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Sullivan, Robert

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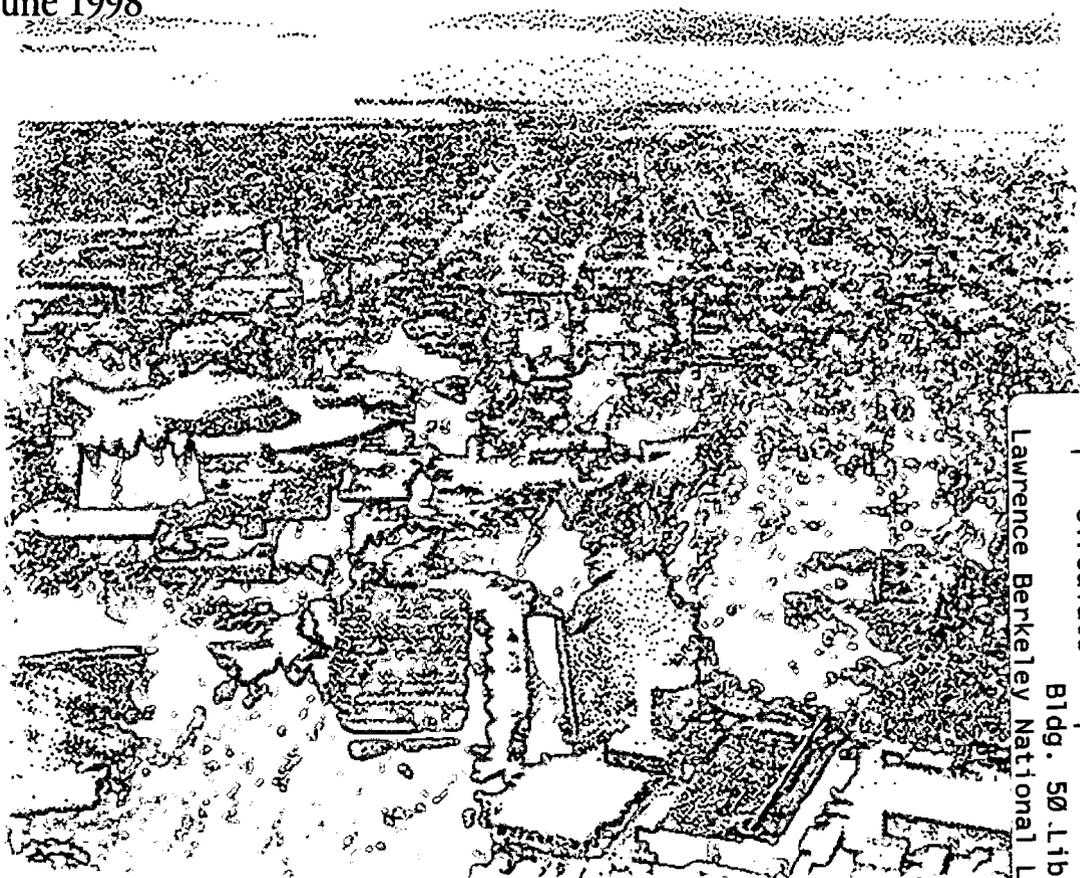
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Validation Studies of the DOE-2 Building Energy Simulation Program Final Report

Robert Sullivan and Frederick Winkelmann

Environmental Energy
Technologies Division

June 1998



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Final Report

Validation Studies of the DOE-2 Building Energy Simulation Program

Robert Sullivan and Frederick Winkelmann
Building Technologies Department
Environmental Energy Technologies Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
One Cyclotron Road
Berkeley, CA

June 1998

Final Report

Validation Studies of the DOE-2 Building Energy Simulation Program

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Executive Summary

This report documents many of the validation studies (Table 1) of the DOE-2 building energy analysis simulation program that have taken place since 1981. Results for several versions of the program are presented with the most recent study conducted in 1996 on version DOE-2.1E and the most distant study conducted in 1981 on version DOE-1.3. This work is part of an effort related to continued development of DOE-2, particularly in its use as a simulation engine for new specialized versions of the program such as the recently released RESFEN 3.1. RESFEN 3.1 is a program specifically dealing with analyzing the energy performance of windows in residential buildings. The intent in providing the results of these validation studies is to give potential users of the program a high degree of confidence in the calculated results.

Validation studies in which calculated simulation data is compared to measured data have been conducted throughout the development of the DOE-2 program. Discrepancies discovered during the course of such work has resulted in improvements in the simulation algorithms. Table 2 provides a listing of additions and modifications that have been made to various versions of the program since version DOE-2.1A. One of the most significant recent changes in the program occurred with version DOE-2.1E. An improved algorithm for calculating the outside surface film coefficient was implemented. In addition, integration of the WINDOW 4 program was accomplished resulting in improved ability in analyzing window energy performance.

Validation and verification of a program as sophisticated as DOE-2 must necessarily be limited because of the approximations inherent in the program. For example, the most accurate model of the heat transfer processes in a building would include a three-dimensional analysis. To justify such detailed algorithmic procedures would correspondingly require detailed information describing the building and/or HVAC system and energy plant parameters. Until building simulation programs can get this data directly from CAD programs, such detail would negate the usefulness of the program for the practicing engineers and architects who currently use the program. In addition, the validation studies discussed herein indicate that such detail is really unnecessary. The comparison of calculated and measured quantities have resulted in a satisfactory level of confidence that is sufficient for continued use of the DOE-2 program. However, additional validation is warranted, particularly at the component level, to further improve the program.

Table 1. List of References

Version DOE-2.1E

1. **Analysis of the Energy Performance of Cooling Retrofits in Sacramento Public Housing Using Monitored Data and Computer Simulations.** CEC R&D Office, No 500-93-053, July 1996. Vincent, B. and Huang, Y.J.
2. **Comparison of DOE-2 with Measurements in the Pala Test Houses.** Lawrence Berkeley Laboratory Report LBL-37979, July 1995; Energy and Buildings 1998, V. 27, pp. 69-81. Meldem, R. and Winkelmann, F.
3. **Empirical Validation of Thermal Building Programs Using Test Room Data.** International Energy Agency Annex 21/Task 12 Final Report, September 1994. Lomas, K.J., Eppel, H., Martin, C., and Bloomfield, D.

Version DOE-2.1D

4. **Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area; Project Design and Preliminary Results.** Lawrence Berkeley Laboratory Report LBL-33342, 1992. Akbari, H., Bretz, S., Hanford, J., Rosenfeld, A., Sailor, D., Taha, H., and Bos, W..
5. **A Procedure for Calibrating the DOE-2 Simulation Program to Non-Weather-Dependent Measured Loads.** *ASHRAE Transactions* 98(1) 1992. Bronson, D.J.; Hinchey, S.B.; Haberl, J.S.; and O'Neal, D.L.

Version DOE-2.1C

6. **Comparisons of Four Computer Models with Experimental Data from Test Buildings in Northern New Mexico.** *ASHRAE Transactions* 91(2) 1985. Robertson, D.K. and Christian, J.E.
7. **A Comparison of DOE-2.1C Prediction with Thermal Mass Test Cell Measurements.** Lawrence Berkeley Laboratory Report LBL-18981, January 1985. Birdsall, B.

Version DOE-2.1B

8. **Validation of Hourly Building Energy Models for Residential Buildings.** *ASHRAE Transactions* 91(2) 1985. Sorrell, F.Y.; Luckenback, T.J.; and Phelps, T.L.

Version DOE-2.1A

9. **DOE-2 Verification Project Phase 1 Final Report.** Los Alamos Laboratory Report LA-10649-MS, February 1986. Diamond, S.C., Cappiello, C.C., and Hunn, B.D.
10. **User Effect Validation Tests of the DOE-2 Building Energy Analysis Computer Program.** *ASHRAE Transactions* 91(2) 1985. Diamond, S.C., Cappiello, C.C., and Hunn, B.D.
11. **Comparisons of Predicted and Measured Energy Use in Occupied Buildings.** *ASHRAE Transactions* 90(2B) 1984. Wagner, B.S.
12. **The Validation of DOE-2 for Application to Single-Family Dwellings.** *ASHRAE Transactions* 90(2B) 1984. Colborne, W.G., Hall, J.D., and Wilson, N.W.
13. **Measured Versus Predicted Performance of the SERI Test House: A Validation Study.** Solar Energy Research Institute Report SERI/TP-254-1953, May 1983. Judkoff, R., Wortman, D., and Burch, J.
14. **A Summary Report of Building Energy Compilation and Analysis (BECA) Part V: Validation of Energy Analysis Computer Programs.** Lawrence Berkeley Laboratory Report LBL-14838, January 1983. Wagner, B.S. and Rosenfeld, A.H.

Table 1. (Cont'd.)

- 15. Comparison of DOE-2 Computer Program Simulations to Metered Data for Seven Commercial Buildings.** *ASHRAE Transactions* 87(1) 1981. Diamond, S.C. and Hunn, B.D.
- 16. A DOE-2.1A Comparison with CERL Data for VAV and REHEAT Systems.** Report by W. S. Fleming and Associates, Inc., November 1981.

Version DOE-1.3, 1.4, 2.0

- 17. DOE-2 Verification Project Phase 1 Interim Report.** Los Alamos Laboratory Report LA-8295-MS, April 1981. Diamond, S.C., Cappiello, C.C., and Hunn, B.D.

Table 2. Major Upgrades to the DOE-2 Program

Version DOE-2.1E, Release November 1993

LOADS

- Improved outside air film conductance
- Window library
- Window frames
- Switchable glazing

SYSTEMS

- Evaporative cooling
- Add-on desiccant cooling units
- Enhanced water-loop heat pump
- Variable-speed electric heat pump
- Packaged variable-volume variable-temperature system
- Service hot water heat pump
- Variable-speed gas heat pump with optional waste heat recovery
- Residential variable-volume variable temperature system
- Additional air-side economizer options
- Additional heat pump defrost options
- Improved cooling coil model
- Sizing enhancements
- Water-cooled condenser option
- Evaporatively-cooled condenser for packaged systems

PLANT

- Ice thermal energy storage
- Improved cooling tower model
- Revised circulation pump simulation

ECONOMICS

- Revised energy cost calculations

Version DOE-2.1D, Release June 1989

BDL

- Functional values in LOADS and SYSTEMS
- Saving files of hourly output for post processing
- Input macros

LOADS

- Automatic calculation of the shading of diffuse solar radiation
- Improved exterior infrared radiation loss calculation

SYSTEMS

- Packaged total-gas solid-desiccant system
- Enhancement to the residential natural ventilation algorithms

PLANT

- Gas-fired absorption chiller
- Engine driven compression chiller
- Component-based ice storage simulation

Table 2. (Cont'd.)

