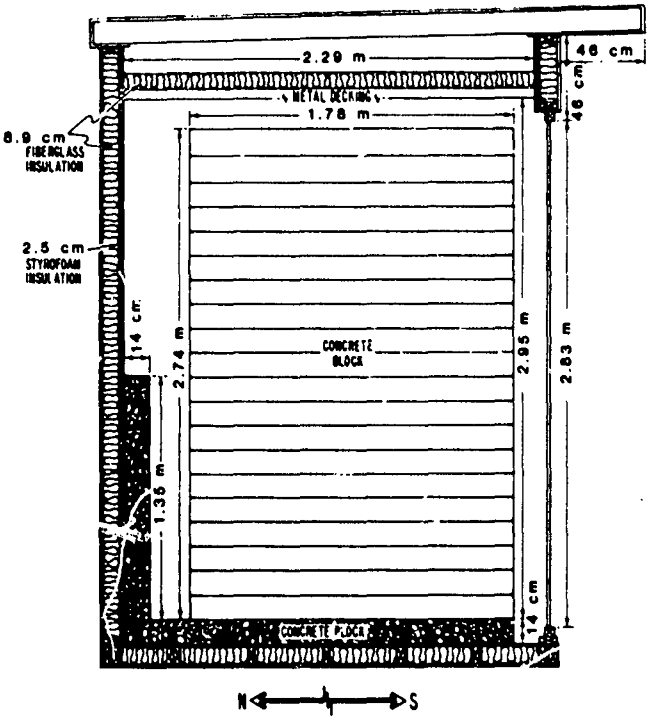

FIG. 1 - SECTION

DIRECT GAIN TEST CELL

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Several computer code comparisons (SUNSPOT [7,8], DOE-1 [9,10], DEROB [11]) have been performed on the same test facilities, as well as hand calculation comparisons [12]. For the direct gain test cell, all incoming direct sunlight fell on the concrete surfaces shown in Fig. 1. The measured mean radiant (globe) and zone (shielded) room air temperatures provide the basic verification information as described in Section D below. A complete description appears in Appendix 1, Reference [1].

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. Estimates of these parameters were made by using data from an Albuquerque TMY[†] weather tape for the same time period and dry bulb temperature. 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 direct normal radiation, horizontal diffuse solar radiation, and ground reflected radiation on a vertical surface. Since only total vertical surface radiation was available, considerable difficulty was experienced in establishing an accurate and internally consistent direct/diffuse breakdown. The method used to construct useful solar data from the measurements is described in [1].

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. In the simple case of the direct gain test cell

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[†] TMY (Typical Meteorological Year) weather data has been developed by N.O.A.A. from more than 20 years of measured weather and solar radiation values for 26 U.S. sites.

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

whose internal thermal activity responds only to environmental excitations, no internal heat sources, such as people, lights, and equipment required specification.

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. BLAST infiltration calculations take the base rate defined by the user and modify it hourly according to changes in wind speed (WS, in units of m/s), and inside-outside temprature difference (ΔT, in units of $^{\circ}C$) using the following relation:

$$\text{Inf. Rate} = \text{Base Rate} \cdot (0.606 + 0.1177 \cdot WS + 0.036 \cdot \Delta T)$$

The choice of the base infiltration rate is discussed below.

The complete BLAST input is included in Appendix 2 of Reference [1].

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;
- Root-mean-square 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. TEST CELL VERIFICATION RESULTS