Version DOE-2.1C, Release May 1984

BDL
User-specified Input Functions

LOADS
Sunspaces
Window management and solar radiation

SYSTEMS
Powered induction unit system
Heat recovery and refrigerated case work
Air source heat pump enhancements
Optimum fan start option
New system equipment default curves

PLANT
Plant equipment operating modes
New electrical equipment simulations
Revised circulation pump simulations replacement of energy-cost command

ECONOMICS
Expanded treatment of energy costs

Version DOE-2.1B, Release November 1982

BDL
Metric option

LOADS
Daylighting
Trombe walls
Fixed shades, fins, overhangs
Distribution of heat from lights
Sherman-Grimsrud infiltration method
Floor multipliers and interior wall types

SYSTEMS
Night ventilation
User-defined curve-fit boundaries
Baseboard heating in plenums
Various control enhancements

PLANT
Sell-back of electricity to utility

Version DOE-2.1A, Release May 1981

BDL
Southern latitude capability

LOADS
Custom weighting factor calculation

SYSTEMS
Revised system sizing calculations
Improved cooling tower algorithms

Validation Study Summaries

Each validation summary describes the important points in each study. We also provide tabular and graphic comparisons of simulated and measured data. The following items are presented:

- a. Version of DOE-2 Program: Specifies the particular version of the DOE-2 program that was validated by comparing simulation results to measured data. Also indicated here are unique versions of the program defined as "modified". Usually, these unique versions were created to enhance the accuracy of the basic program.
- b. Building Type: A brief description of the building that was simulated and measured. When available, specific information is provided indicating internal load profiles, HVAC system type, window types and sizes, etc.
- c. Verification Type: Validation studies of the DOE-2 program have generally involved an iterative process in which simulation results are calibrated to the monitored data. This usually involved revising the DOE-2 program creating more accurate simulation algorithms or revising the input description of the building and/or equipment so that it is a more realistic representation of the configuration being measured. Items that are dependent on scheduling such as occupancy, lighting, equipment, and natural ventilation are particularly difficult to ascertain and thus affect the resultant comparison. Accurate HVAC system performance parameters as well as the level of infiltration also have a pronounced effect. For each validation study summary reported, we indicate whether the comparison of simulated and measured data was non-iterative or iterative.
- d. Location: Geographic location, including latitude, longitude, and altitude, of the building.
- e. Dates Monitored: Specific dates when the validation measurements were conducted.
- f. Configurations Monitored: In several of the validation studies, a base case building was modified and additional measurements taken. A brief description of these configuration changes is provided.
- g. Data Monitored: The data that was measured and compared to the DOE-2 program results.
- h. Monitoring Interval: The monitoring interval and extent of the measurements.
- i. Conclusions: The general conclusions that were made as a result of the comparison of simulated and measured data. In some instances, direct quotations have been taken from the particular reference; in other studies, we have written our own conclusions.
- j. Summary: Quoted abstract from each reference.

It should be noted that References 9 and 17 present results related to validation of DOE-2 conducted as part of a formal U.S. Department of Energy validation exercise. In these cases, we present the complete Executive Summary from the referenced report. References 11 and 14 present compilations of studies related to validation of DOE-2 and other energy analysis computer programs. In these cases, the overall summary and conclusions are presented.

Acknowledgment

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Systems of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

1. **DOE-2.1E: "Analysis of the Energy Performance of Cooling Retrofits in Sacramento Public Housing Using Monitored Data and Computer Simulations."** California Energy Commission Research and Development Office, Contract Number 500-93-053, July 1996. Vincent, B. and Huang, Y.J.
 - a. Version of DOE-2 Program: DOE-2.1E (modified)
 - b. Building Type: Presents results for analyzing residential building evaporative coolers, ground-source heat pumps, roof albedo, and building orientation.
 - (1) Evaporative cooling was analyzed for four occupied one-story wood-frame houses with floor areas of 82 m² (937 ft²), 96 m² (1035 ft²), 119 m² (1281 ft²), and 90 m² (970 ft²). The homes had R-38 ceilings, R-19 walls, and blue-tinted double-pane windows with vinyl frames.
 - (2) Evaporative cooling was analyzed for five occupied one-story wood-frame houses with floor areas of 87 m² (884 ft²), 173 m² (1860 ft²), 158 m² (1700 ft²), 130 m² (1400 ft²), and 114 m² (1230 ft²). The homes had R-30 or R-19 ceilings, R-11 or R-0 walls, and single-pane windows with aluminum or steel frames. Each house was also equipped with a standard air-conditioners.
 - (3) Ground-source heat pumps were analyzed using two occupied slab-on-grade two-story community center buildings including a Childcare Center and a Family Services Center, and a one-story Computer Training Center. The buildings had R-38 ceilings, R-13 walls, and double-pane, tinted windows with vinyl frames. Six ground-source heat pumps served the Childcare Center, two served the Family Services Center, and one served the Computer Training Center.
 - (4) The impact of roof coatings was analyzed using two unoccupied and unconditioned slab-on-grade two-story, multifamily residential buildings with wood-frame walls and stucco siding. The buildings had R-38 ceilings, R-13 walls, and double-pane, tinted windows with vinyl frames.
 - (5) The impact of building orientation was analyzed using four unoccupied and unconditioned slab-on-grade two-story, multifamily residential buildings with wood-frame walls and stucco siding. The buildings had R-38 ceilings, R-13 walls, and blue-tinted double-pane, tinted with windows with vinyl frames.
 - c. Verification Type: Iterative. Initial estimates of internal loads, thermostat setpoints, and window venting modified based on physical observation. Weather data obtained from the NCDC for the years 1993, 1994, and 1995 for three locations in the vicinity of Sacramento, California were compared to monitored exterior temperatures and the weather file most closely matching the measured conditions was use in the DOE-2 simulations.
 - d. Location: (1)-(5) Sacramento, CA and vicinity; latitude-38.5N, longitude-121.5W.
 - e. Dates Monitored:
 - (1) July to November, 1995.
 - (2) June to September, 1993.
 - (3) July to November, 1995.
 - (4) September to November, 1994.
 - (5) July to November, 1995.
 - f. Configurations Monitored:
 - (1)-(2) Buildings with evaporative coolers. Tests DOE-2 model of evaporative cooler and its effects on basic heat transfer processes.
 - (3) Buildings with ground-source heat pumps. Tests DOE-2 model of GSHP and its effect on basic heat transfer processes.
 - (4) Two identical buildings, one with a high albedo roof coating with a solar reflectance of 73% and one with a dark built-up roof surface with a reflectance of 10% were compared. Tests DOE-2 ability to simulate the effects of surface absorptance on basic heat transfer processes.

(5) Four identical buildings, two facing northwest and two facing north were compared. Test DOE-2 ability to simulate the effects of building orientation on basic heat transfer processes.

g. Data Monitored:

- (1) Air temperature, relative humidity, evaporative cooler electricity input.
- (2) Air temperature, ground source heat pump electricity input.
- (3) Air temperature.
- (4) Air temperature.
- (5) Air temperature.

h. Monitoring Interval: (1)-(5) 15-20 minutes.

i. Conclusions: “The main objectives of this project were to gather data on the energy performance of cooling strategies implemented by the Sacramento Housing and Redevelopment Agency (SHRA), use these data to validate an indirect/direct evaporative cooler (IDEC) model developed by LBNL and a ground-source heat pump (GSHP) model developed by independent consultants, both implemented in developmental versions of the DOE-2 program, and then use these validated models to assess the energy benefits of these strategies throughout California...”

(1)-(2) “...Considering the five 1993 SMUD evaporative cooling sites as a whole, the simulation results agreed with the monitored energy consumption to within 8%, although the variations for individual houses were somewhat larger...The primary concern about IDECs is not their energy usage, which are roughly 40% less than for air-conditioning, but their ability to maintain indoor comfort, particularly during peak cooling periods. Both the monitored and simulated data show increases in relative humidity of 10% or less, and a maximum relative humidity of 75%, in houses where the evaporative coolers were operated continuously for many days...” Tables 1.1 and 1.2 summarize the comparison of monitored and simulated results.

(3) “...The monitored data for GSHPs were marked by poor quality due to apparently inconsistent operations. However, the simulated results for the system serving the Computer Technology Center, which was operated regularly and consistently, agreed with the monitored energy usage and time of operation to within 20%...”

(4) Simulated attic temperatures for both dark and coated roof surface tracked the monitored data quite closely. The temperature range during the course of a typical day was 10°C (50°F) to 43°C (110°F). Simulated interior space temperatures with a range of 18°C (65°F) to 22°C (72°F) were also similar to the monitored data. On the second floor, the temperatures differed by about 0.6°C (1°F); while the first floor temperatures were almost identical. Figures 1.1 and 1.2 present a comparison of monitored and simulated results for the different roof coatings.

(5) Simulated attic temperatures for the different orientations were identical; whereas, the monitored data showed higher peaks and lower valleys in the northwest facing buildings. The simulated interior space temperatures in both the first and second floors had an unusual appearance due to the natural ventilation algorithm used in DOE-2; however, the simulated temperatures showed the same general trends as the monitored data.

j. Summary: “Evaporative coolers, ground-source heat pumps, and high-albedo roof coatings are three advanced cooling technologies recently employed in Sacramento public housing. The benefits of these retrofits were evaluated using both field monitoring and computer simulations. Comparisons of the monitoring and simulation results were used to gauge the accuracy and usefulness of computer models. The models were shown to provide reasonably accurate performance predictions when calibrated to robust field data. The calibrated models were then used to predict the statewide applicability of the technologies. Evaporative coolers were demonstrated to be practical for well insulated buildings in all but the hottest California climates, yielding substantial energy savings in comparison to standard air conditioners while providing equivalent comfort without excessive indoor humidity. Ground-source heat pumps were similarly

found to provide savings over standard furnace and air conditioner combinations, with 25-38% reductions in cooling energy costs and no heating cost penalties in buildings with moderate heating loads. In colder locations, however, the heating cost may be increased by up to a third. Modest cooling savings and heating penalties were predicted for high-albedo roof coatings.”

Table 1.1

1995 SHRA Evaporative Cooler Monitoring Results

| House | EC Energy (kWh) | EC Oper (h) | RH _{in} Avg (%) | RH _{in} EC _{on} (%) | RH _{in} EC _{off} (%) | RH _{at} Avg (%) | RH _{ou} Avg (%) | T _{in} Avg (°F) | T _{in} EC _{on} (°F) | T _{in} EC _{off} (°F) | T _{at} Avg (°F) | T _{out} Avg (°F) |
|-------|-----------------|-------------|--------------------------|---------------------------------------|--|--------------------------|--------------------------|--------------------------|---------------------------------------|--|--------------------------|---------------------------|
| 95-1 | 110 | 239 | 56 | 63 | 55 | 51 | 59 | 74 | 74 | 74 | 76 | 70 |
| 95-2 | N/A | N/A | 54 | N/A | N/A | N/A | N/A | 75 | N/A | N/A | 75 | N/A |
| 95-3 | 30 | 68 | 51 | 47 | 51 | N/A | 58 | 75 | 84 | 75 | N/A | 70 |
| 95-4 | 652 | 596 | 61 | 68 | 59 | N/A | 51 | 73 | 75 | 73 | N/A | 73 |

1993 SMUD Evaporative Cooler Monitoring Results

| House | EC Energy (kWh) | EC Oper (h) | RH _{in} Avg (%) | RH _{in} EC _{on} (%) | RH _{in} EC _{off} (%) | RH _{out} Avg (%) | T _{in} Avg (°F) | T _{in} EC _{on} (°F) | T _{in} EC _{off} (°F) | T _{sup} EC _{on} (°F) | T _{sup} EC _{off} (°F) | T _{out} Avg (°F) | H ₂ O Usage (gal) | H ₂ O Avg (gal/h) |
|-------|-----------------|-------------|--------------------------|---------------------------------------|--|---------------------------|--------------------------|---------------------------------------|--|--|---|---------------------------|------------------------------|------------------------------|
| 93-1 | 342 | 745 | 53 | 61 | 49 | 48 | 77 | 78 | 77 | 70 | 77 | 78 | 4363 | 5.9 |
| 93-2 | 595 | 596 | 50 | 52 | 50 | 51 | 78 | 79 | 77 | 74 | 76 | 77 | 3058 | 5.1 |
| 93-3 | 252 | 380 | 51 | 56 | 50 | 50 | 77 | 79 | 77 | 73 | 77 | 76 | 2992 | 7.9 |
| 93-4 | 1126 | 1453 | 60 | 62 | 58 | 53 | 76 | 78 | 77 | 72 | 76 | 77 | 19725 | 13.6 |
| 93-5 | 560 | 1063 | 60 | 64 | 57 | 55 | 76 | 77 | 77 | 72 | 76 | 76 | 7116 | 6.7 |

Notation: EC = evaporative cooler, Oper = operating time, RH = relative humidity, T = temperature, Avg = average, in = interior, sup = supply, out = exterior, on, off = averaged for hours during which evaporative cooler is on or off.

Table 1.2

Evaporative Cooler Simulation Results

| House | EC Energy (kWh) | EC Oper (h) | RH _{in} Avg (%) | RH _{in} EC _{on} (%) | RH _{in} EC _{off} (%) | RH _{out} Avg (%) | T _{in} Avg (°F) | T _{in} EC _{on} (°F) | T _{in} EC _{off} (°F) | T _{at} Avg (°F) | T _{out} Avg (°F) | H ₂ O Usage (gal) | H ₂ O Avg (gal/h) |
|-----------------------------|-----------------|-------------|--------------------------|---------------------------------------|--|---------------------------|--------------------------|---------------------------------------|--|--------------------------|---------------------------|------------------------------|------------------------------|
| <i>1995 Monitored Sites</i> | | | | | | | | | | | | | |
| 95-1 | 111 | 352 | 59 | 68 | 58 | 57 | 71 | 78 | 70 | 76 | 68 | 396 | 1.13 |
| 95-2 | 56 | 205 | 52 | 60 | 52 | 55 | 71 | 77 | 70 | 71 | 67 | 175 | 0.86 |
| 95-3 | 118 | 307 | 52 | 52 | 52 | 57 | 71 | 79 | 70 | 75 | 68 | 637 | 2.08 |
| 95-4 | 445 | 663 | 56 | 57 | 56 | 57 | 71 | 73 | 70 | 71 | 68 | 1072 | 1.62 |
| <i>1993 Monitored Sites</i> | | | | | | | | | | | | | |
| 93-1 | 472 | 973 | 53 | 54 | 52 | 51 | 75 | 78 | 73 | 79 | 76 | 1949 | 2.00 |
| 93-2 | 560 | 853 | 48 | 50 | 48 | 51 | 77 | 79 | 75 | 80 | 76 | 2455 | 2.88 |
| 93-3 | 332 | 580 | 49 | 51 | 48 | 51 | 76 | 78 | 75 | 78 | 76 | 1797 | 3.10 |
| 93-4 | 1037 | 1423 | 53 | 55 | 51 | 51 | 74 | 75 | 73 | 78 | 76 | 4307 | 3.03 |
| 93-5 | 698 | 1240 | 56 | 57 | 55 | 51 | 73 | 74 | 72 | 80 | 76 | 3954 | 3.19 |

Notation: EC = evaporative cooler, Oper = operating time, RH = relative humidity, T = temperature, Avg = average, in = interior, at = attic, out = exterior, on, off = averaged for hours during which evaporative cooler is on or off.