A. 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. 4 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

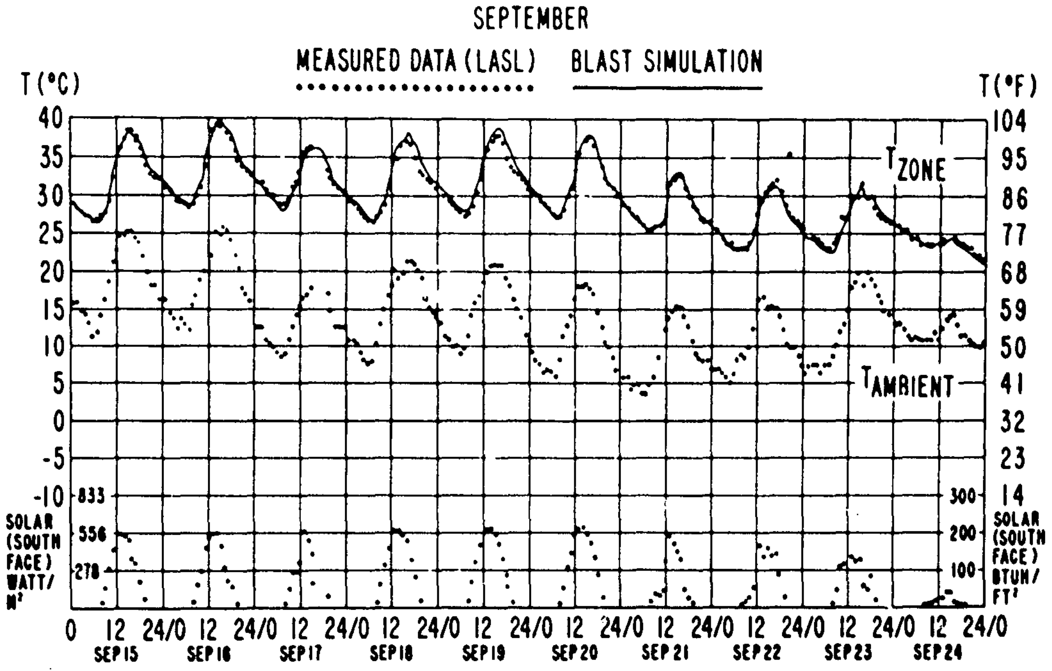

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FIG. 2 - SEPTEMBER RESULTS

DIRECT GAIN TEST CELL

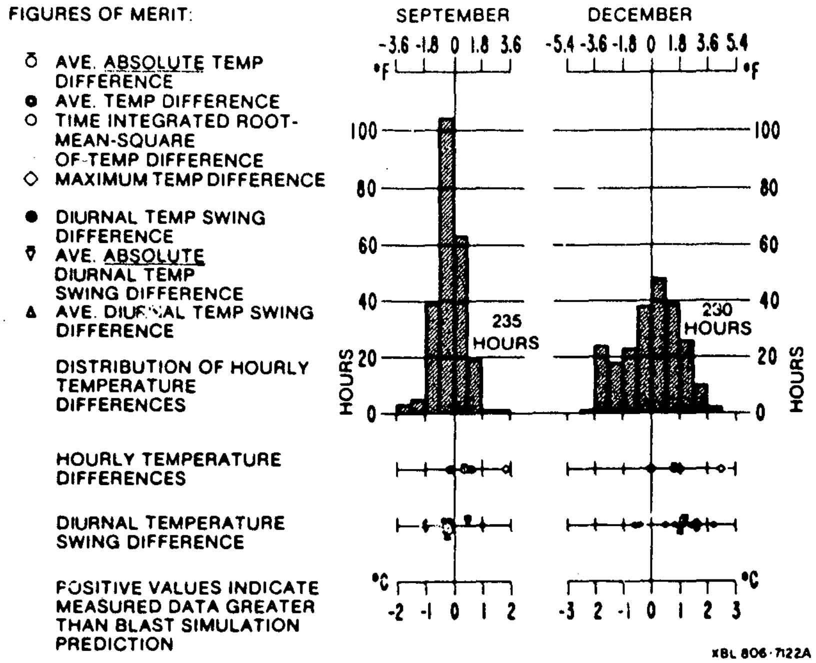

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FIG. 3- FIGURES OF MERIT

DIRECT GAIN TEST CELL

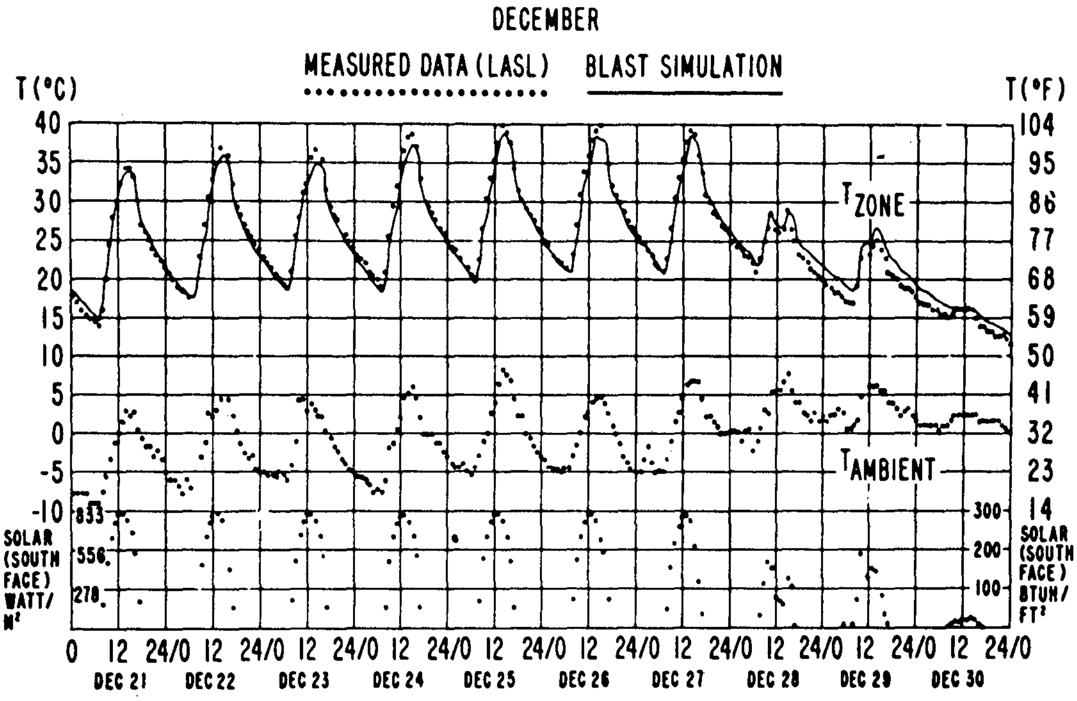

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FIG. 4 - DECEMBER RESULTS

DIRECT GAIN TEST CELL

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.

B. 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. 4 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. The December curves suggest an overestimation of the 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. TEST CELL VERIFICATION SENSITIVITIES

Several of the input parameters used in the BLAST verification were based on subjective estimates rather than experimental measurements. In addition, some of the internal parameters and procedures used in BLAST are approximations, especially when applied to a test cell. For these reasons, several sensitivity studies were performed. The parameters examined include infiltration level; direct/diffuse split of the incident solar radiation; distribution of transmitted solar radiation on internal surfaces; values of the absorptivity of external surfaces; total incident solar radiation; steady state U-values of the opaque envelope surfaces; and exposed area, thickness, and specific heat of the thermal storage mass. A high degree of sensitivity of the simulation to any of these 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.