Monitored Data for Roof Coatings, Oct 1 - Oct 18, 1994

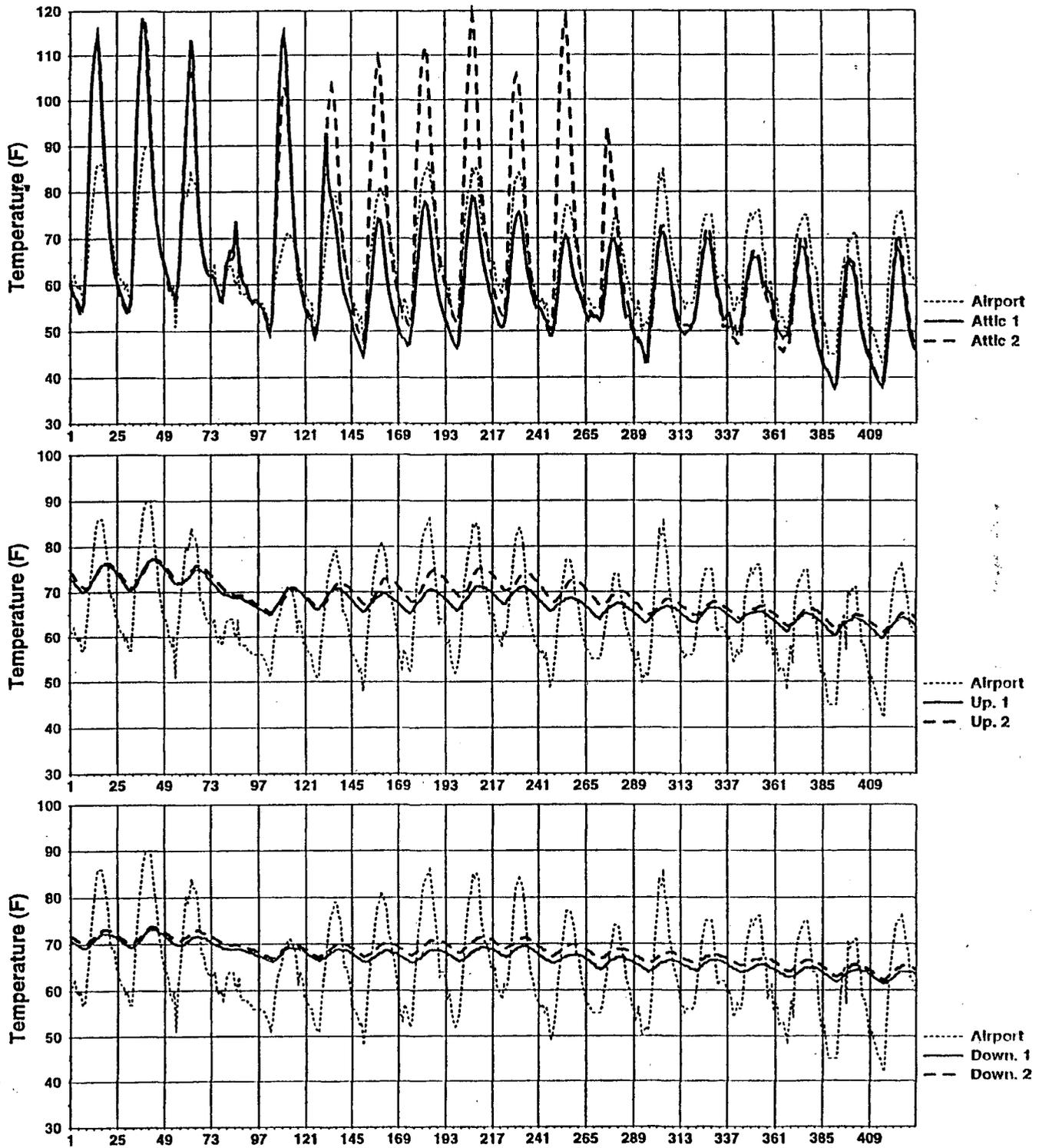


Figure 1.1

DOE-2.1E Results for Roof Coatings, Oct 1 - Oct 18, 1994, Exec

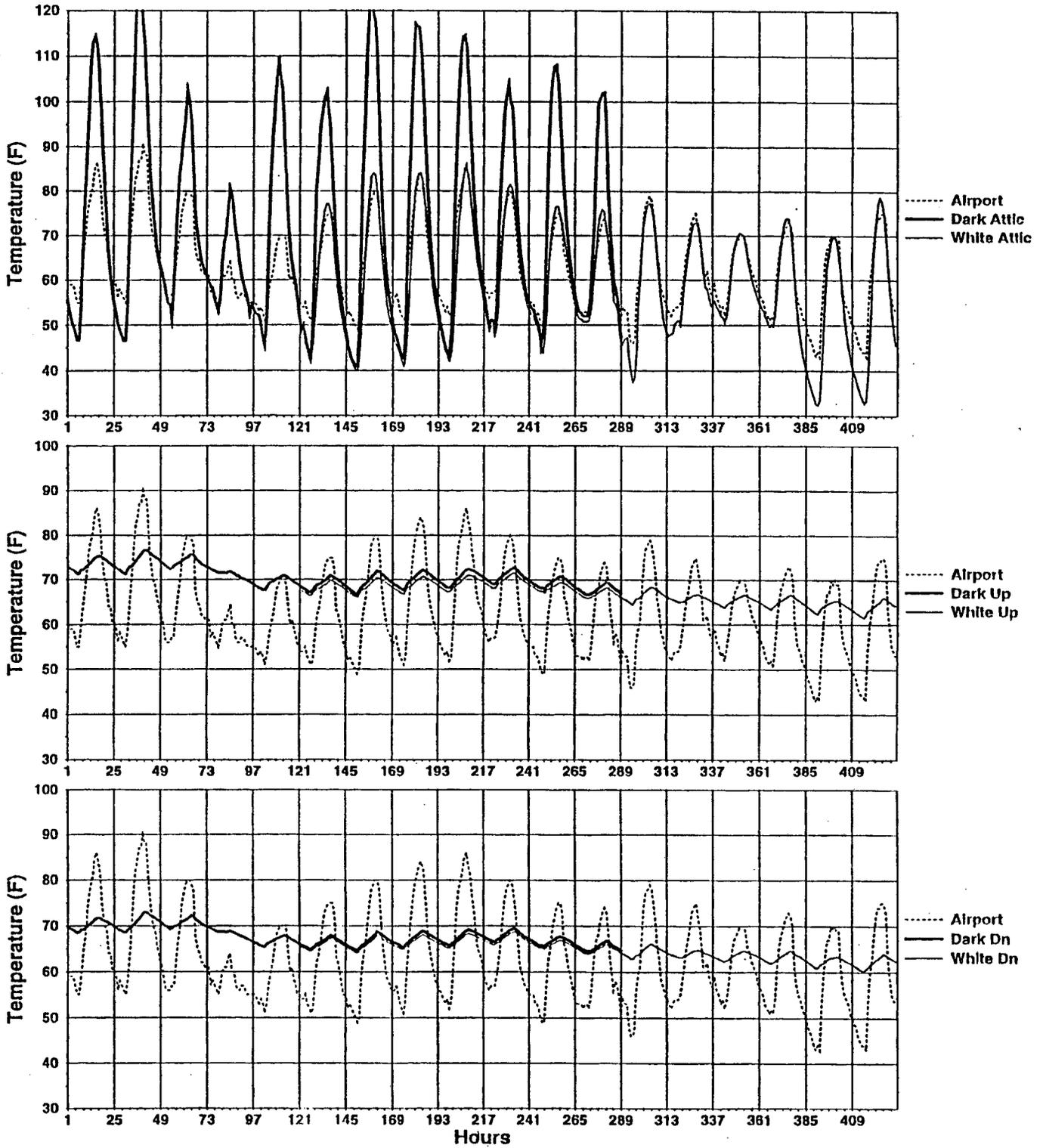
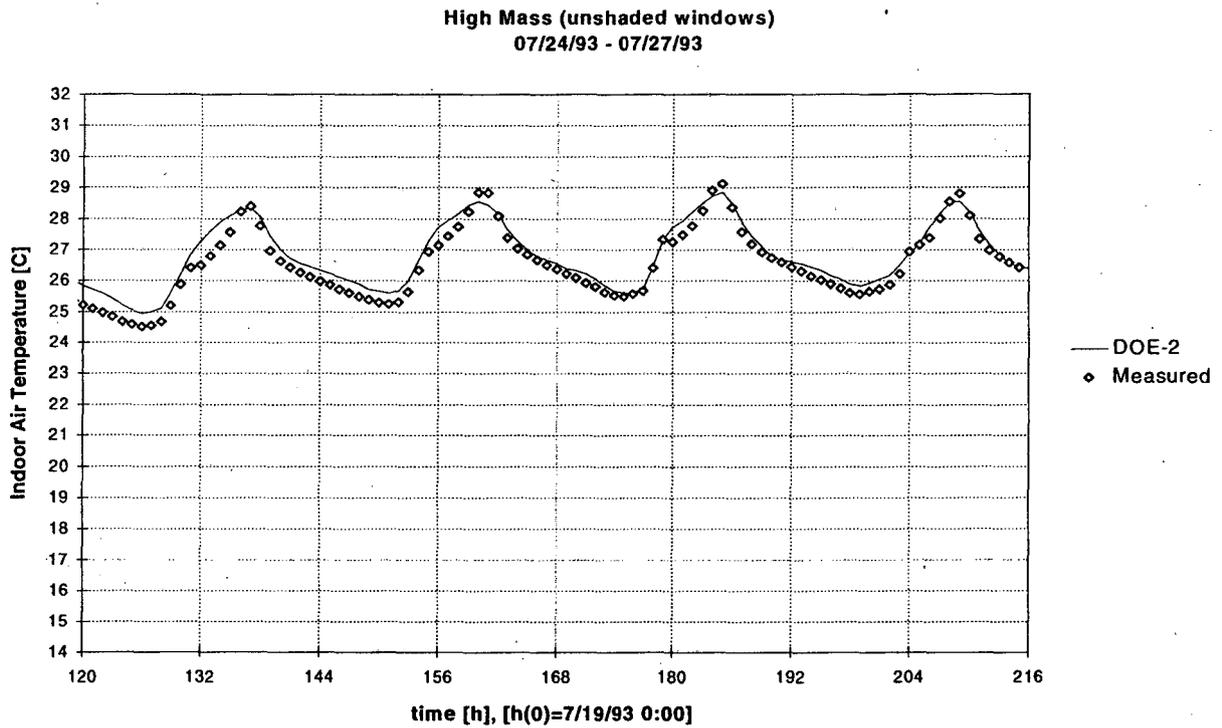
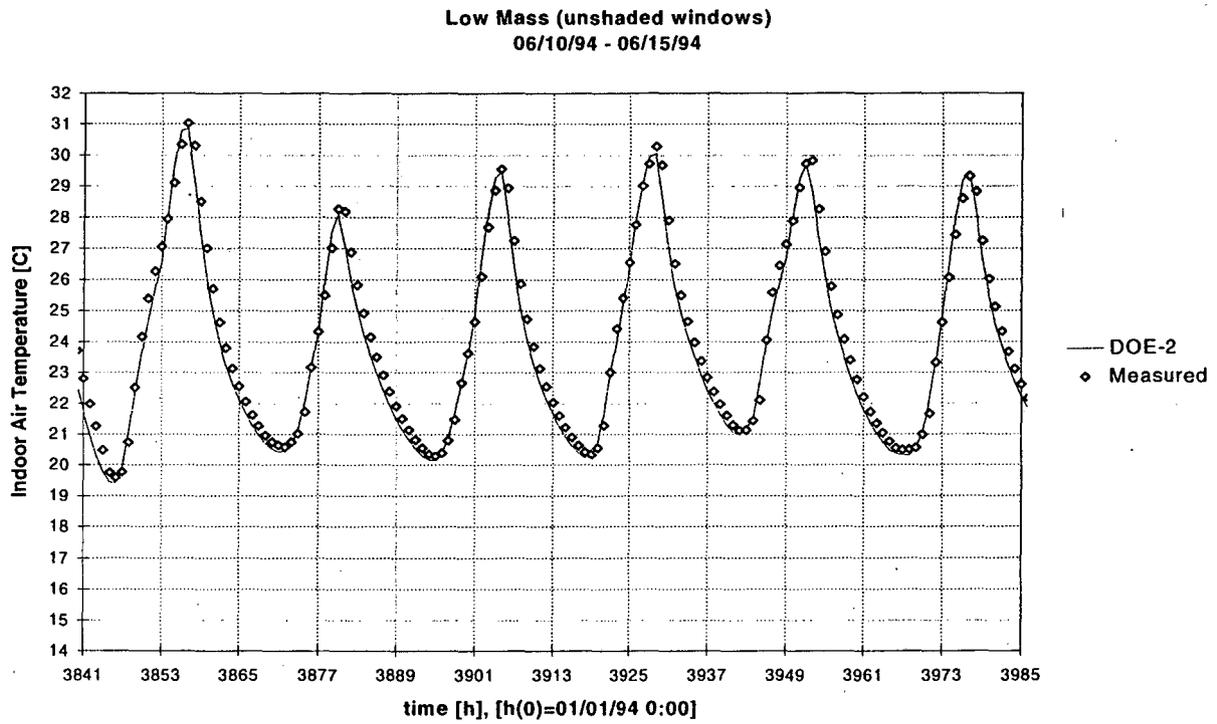


Figure 1.2

2. **DOE-2.1E: "Comparison of DOE-2 with Measurements in the Pala Test Houses."** Energy and Buildings 1998, V. 27, pp. 69-81. Meldem, R. and Winkelmann, F.
- a. Version of DOE-2 Program: DOE-2.1E (modified)
 - b. Building Type: Low-mass and high-mass houses built in 1981 with floor areas of 27 m² (291 ft²). The low-mass house had conventional stud wall construction; the high-mass house had 0.1m (4in) thick concrete walls with exterior insulation. The interiors was separated into 2 rooms with an open doorway and vented attic. The windows were single glazed with aluminum frame with a total area of 2.8 m² (30.1 ft²) and were distributed equally on all four facades. The buildings were unoccupied and had no interior loads. There was no mechanical heating or cooling.
 - c. Verification Type: Iterative. Exploratory sensitivity analysis resulted in DOE-2 modifications to the infiltration rate, ground surface absorptance, ground surface temperature, foundation heat transfer, cloud cover, and simulation warm-up period.
 - d. Location: Pala test site, latitude-33.5N, longitude-117.0W; 75 km north of San Diego, CA and 35 km from the coast.
 - e. Dates Monitored: Summer, 1995.
 - f. Configurations Monitored:
 - (1) Baseline: windows closed and unshaded; exterior walls and roof with original color; no night ventilation. Tests DOE-2 ability to simulate the basic heat transfer processes of conduction, convection, and radiation,
 - (2) Shaded windows: South, east, and west windows covered by exterior shades that reduce the solar gain by 80%. Tests DOE-2 ability to simulate exterior shading.
 - (3) Shaded windows, white walls and roof: Same as (2) with the exterior opaque surfaces painted white reducing the absorptance levels. Tests DOE-2 ability to simulate the solar radiation absorbed by walls and roof and the fraction of absorbed radiation that is conducted into the rooms.
 - (4) Shaded windows, white walls and roof, night ventilation: Same as (3) with rooms ventilated at 30 air changes per hour from 7pm-7am. Tests DOE-2 ability to simulate convective cooling of the building mass.
 - g. Data Monitored: Inside air and surface temperatures.
 - h. Monitoring Interval: Hourly for six days.
 - i. Conclusions: "The comparison results show that DOE-2 is in excellent agreement with the measurements for all the configurations for both the low-mass and high-mass houses" As a results of this work, three recommendations were made for improving DOE-2:
 - (1) The warm-up period in DOE-2 should be extended from its current sever days. to better account for the effective heat capacity of the building being simulated.
 - (2) The steady-state ground heat transfer model should be replaced by a 2-D dynamic model.
 - (3) The ground surface temperature should be calculated rather than assuming its equals the outside air temperature.
 - j. Summary: "The predictions of the DOE-2 program for building energy analysis have been compared with measurements in the Pala test houses near San Diego. This work is part of the California Institute for Energy Efficiency "Alternatives to Compressor Cooling in California Transition Zones" project in which DOE-2 is being used for parametric analysis of cooling strategies that reduce peak electrical power in hot, dry climates. To establish the validity of DOE-2 for this kind of analysis the program was compared with room air temperature measurements in a "low-mass" house with conventional insulated stud wall construction and a "high-mass" house with insulated concrete walls. To test different aspects of the DOE-2 calculation, four different unconditioned thermal configurations of these houses were considered: unshaded windows, shaded windows, white exterior surfaces, and forced nigh ventilation. In all

cases DOE-2 agreed well with the air temperature measurements, with a mean deviation between simulation and measurement ranging from 0.2 to 1.0 K depending on configuration and type of house. Using a development version of DOE-2 comparisons with inside surface temperature measurements were also made. These comparisons showed good agreement." Figure 2.1 is one example for the base configurations with shaded windows, an exterior solar absorptance of 0.60, and no ventilation.



DOE-2 vs. measurement for low-mass house (top) and high-mass house (bottom) for Configuration 2: original outside color, shaded windows and no ventilation.

Figure 2.1

3. **DOE-2.1E: "Empirical Validation of Thermal Building Programs Using Test Room Data."** International Energy Agency Annex 21/Task 12 Final Report, September 1994. Lomas, K.J.; Eppel, H.; Martin, C. and Bloomfield, D.
- a. Version of DOE-2 Program: DOE-2.1E
 - b. Building Type: Three low-mass test rooms, each with a floor area of 27 m² (291 ft²), with conventional stud wall construction and concrete slab floor raised clear of the ground were monitored. The spaces were highly insulated and also sealed to reduce infiltration to a minimum. The south-facing facade for the three test rooms contained either an opaque wall or window with wood frame with an area of 1.5m² (16.1 ft²). The buildings were unoccupied and had no interior loads. Heating was provided during one test period by an oil-filled radiator to maintain a setpoint temperature of 30°C (86°F).
 - c. Verification Type: Non-iterative. Data provided describing the test rooms and measured weather data.
 - d. Location: Cranfield airfield test site, Milton Keynes, UK, latitude-52.1N, longitude-0.63W, altitude-100m (328ft).
 - e. Dates Monitored: October, 1987 (heated) and May, 1990 (free-floating).
 - f. Configurations Monitored:
 - (1) South-facing opaque wall: Tests DOE-2 ability to simulate envelope conduction.
 - (2) South-facing single glazed window: Tests DOE-2 ability to simulate window conduction and solar heat gain.
 - (3) South-facing double glazed window: Tests DOE-2 ability to simulate window conduction and solar heat gain.
 - g. Data Monitored: South-facing vertical solar irradiance, inside air temperature, and for the heated rooms during the October tests, the energy consumption of a radiator.
 - h. Monitoring Interval: Hourly for seven days with a three day start-up during each test.
 - i. Conclusions: "The major problem with DOE-2 relative to this exercise is that the heat from the radiator is assumed to be 100% convective. The result...leads to an under-estimation of radiator output needed to maintain 30°C inside air temperature." If corrected with a more accurate radiator model, the resulting heating energy results were with 5% of the measurements for the rooms with the opaque wall and double glazed window. The DOE-2 1E calculated solar irradiance and inside air temperatures for the free-floating test agreed well with the measurements.
 - j. Summary: This report documents an IEA study aimed at validations of thermal simulation programs by comparing their results to measurements in real buildings. The USA was one of 12 participating countries and DOE-2.1E one of 17 simulation programs evaluated. Measured data was collected from three test rooms on an unobstructed site in England during a 10-day period in May in which they were free-floating and a 10-day period in October in which the rooms were intermittently heated. The rooms were single-zoned and well insulated with very low air infiltration and they were raised clear of the ground. Only the south facades of the rooms differed, two had different glazing and the third was opaque. Room air temperature and heating energy use compared as well as incident solar radiation.