As shown in [1], some degree of sensitivity of the BLAST predictions to variations in each of these parameters was observed. The two parameters judged to be most uncertain in the verification simulations were also among those which demonstrated the strongest influence on the predictions of the program. They were the infiltration level and the direct/diffuse split of the incident solar radiation. Results from these two 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 BLAST temperature predictions were very sensitive to the infiltration rate, shifting by up to 4°C in response to a 50 percent change. A 50 percent increase in the infiltration rate caused the average temperature difference between predicted and measured values to rise from 0.4°C in the base case 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 susceptible 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. Twenty percent of the incident direct radiation was replaced by an equivalent amount of incident diffuse radiation. The effect of this change during September days is 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. A shift of direct radiation to diffuse radiation has a more dramatic influence during December, when the direct solar transmittance is noticeably larger than the diffuse. For December, the average temperature difference between measured and predicted values was doubled as a result of the solar radiation shift.

VI. TEST CELL VERIFICATION LIMITATIONS

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 .25-2.5 air changes have been used* by different researchers. 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 <u>base</u> infiltration rate for two seasons, in which its effect would be very different, and having maintained accuracy in the results, some confidence is felt in the infiltration estimate. However, physical measurements of the test cell in question are clearly required in order to remove the uncertainty of the infiltration estimates.