Figure 3.1 and 3.2 show results for a double-glazed test cell during a free-floating day in May and a heated day in October. For both days, the incident solar as calculated by DOE-2.1E tracks the measured data quite well. The total south-facing vertical solar irradiance for two 7-day periods is shown on Figure 3.3 and again DOE-2 does comparatively well. In the case of indoor air-temperature in the free-floating case (Fig. 3.1), the comparison between DOE-2.1E and measured

data is also very good; however, the heated test cell comparisons (Fig. 3.2) are not as good in air temperature and heating energy. This discrepancy was explained in the report as being due to the fact that heating was modeled as 100% convective baseboards; whereas, the actual heater used in the test cell was an upright radiator with a substantial radiative output component.

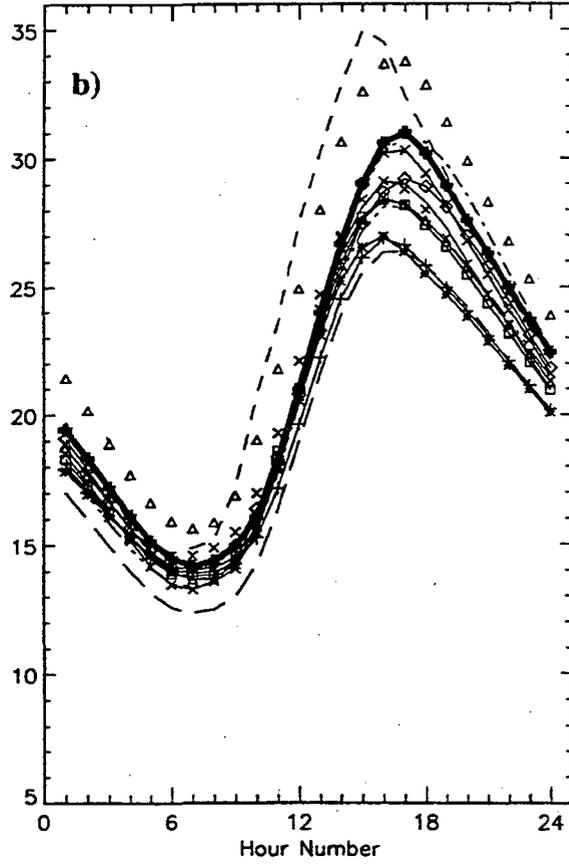
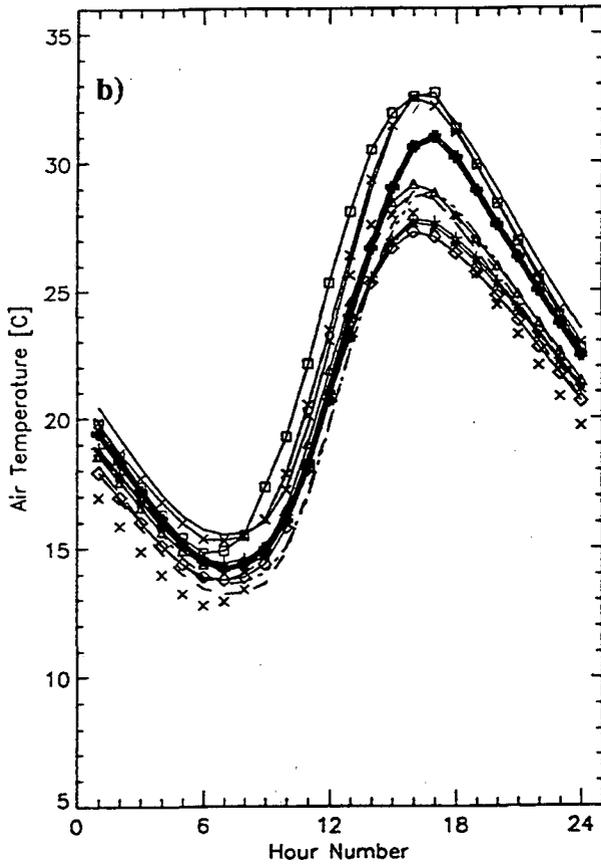
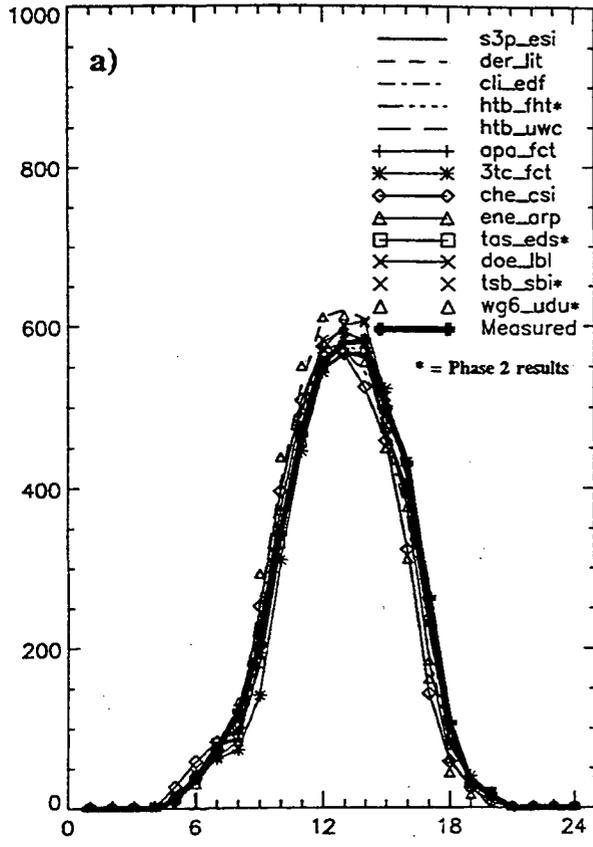
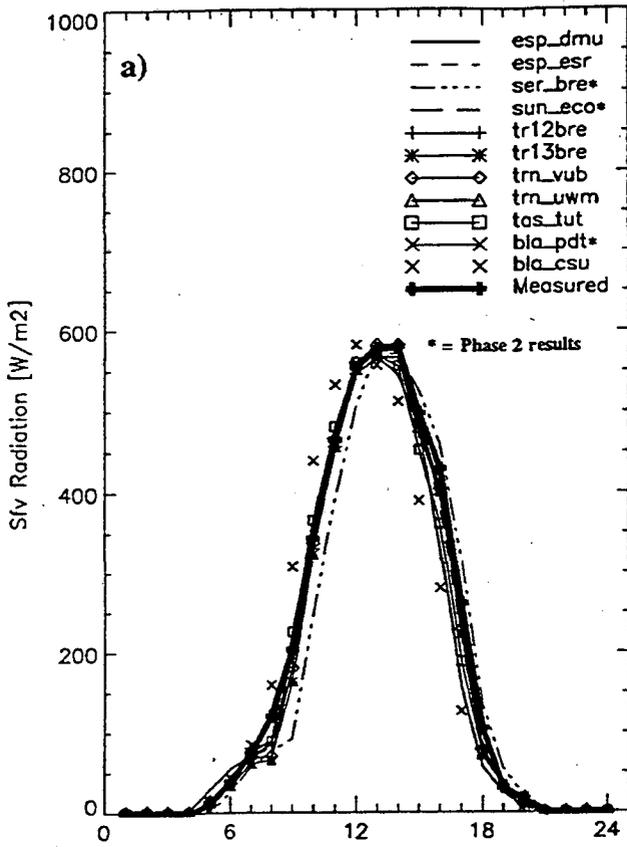


Figure 3.1. Phase 2 - Typical hourly predictions for one day in the free-floating (May) period (Day No. 147, double glazing)

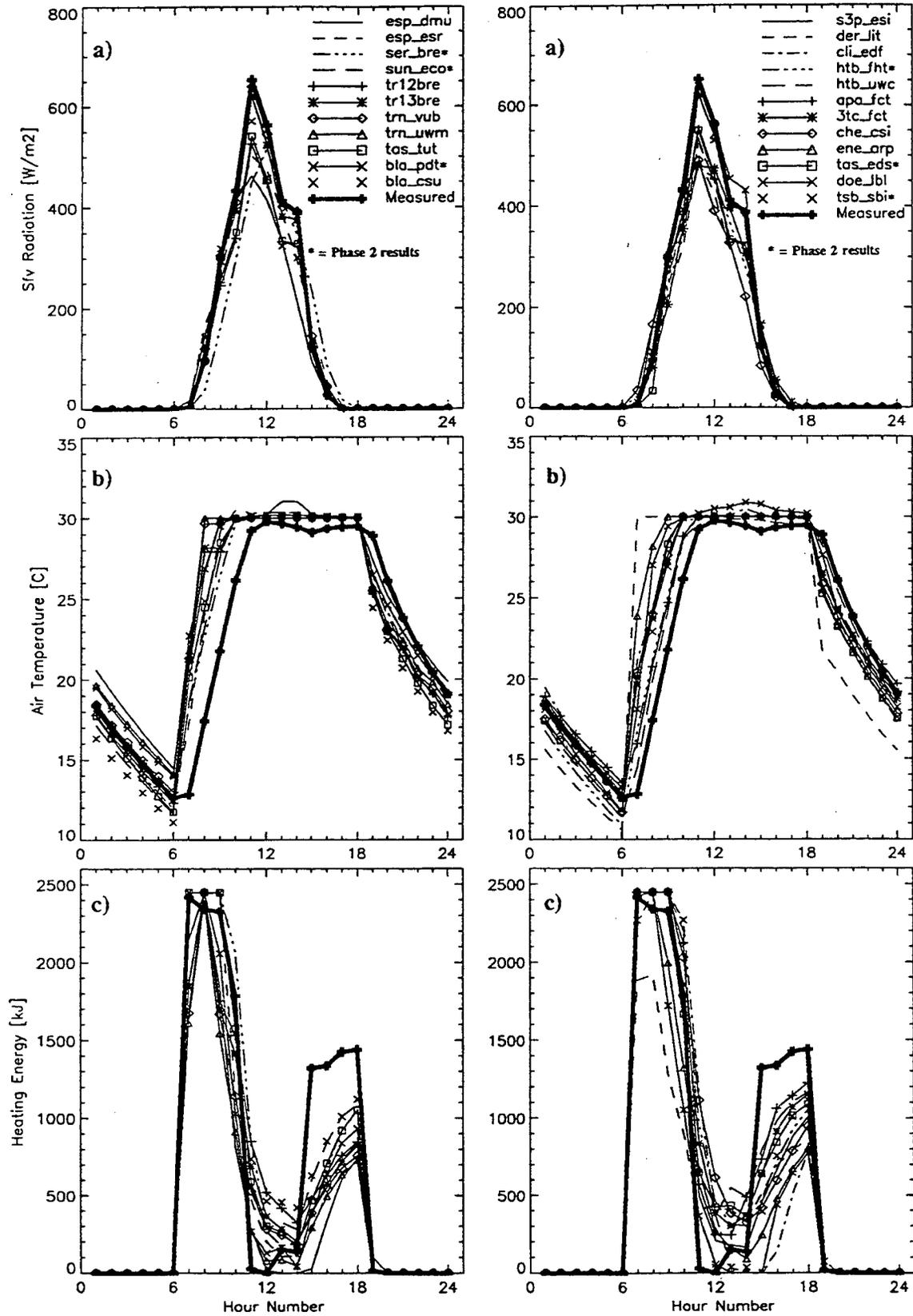


Figure 3.2. Phase 2 - Typical hourly predictions for one day in the heated (October) period (Day No. 296, double glazing)

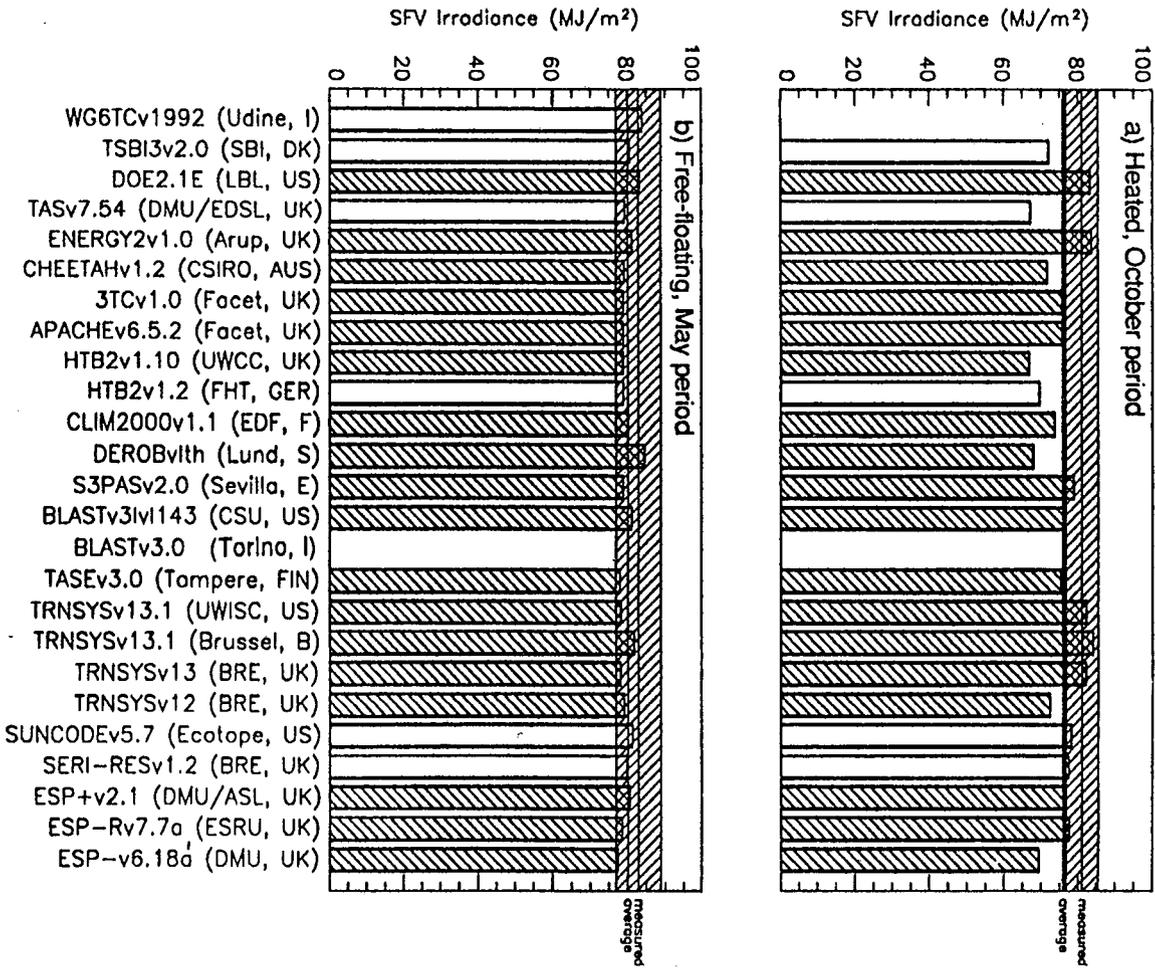


Figure 3.3. Total south facing vertical solar irradiances for the two seven-day periods

4. **DOE-2.1D: "Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area; Project Design and Preliminary Results."** Lawrence Berkeley Laboratory Report LBL-33342, 1992. Akbari, H., Bretz, S., Hanford, J., Rosenfeld, A., Sailor, D., Taha, H, and Bos, W..
- a. Version of DOE-2 Program: DOE-2.1D
 - b. Building Type: Six occupied low-mass residential houses with floor areas varying from 104.2 m² (1122 ft²) to 158.0 m² (1701 ft²) and one occupied school classroom bungalow with a floor area of 89.1 m² (960 ft²) were monitored. Site surveys were conducted to establish building configuration characteristics such as wall/roof insulation levels, window characteristics, shading details, HVAC system types and capacities, and thermostat setpoints. These were supplemented by assuming typical internal loads schedules and product literature when available.
 - c. Verification Type: Non-iterative. Data provided describing the buildings. Hourly weather data for the Sacramento airport during the testing period provided by the National Climatic Data Center, supplemented by on-site measurements of ambient weather data at one test site (Site 2). Simulation results were compared to measured data to study the sensitivity of increasingly more detailed building descriptions related to surface absorptance and or reflectance (albedo) and vegetative (shading) variations.
 - d. Location: Sacramento, CA; latitude-38.5N, longitude-121.5W.
 - e. Dates Monitored: August 1 through October 31, 1991.
 - f. Configurations Monitored:
 - (1) Site 1: Control site, no exterior surface absorptance or vegetation modifications.
 - (2) Site 2: Roof absorptance modified. Test DOE-2 ability to simulate surface absorptivity.
 - (3) Site 5: Vegetative shading on the east side modified. Test DOE-2 ability to simulate exterior shading.
 - (4) Site 6: Vegetative shading on the south and west side modified. Test DOE-2 ability to simulate exterior shading.
 - (5) Site 7: Vegetative shading on the south side modified. Test DOE-2 ability to simulate exterior shading.
 - (6) Site 8: Vegetative shading on the south side modified. Test DOE-2 ability to simulate exterior shading.
 - (7) Site B: Roof and south-east wall absorptance and emissivity modified. Test DOE-2 ability to simulate surface absorptivity and emissivity.
 - g. Data Monitored: Compressor watt-hours and interior air temperature.
 - h. Monitoring Interval: Hourly for one week.
 - i. Conclusions: "...Overall, the calibration exercise highlights the difficulty in matching simulation models with measured data. The types and magnitudes of the errors are not consistent across the sites. At Sites 5,7,and 8, the cooling load shapes from DOE-2 and measured data are similar, but the model underpredicts the actual magnitude. This suggests that the cooling system efficiency underpredicts the actual magnitude. Conversely, the model overpredicts the magnitude of the cooling load at Site 6, but the disagreement is potentially due to a thermostat which allows indoor temperatures to rise well above any setpoint

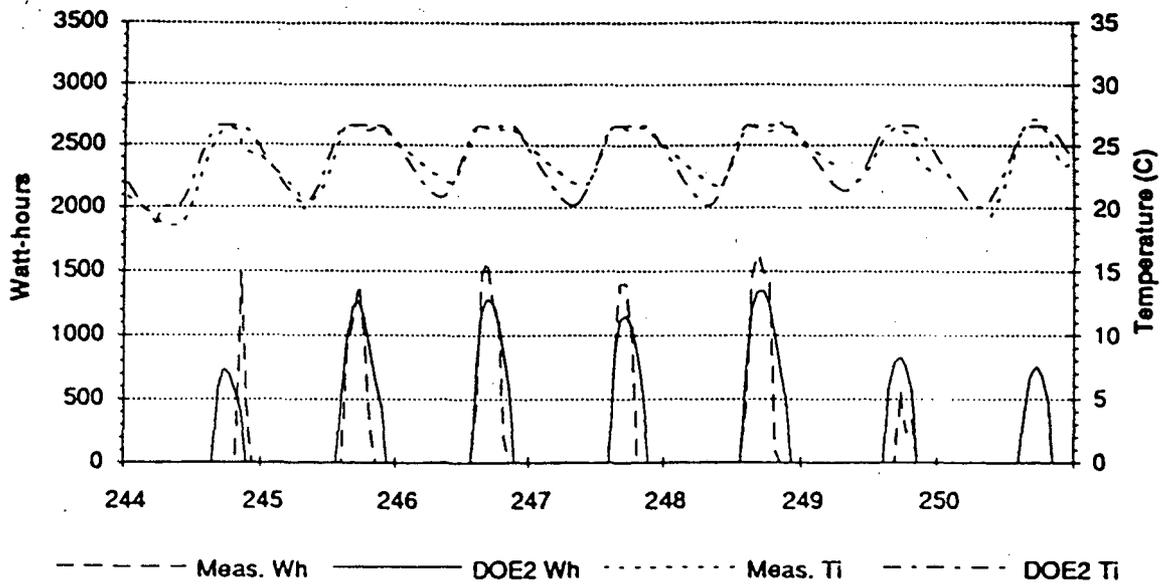
At Site 1, the control site, the model predictions and measured data agree well on daily cooling consumption, but the load shape is quite different due to a thermostat which appears to operate with a threshold before cooling is activated. At Site B, the agreement is satisfactory for the test building, but less so for the control unit....Site 2, however, has the most problematic disagreements between the simulated and measured data. The source is perhaps an incomplete characterization of the building's microclimate which is already heavily impacted by vegetation.

However, even when using site temperature and windspeed as model inputs, the model predicts more hours of cooling per day than shown in the measured data...” Figure 4.1 shows the comparison of measured and simulated data for Site 2 both before and after the surface absorptance modifications.

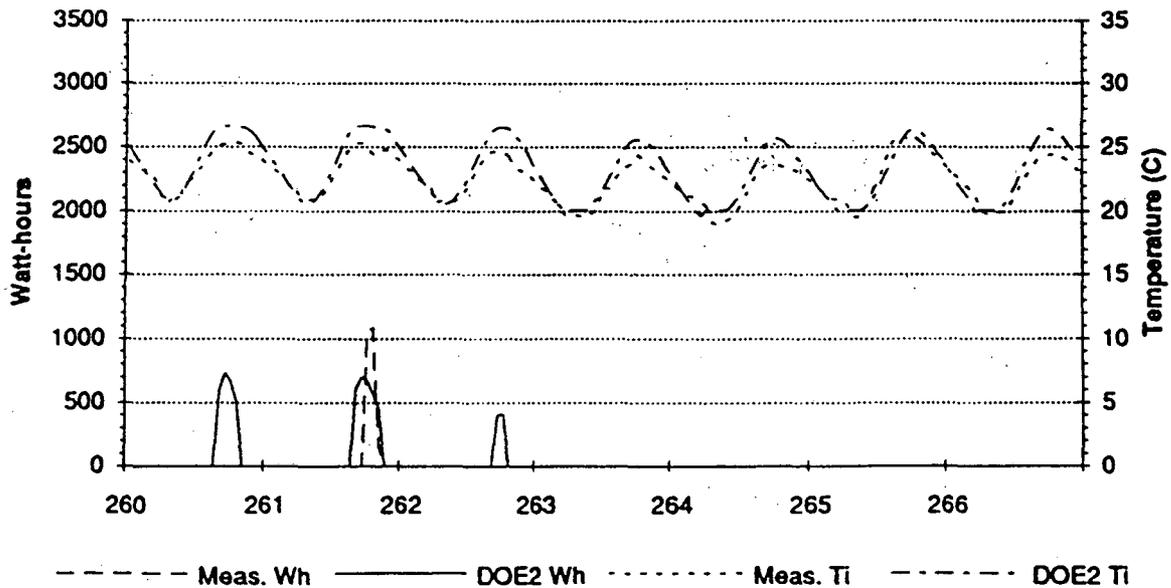
- j. Summary: “...Seven sites (six residences and one classroom bungalow) were instrumented and monitored in Sacramento, CA during the months of August, September, and October 1991. Measured variables included those of outdoor microclimate, envelope parameters, indoor microclimate, and cooling energy use. One site was selected for control, two sites were chosen for albedo modifications, and four sites were selected for vegetation modifications.