B. Solar Radiation

Most important to the proper simulation of the test cell is a specific set of solar radiation data, particularly a distinction between direct, diffuse, and ground reflected radiation. Because of the differences in transmission between these components of the solar excitation, large discrepancies at certain times of day and year can result from an improper allocation of the total radiation. 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 glazing. As a result, the test cell is extremely sensitive to solar gains, much more so than conventional passive buildings would be. 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. Because of the importance of solar gains in the simulation, 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. In addition, the test cell does not include auxiliary heating or cooling systems. Therefore, the verification cannot be extrapolated directly to an occupied building or one with a direct gain system that includes conventional back-up systems.

D. 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 a full-scale 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 B above, the ratio of glazing area to total internal surface area is large relative to real 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 and the lack of partitions implies that multidimensional conductive heat flow effects may be exaggerated in comparison to an occupied building where walls, floors, and ceilings are much more expansive and internal obstructions prevent direct radiative exchange between envelope elements.

VII. MASSIVE BUILDING VERIFICATION

In order to (1) extend the verification of BLAST to full scale systems which are not heavily driven by the direct gain of solar radiation into the conditioned space; (2) examine the capability for predicting dynamic thermal storage effects; and (3) examine the interaction of the structure with ventilative cooling schemes, a second verification study has been conducted. The specific building chosen for this verification was a well insulated, thermally massive structure which was

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*The SUNSPOT simulation used approximately 1 air change, based on a crack calculation [8]. DOE-1 simulations have used 1.0 and 2.5 air changes [9,10]. Goldstein used .25 air changes with his hand calculation method [12].

constructed in a large environmental chamber at the U. S. National Bureau of Standards (NBS). NBS performed tests on this structure in order to obtain a quantitative, measured estimate of the performance of a well-insulated, thermally massive building in relatively severe summer climate conditions. Building loads and interior temperatures were measured during the imposition of several dynamic, diurnal temperature profiles. BLAST predictions were compared to measurements from two experimental tests, one when the building was cooled by a chilled water coil during part of the night, and the other when it was ventilated during cool nighttime hours. Details of the construction and geometry of the test building are shown in Fig. 5 and described in reference [13]. Complete details of the BLAST simulation parameters, including a listing of the input, are given in reference [2].

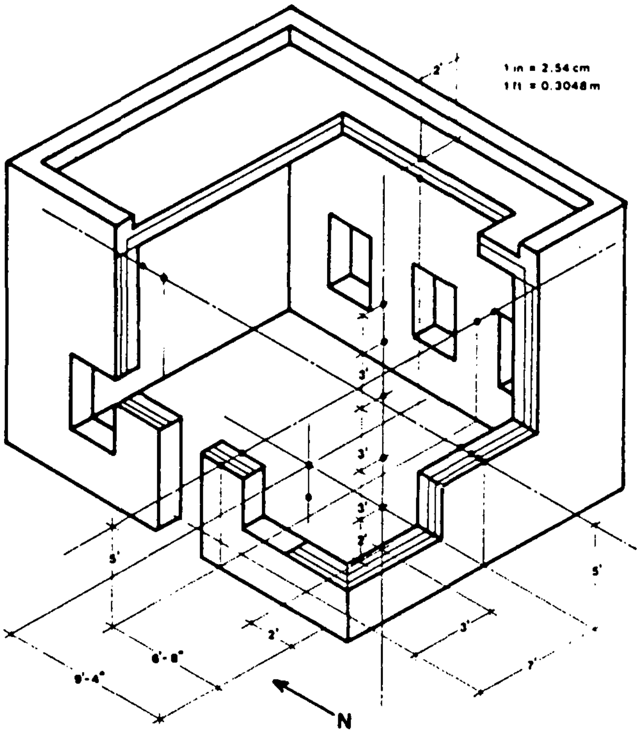


FIG. 5 - ISOMETRIC CUTAWAY

MASSIVE STRUCTURE

XBL 811-7529

A. Environmental Data

Weather data used for the BLAST simulations consisted of the same diurnal air temperature profiles which were experimentally imposed on the exterior of the structure for each of the tests (night cooling and night ventilation). No actual solar radiation was imposed on the structure during the experiment or used in the input to the BLAST simulation. The specific profiles that were used are shown in Figures 6 and 7. The ground temperature used in the simulations was a constant 25.6°C (78°F).