The purpose was to quantify the potential of high-albedo materials and vegetation for reducing cooling energy use in buildings. The analysis measured data indicates that albedo modifications had significant impacts on cooling energy use, whereas vegetation modifications did have measurable impact in two sites but only small effects in others...”

“...The analysis suggests the models could benefit from further refinements. However, given the current level of characterization for each site, the models perform reasonably well. The necessary refinements would focus on details of the cooling systems, which is the primary method of assessing albedo and vegetation impacts, occupancy patterns, thermostat operations, building thermal mass, and the local climate characteristics...”



Compressor watt hours and building interior temperature for 9/1 to 9/7 at Site 2. Comparison before albedo modification using ACTUAL SITE temperature and windspeed. Days 245 to 248 Measured: 5.5 kWh/day DOE-2: 7.0 kWh/day.



Compressor watt hours and building interior temperature for 9/17 to 9/23 at Site 2. Comparison after albedo modification using ACTUAL SITE temperature and windspeed. Days 260 to 266 Measured: 0.3 kWh/day DOE-2: 0.9 kWh/day.

Figure 4.1

5. **DOE-2.1D: "A Procedure for Calibrating the DOE-2 Simulation Program to Non-Weather-Dependent Measured Loads."** *ASHRAE Transactions* 92(1) 1992. Bronson, D.J.; Hinchey, S.B.; Haberl, J.S.; and O'Neal, D.L.
- a. Version of DOE-2 Program: DOE 2.1D
 - b. Building Type: A large, multipurpose building that contains classrooms, laboratories, faculty staff offices, and a central computer facility was monitored. It is a four-story building with a total floor area of 30,136 m² (324,400 ft²). The building measures 103.3m (339ft) by 67.4m (221ft) and is 18.3m (60ft) high. The long axis is oriented in a NE to SW direction. Nine percent of the building envelope is glazed. This consists of 232.3 m² (2,500 ft²) of single-pane clerestory windows and 836 m² (9000 ft²) of single-pane windows that are set back 0.9m (3ft). The building has a maximum occupancy of 2,300 people. The building has 12 constant-volume, dual-duct air-handling units that provide 15,962 L/s (330,500 cfm) to the 90+ zones in the building.
 - c. Verification Type: Iterative.
 - d. Location: Central Texas, latitude-31.6N, longitude-97.1W; two hours NW of Houston. .
 - e. Dates Monitored: September 1881-February 1993.
 - f. Configurations Monitored: Four different day-type electric and occupancy load profiles were varied in the DOE-2 input and the resultant energy use compared to monitored data. Tests DOE-2 ability to more accurately simulate building energy performance using better defined input load profiles.
 - (1) Baseline: DOE-2 Day-Type Profiles from the DOE-2 Reference Manual.
 - (2) ELF-OLF (Electric Load Factor - Occupancy Load Factor) Day-Type Profiles which utilize monthly electricity use and electric demand information and occupancy schedules.
 - (3) Auditor's Two-Week Day-Type Profiles that were created with hourly data selected from a two-week period meant to represent data that an energy auditing firm could have collected with portable measuring equipment.
 - (4) Katipamula-Haberl Day-Type Profiles results from a statistical day-typing of hourly data from a six-month data set.
 - g. Data Monitored: Electricity consumption of the whole building, submetered data for the motor control centers and the computer facility.
 - h. Monitoring Interval: Hourly for six months.
 - i. Conclusions: A procedure for calibrating DOE-2 to non-weather dependent loads was presented. Four day-typing methods were investigated. For the baseline using day-type profiles from the DOE-2 Reference manual, DOE-2 underestimated the electricity use by 26% for a six-month period. This figure was reduced to 1% by tuning the simulation day-type profiles. Table 5.1 presents a comparison of the simulated and measured data.
 - j. Summary: "Hourly building energy models such as DOE-2 and BLAST provide an effective method for simulating the energy use of a building during the design stage. Increasingly, such models are being used to evaluate retrofits in existing buildings. However, little agreement exists among the users of the models as to how to calibrate the simulation to measured data from a building. This paper presents a procedure for calibrating DOE-2 to non-weather-dependent (or scheduled) loads. The procedure relies on comparative three-dimensional graphics that allow for hourly differences to be viewed over the entire simulation period. Four different types of day-typing routines are demonstrated. DOE-2 simulations of the case study building were significantly improved when schedules based on measured data were introduced. For the case study building, the use of "canned" DOE-2 day-type profiles understated the electricity use by 26% for a six-month simulation period. Most importantly, the availability of comparative three-dimensional surface plots significantly improved the ability to view small differences

between the simulated and measured data, which allowed for the creation of a “super-tuned” DOE-2 simulation that matched the electricity use within 1%. The process of identifying and fixing unknown “misfits” between the simulation and the measured data was significantly enhanced by use of the plots.”

Table 5.1.

Comparisons of DOE-2 Simulated and Measured Non-Weather-Dependent Loads for the Engineering Center
 (Total monthly loads (MWh) are shown from the monitored data as simulated using day types from
 the auditor's two-week monitoring and using Katipamula and Haberi day types from the full data.)

| | Sep.1989 | Oct.1989 | Nov.1989 | Dec.1989 | Jan.1990 | Feb.1990 | Total |
|------------------------------|----------|----------|----------|----------|----------|----------|---------|
| (NOTE: All units are in MWh) | | | | | | | |
| Monitored | 847.6 | 879.5 | 848.4 | 796.5 | 792.1 | 749.8 | 4,914.0 |
| DOE-2 | 611.9 | 636.5 | 612.6 | 614.0 | 624.6 | 555.7 | 3655.3 |
| (% diff.) | -27.8% | -27.6% | -27.8% | -22.5% | -21.2% | -25.9% | -25.6% |
| ELF/OLP | 847.0 | 878.8 | 848.0 | 795.9 | 791.7 | 749.1 | 4,910.7 |
| (% diff.) | -0.1% | -0.1% | -0.03% | -0.1% | -0.05% | -0.1% | -0.1% |
| Auditor's | 795.7 | 823.8 | 792.3 | 801.0 | 789.5 | 744.4 | 4,746.6 |
| (% diff.) | -6.1% | -6.3% | -6.6% | 0.6% | -0.3% | -0.7% | -3.4% |
| Full Data | 874.0 | 876.4 | 832.0 | 815.4 | 823.4 | 725.0 | 4,946.3 |
| (% diff.) | 3.1% | -0.4% | -1.9% | 2.4% | 4.0% | -3.3% | 0.7% |

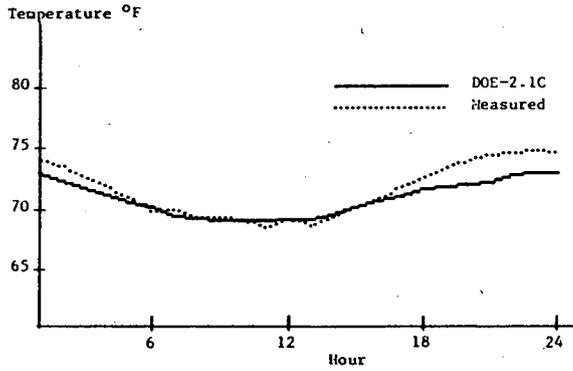
6. **DOE-2.1C: "Comparisons of Four Computer Models with Experimental Data from Test Buildings in Northern New Mexico."** *ASHRAE Transactions* 91(2) 1985. Robertson, D.K. and Christian, J.E.

- a. Version of DOE-2 Program: DOE-2.1C and DOE-2.1A
- b. Building Type: Four SWTMS windowless one-room test buildings with identical construction except for their exterior walls were analyzed. The rooms included: adobe with floor area of 37.2 m² (400 ft²), concrete masonry with floor area of 37.2 m² (400 ft²), and insulated wood-frame construction with floor area of 39.8 m² (428.5 ft²). The heating system consisted of three 1500W (5120 Btu) electrical resistance heaters controlled by a thermostat located in a centrally located destratification plenum space. There were no windows or doors.
- c. Verification Type: Iterative.
- d. Location: Southwest thermal mass study test site, latitude-35.8N, longitude-107.0W, altitude-1930m (6330ft), near Tesuque, NM.
- e. Dates Monitored: Midwinter-Jan 12-20, 1982; late winter-Feb 28 Mar 10, 1982; and spring-May 25-Jun 5, 1982.
- f. Configurations Monitored: Four one-room windowless buildings that are geometrically identical tests DOE-2 ability to simulate the effects of thermal mass on heating energy consumption, interior air temperature, and wall heat transfer.
- g. Data Monitored: Heating energy use, interior air temperature, and wall heat flux.
- h. Monitoring Interval: Hourly for six months.
- i. Conclusions: "...The simple 20ft (6.1m) by 20ft (6.1m) test cells with no windows, no doors, and well-insulated roof and floors are not simple to model. The principal reason is that the lack of detailed measurements on distribution of plenum air and natural convection within the test buildings creates uncertainty in how best to model the interior conditions. A second uncertainty surfaced due to the one-dimensional heat flow constraint in most commonly used mainfarme building simulation computer models... A third problem arising in these test buildings, designed to highlight the effect of exterior thermal mass, is caused by the relative importance of film coefficients in low r-value walls. The inside and outside film coefficients, although experimentally measured to some extent, vary continuously and are difficult to model..."
 - (1) Cumulative Heat Loads: "...The models seem to predict about 10% above measured loads for the massive cell and 10% below what was measured for the frame cell...The percentage errors in the spring are large compared to the winter periods; however, the absolute values are more than an order of magnitude smaller than those in the winter period...The conclusion...is that the heating load measurements are reproducible within the most likely experimental measuring error..."
 - (2) Interior Temperatures: "...A major complication in modeling these small test buildings is that the air temperature is horizontally stratified...Using DOE-2.1A, ...the least squares comparison of measured and predicted building interior air temperatures (mid-plane average near the wall) produced correlation coefficients for the massive cell of 0.76, 0.84, and 0.91 for the midwinter, late winter, and spring periods. For the frame cell, the same values are 0.89, 0.92, and 0.97..." Figure 6.1 shows a comparison of the measured and simulated interior air temperature for the adobe and wood-frame test buildings during the spring test period.
 - (3) Wall Heat Flux: "...The least squares correlation coefficients of the DOE-2.1A average hourly heat flux predictions and measurements for the massive building are 0.87, 0.93, and 0.84 for the midwinter, late winter, and spring periods, respectively. For the insulated frame, the correlation coefficients for measured versus DOE-2.1A heat flux predictions are 0.95, 0.98, and 0.90..."

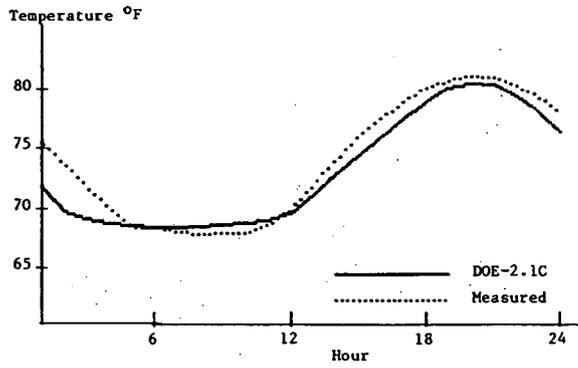
- j. Summary: "... one-room test buildings, 20ft (6.1m) square and 7.5ft (2.3m) high, were constructed on a high desert site near Tesuque, New Mexico, to study the influence of wall dynamic heat transfer characteristics on building heating energy requirements (the "thermal mass effect"). The buildings are nominally identical except for the walls (adobe, concrete and masonry unit, wood frame, and log) and are constructed so as to isolate the effects of the walls. The amount of mass in the walls varies from 240 lb/ft² (1171 kg/m²) for the 3ft (0.61m) thick adobe wall to 4.3 lb/ft² (21 kg/m²) for the insulated wood-frame wall. The roof, floor, and stem walls are all well insulated and the buildings were constructed with infiltration rates less than 0.4 air change per hour. The site is instrumented to record building component temperatures and heat fluxes, outside weather conditions, and heating energy use. Data was collected for two heating seasons from midwinter to late spring with the buildings in two configurations, with and without windows.