B. Temperature Schedules and Internal Loads

Unlike the test cell, thermostat settings and internal loads play an important role in this part of the verification effort. Infiltration was also carefully measured. Actual assumptions used were:

(a) Thermostat: Set to 23.9°C (75°F) for the night cooling test; not used for the night ventilation test.

(b) Internal Loads: .3 kW (1000 Btu/hr) from 7 p.m. to midnight. The experiment used incandescent light bulbs to supply this heat.

(c) Infiltration: The measured infiltration rate varied from about 0.02 to about 0.05 air changes/hr, depending on the air temperature difference between inside and outside.

C. Results: Night Cooling Test

For this test the experimental temperatures imposed on the structure represent relatively severe summer conditions. The interior air of the structure was cooled with a thermostatically controlled chilled water coil to 23.9°C (75°F) from 6 p.m. to 6 a.m. For the other twelve daytime hours, the space was unconditioned and the interior temperature was allowed to float. The daily experimental procedure was repeated until the structure reached steady-periodic equilibrium, as determined by the measurements. Hourly cooling loads and interior temperatures were reported for the structure after it had reached equilibrium. We have duplicated the experimental conditions of this test for the BLAST simulation.

Results of the BLAST predictions are compared with the measured test data in Fig. 6. During the early part of the cooling period when the differences are largest, the predicted loads are consistently lower than the measured values. There is a maximum difference between simulation predictions and measured values of about .3 kW (15%) at the beginning of the daily cooling period, which decreases to essentially zero (within the scatter of the measured data) during the last several hours of the cooling period.

The interior temperatures predicted by BLAST during the non-conditioned period, also shown in Fig. 6, exhibit the same time dependence as the measured values, floating up slowly over the twelve-hour period. The predictions, however, are consistently higher than the measured values by an almost constant value of about 2°C (4°F). This difference is too large to be entirely due to temperature measurement error, which would be expected to be no more than on the order of

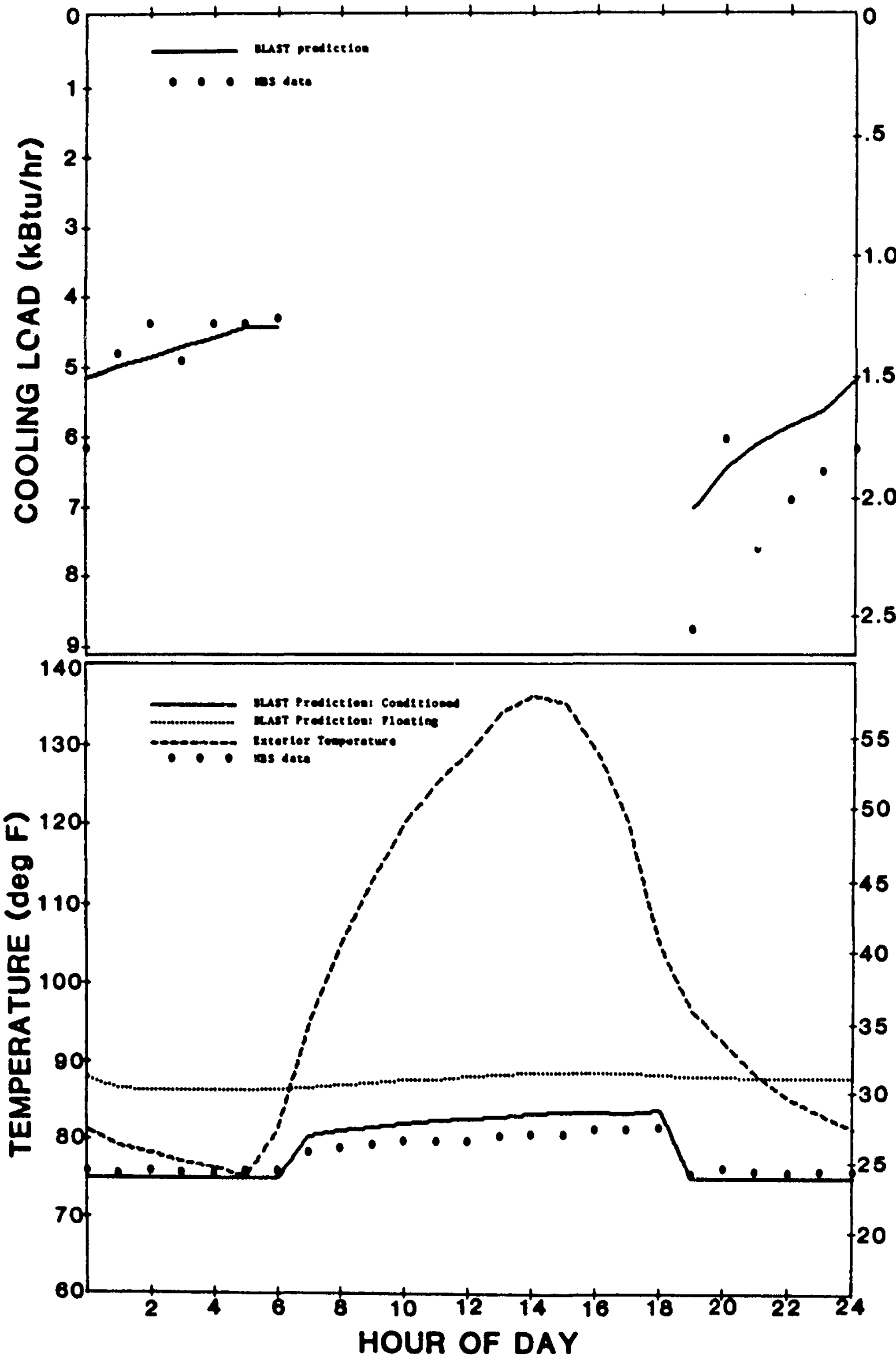


FIG. 6 – NIGHT COOLING

MASSIVE STRUCTURE

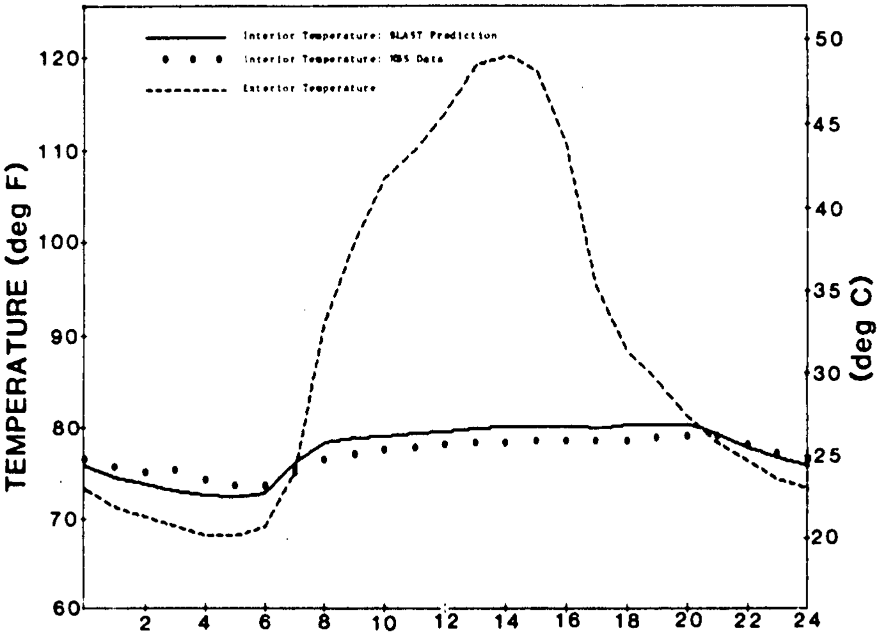
XBL 811-7531

±1°C for the type of measurements that were made. This discrepancy needs to be explored in more detail. For example, the BLAST-predicted temperatures shown are only air temperature and not any weighted average which includes surface temperatures. The simulated surface temperatures were examined and all were found to be lower than the predicted inside air temperature. Thus, a weighted average of them will be lower than the predicted air temperature alone, and will agree more closely with the measured values which are shown. Consequently, one possible reason for the observed difference might have been that the measured values which are reported are some weighted average of the true air temperature and the temperatures of the inside surfaces of the room. However, checking with the experimenters, we found that the thermocouples that measured interior air temperature were shielded from radiative effects. Perhaps a small part of the observed discrepancy between measurement and prediction could be explained this way, but certainly not all of it. For comparison, Fig. 6 also shows the BLAST-predicted interior temperature in the case where the structure is not conditioned at all, and floats for all hours.

D. Results: Night Ventilation Test

The external air temperatures imposed for this test are representative of moderate summer conditions. During this test, the building was unconditioned at all times and the interior air temperature was allowed to float freely. The building was sealed during the daytime period when the (floating) interior temperature was lower than the outside temperature. When the external temperature in the test chamber dropped below the inside temperature, the building windows and door were opened, and it was ventilated with outside air at a rate of about 14 air changes per hour. Like the night cooling test, the daily experimental procedure was repeated until the structure reached steady-periodic equilibrium. Hourly interior temperatures were reported for the structure after it had reached equilibrium. Results of the BLAST predictions based on duplicating the experimental conditions of this test are compared with the reported data in Fig. 7.

The agreement between the BLAST predictions and the measured temperatures shows a maximum difference of about 1°C (2°F). The time dependence for measured and predicted results shows qualtitative agreement, and the



XBL 811-7532

FIG. 7 - NIGHT VENTILATION

MASSIVE STRUCTURE

BLAST simulation correctly predicts the times of the day when the ventilation starts and stops. Like the night cooling test, the measured temperatures are actually a weighted average of air temperature and inside surface temperatures, while the BLAST prediction shown includes only the inside air temperature. As in the previous test, a weighted average of simulated air temperature and simulated inside surface temperature will agree more closely with the measured values.

E. Discussion

As can be seen from the comparisons between predicted and measured values for the thermally massive structure that are described in this section, the quality of agreement is generally good, but with observable discrepancies. There are two main categories into which reasons for these discrepancies seem to fall: (1) gaps and ambiguities in the description of the experiment, including information about the structure itself, about the experimental procedures, and experimental uncertainty in the measured data; and (2) limitations in the ability of BLAST to properly simulate the actual physical phenomena that occurred in the experiments.

The first category includes the thermophysical properties of materials from which the structure was built, which as reported in [13], are typical values from the literature, and not values that were actually measured for the actual structure. Additionally, measured ground temperatures and inside surface temperatures were not available. The ground temperatures had to be estimated from the experimental description, because they are required as input to the BLAST simulation. The inside surface temperatures are not needed for the simulation, but could provide valuable information about the causes for the observed discrepancies between measured and predicted loads and inside air temperatures.

In the second category, there are some necessary differences between the actual building and its thermal interpretation for BLAST input due to limitations and simplifying assumptions in the computer model. Specifically: (1) the lengths of the walls and roof were increased at each edge except at the floor to account in an approximate way for the increased heat conduction at edges; (2) the roof was modelled as two separate pieces, one representing the solid part of the cross section, the other representing the hollow core part of the cross section; (3) the slab floor was also separated into two pieces, one representing the central part of the floor, and one representing the area equivalent to a one-foot wide perimeter to approximate the thermal behavior of the actual perimeter of the experimental building; (4) the values of the inside convective film coefficients for the surfaces have been modified according to a procedure described in [14], in order to account for the existence of air movement due to natural convection in the structure.

It is not possible to unambiguously conclude at this time what the effects of each of these causes have with regard to the observed discrepancies. However, the similarity of the time-dependence of the simulated predictions to the measured data suggests that the mass effects of the actual structure are generally being reflected properly in the simulation. Plausible changes in the assumptions used have been shown to decrease the discrepancies between predicted and measured loads and temperatures substantially from those shown in the figures. Sensitivity studies to investigate the discrepancies described above are in progress and are reported in detail elsewhere [2].

VIII. 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 0.4 and 0.8°C (0.7 and 1.4°F) for the two simulated periods. Sudden test cell temperature changes due to sun, outside temperature, and/or wind are invariably reflected in the BLAST simulations. In both simulation periods, there is no long-term systematic shift away from the measured data points, even over a ten-day period.

The comparisons of BLAST predicted values with the measurements of the NBS high-mass test building are complementary to the LASL test cell comparisons because the former look only at conductive, convective, and thermal mass effects, while the test cell comparison examines solar radiation and infiltration effects. As can be seen from the work presented here, the agreement with the NBS measurements are quite good, and the remaining discrepancies are due either to lack of experimental information or input ambiguities. The work verifies the ability of BLAST to simulate thermal mass effects with reasonable accuracy in practical applications for high mass structures, even though the reasons for the observed discrepancies are not unambiguously explained. This verification is important because of the fundamental role thermal mass effects play in passive solar designs.

The verifications presented here cannot be directly transferred to buildings 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 both the test cell (solar gains, thermal storage, materials properties, infiltration) and the massive structure (thermal storage, ventilation) 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 investigated with the same rigor that has been applied to the BLAST verification. Specific building types should be identified, and suitable examples should be found, instrumented, and strictly controlled for periods long enough to provide sufficient data for verification.

IX. REFERENCES

[1] B. Andersson, F. Bauman, R. Kammerud, "Verification of BLAST by Comparison with Measurements of a Direct Gain Test Cell," Lawrence Berkeley Laboratory Report LBL-10619, October 1980.

[2] W. Carroll, N. Friedman, "Comparison of BLAST Predictions with Measured Performance for a Thermally Massive Building," Lawrence Berkeley Laboratory Report LBL-11679, to be published.

[3] M. Lokmanhekim, Ed., Procedure for Determining Heating and Cooling Loads for Computerized Energy Calculations, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, 1976.

[4] T. Kusuda, "Thermal Response Factors for Multi-Layer Structures of Various Heat Conduction Systems," ASHRAE Transactions, Part I (1969), pp. 250-269.

[5] G. Walton, "The Application of Homogeneous Coordinates to Shadowing Calculations," ASHRAE Transactions, Part I (1979).

[6] Bickle/CM Inc., "Performance Data for Passive Systems: The Los Alamos Laboratory Test Rooms", Report SERI/TR-0924-2, prepared for the Solar Energy Research Institute, June 1980.

[7] J. Balcomb and W. Wray, "Evaluation of Passive Solar Heating," Proceedings, 1978 Annual Meeting of the American Section of I.S.E.S., August 1978, pp. 64-68.

[8] B. Hunn, N. Schnurr, J. Peterson, J. Kerrisk, J. Moore, "Applications of DOE-1 to Passive Solar Heating of Commercial Buildings: Preliminary Results," Proceedings, 3rd National Passive Solar Conference, January 1979, pp. 159-163.

[9] CCB/Cumali Associates, "Passive Solar Calculation Methods: Interim Report," U.S. Department of Energy, DSE-5221-T2, April 1979.

[10] N. Schnurr, J. Kerrisk, J. Moore, B. Hunn, Z. Cumali, Applications of DOE-2 to Direct Gain Passive Solar Systems: Implementation of a Weighting-Factor Calculative Technique," Proceedings, of the 4th National Passive Solar Conference, October 1979, pp. 182-186.

[11] F. Arumi-Noe, "Field Validation of the DEROB/PASOLE System," Proceedings, 3rd National Passive Solar Conference, January 1979, pp. 152-158.

[12] D. Goldstein, "Some Analytic Models of Passive Solar Building Performance: A Theoretical Approach to the Design of Energy-Conserving Buildings," Lawrence Berkeley Laboratory Report LBL-7811, November 1978.

[13] P. Gujral, R. Clark, D. Burch, "An Evaluation of Thermal Energy Conservation Schemes for an Experimental Masonry Building," U.S. National Bureau of Standards, Building Science Series, to be published.

[14] A. Gadgil, F. Bauman, R. Kammerud, K. Ruberg, "Natural Convection in Room Geometries", Proceedings, 1980 Annual Meeting of A.S. of I.S.E.S., June, 1980, pp. 808-815.