Four computer codes were used to simulate the performance of the test buildings without windows, using site weather data. The codes used were DOE-2.1A and DOE-2.1C, BLAST, and DEROB. Each code was run by a different analyst. Simulations were done for midwinter, late winter, and spring. Two of the test wall comparisons are discussed: the insulated frame and an 11 in (0.28m) adobe.

This work presents a quantitative and qualitative critical comparison of the modeling and experimental results. Cumulative heating loads, wall heat fluxes, and air and surface temperatures are compared, as well as input assumptions to the models. Explanations of differences and difficulties encountered are reported. The principal findings were that cumulative heating loads and the characteristic influence of wall thermal mass on hourly behavior were reproduced by the models."



a. Summer - Floating, May 31, 1982, 63.7°F average OA temperature.



b. Summer - Floating, May 31, 1982, 63.7°F average OA temperature.

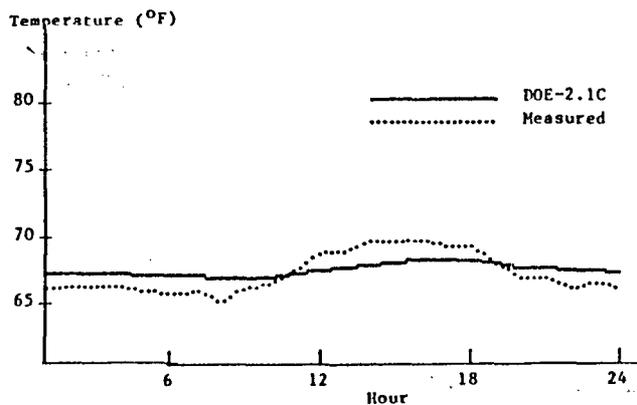
Figure 6.1.
Comparisons of DOE-2 predicted and measured interior air temperature
for adobe and wood-frame test buildings during spring.

7. **DOE-2.1C: "A Comparison of DOE-2.1C Prediction with Thermal Mass Test Cell Measurements."** Lawrence Berkeley Laboratory Report LBL-18981, January 1985. Birdsall, B.
- a. Version of DOE-2 Program: DOE-2.1C
- b. Building Type: Presents results for two separate validation experiments consisting of:
- (1) Three SWTMS windowless one-room test buildings with identical construction except for their exterior walls were analyzed. The rooms included: adobe with a floor area of 37.2 m² (400 ft²), concrete masonry with a floor area of 37.2 m² (400 ft²), and insulated wood-frame construction with a floor area of 39.8 m² (428.5 ft²). The heating system consisted of three 1500W (5120 Btu) electrical resistance heaters controlled by a thermostat located in a centrally located destratification plenum space. There were no windows or doors.
 - (2) Three NBS one-room test buildings, each with a floor area of 37.2 m² (400 ft²), with identical construction except for their exterior walls which consisted of: insulated wood frame, insulated masonry, and bare logs. Each building was heated by electric resistance heat and cooled by a split-system air conditioner.
- c. Verification Type: Iterative. Exploratory sensitivity analysis resulted in DOE-2 modifications to the wall construction and modeling the thermostat control setpoints.
- d. Location:
- (1) Southwest thermal mass study (SWTMS) test site, latitude-35.8N, longitude-107.0W, altitude-1930m (6330ft), near Tesuque, NM.
 - (2) NBS test site, Gaithersburg, MD, latitude-39.2N, longitude-77.2W.
- e. Dates Monitored:
- (1) Jan 1 - Jun 25, 1981.
 - (2) Jan 4 - Aug 5, 1982.
- f. Configurations Monitored:
- (1) Four one-room windowless buildings that are geometrically identical tests DOE-2 ability to simulate the effects of thermal mass on energy consumption, interior air temperature, and wall heat transfer.
 - (2) Three one-room buildings that are geometrically identical tests DOE-2 ability to simulate the effects of thermal mass on energy consumption, interior air temperature, and wall heat transfer.
- g. Data Monitored:
- (1) Heating energy use and interior air temperature.
 - (2) Heating and cooling energy use and interior air temperature.
- h. Monitoring Interval:
- (1) Hourly for heating (Jan 12 to 20), intermediate (Feb 28 to Mar 10), floating (May 25 to Jun 5).
 - (2) Hourly for heating (Feb 23 to 24, Mar 4), floating (Apr 19 to 22), cooling (Aug 1 to 3).
- i. Conclusions:
- (1) Comparisons of measured and simulated data of the SWTMS test cells was complicated by the thermostat in the each test cell being located in the central plenum space. Differences in energy use for extended test periods varied from 3% to 15% depending on the test cell construction and heating period. Space air temperature variations, in general, were within 1°C-2°C (1F-2°F) for most case; however, the variation was not consistent throughout the day.

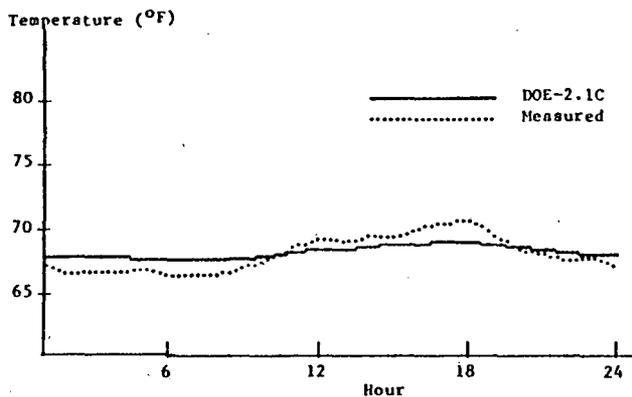
- (2) Modeling the three NBS test cell to close within 20% of the measured data was very difficult. There were a number of reasons for the disparity, both related to the modeling and also the validity of the measured data.
- j. Summary: “This report describes a comparison of DOE 2.1C predictions with thermal mass test cell measurements performed by the Building Energy Simulation Group of the Applied Science Division (ASD) at Lawrence Berkeley Laboratory, Berkeley, California. It is a companion study to one performed by the Passive Solar Group, ASD, at LBNL. The purpose of the study was twofold: first, a comparison was made of simulated results with measured data taken from test cells of differing wall constructions at Gaithersburg, MD and Tesuque Pueblo, NM. Second, a comparison was made of two computer simulations of a prototypical residence when using the programs to characterize the effects of wall thermal mass. The results indicate that the DOE-2 Computer Program for Building Energy Analysis and the Building Loads Analysis and System Thermodynamics (BLAST) programs give similar results and that DOE-2 closes within a reasonable tolerance plus or minus 20% to measured data from the test cells...” Figure 7.1 presents a comparison of simulated and measured air temperature data for the insulated frame building in New Mexico.

SWIMS CELL 7 — Frame Insulated

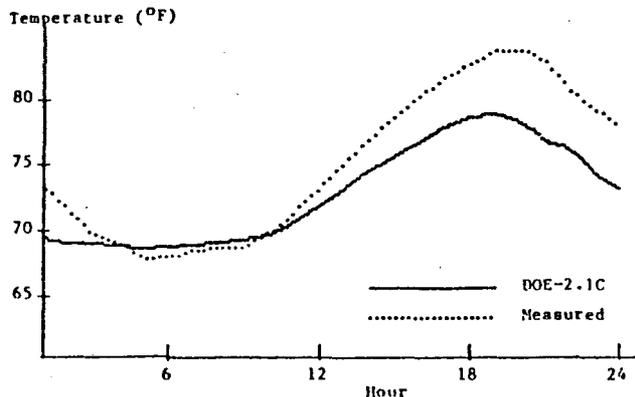
Measured versus DOE-2.1C space temperatures



Heating always on — January 14, 1982, 19.9°F average OA temperature



Intermediate — Modulating heat, February 28, 1982, 38.6°F average OA temperature



Summer — Floating, May 31, 1982, 63.7°F average OA temperature

Figure 7.1

8. DOE-2.1B: "Validation of Hourly Building Energy Models for Residential Buildings"
ASHRAE Transactions 91(2) 1985. Sorrell, F.Y.; Luckenback, T.J.; and Phelps, T.L.

a. Version of DOE-2 Program: DOE-2.1B

b. Building Type: Presents results for three separate validation experiments consisting of:

- (1) Four one-room test buildings, each with a floor area of 37.2 m² (400 ft²), with identical construction except for their exterior walls which consisted of: insulated lightweight wood frame, uninsulated lightweight wood frame, insulated masonry with mass outside, and uninsulated masonry. Each building was heated by electric resistance heat and cooled by a split-system air conditioner.
- (2) ORNL Annual Cycle Energy Storage (ACES) Control House is conventional frame construction with a floor area of 185 m² (2000 ft²). The house has three bedrooms, two baths, living-dining room, utility room, and entry hall. The house was unoccupied and during the testing period was operated with electric resistance heating and central air conditioning system.
- (3) NBS Houston Test House is a ranch style house, built with slab-on-grade with brick veneer construction. Its floor area is 122.6 m² (1320 ft²). It has three bedrooms, a combination living/dining room, and an integral two-car garage. The house was unoccupied and cooling supplied by a conventional central air conditioning system.

c. Verification Type: Iterative. On-site weather data including solar radiation, infiltration, and internal loads measured and used in the simulations. Although the basic experiments herein were non-iterative, the required inputs to the DOE-2 program that describe each building were developed from previous testing periods.

d. Location:

- (1) Gaithersburg, MD, latitude-39.2N, longitude-77.2W.
- (2) Oak Ridge, TN, latitude-35.8N, longitude-84.4W.
- (3) Houston, TX, latitude-30.0N, longitude-95.4W.

e. Dates Monitored:

- (1) Winter and summer.
- (2) Winter and summer, 1978.
- (3) Summer, 1979.

f. Configurations Monitored:

- (1) Four NBS windowless buildings that are geometrically identical tests DOE-2 ability to simulate the effects of thermal mass on heating energy consumption, interior air temperature, and wall heat transfer.
- (2) ORNL ACES Control House tests DOE-2's ability to simulate the basic heat transfer processes and interior air temperature variations in a residential building.
- (3) NBS Houston Test House tests DOE-2's ability to simulate the basic heat transfer processes and interior air temperature variations in a residential building.

g. Data Monitored:

- (1) Interior air temperature, energy consumption, and floor and wall heat transfer.
- (2) Interior air temperature and energy consumption.
- (3) Interior air temperature

h. Monitoring Interval:

- (1) Hourly for three days.
- (2) Hourly for six weeks.
- (3) Hourly for one day.

- i. Conclusions: “As a result of the present validation work, the following conclusions have been made:
- (1) Accuracy in predicting absolute energy use for a typical residential structure is 5% to 20% for a one to three day period. The computed results are generally in better agreement for longer time periods. The uncertainty in energy consumption is due to a combination of lack of knowledge about and thus ability to model the building and in the accuracy of the models themselves.
 - (2) DOE-2.1B is more accurate for frame and/or low-mass structures, at least for residential site buildings. The largest difference in computed and measured values occurred with DOE-2.1B in predicting the cooling load in small high-mass buildings.
 - (3) The models predict the relative hourly energy use or load profile of residential buildings to within 10% to 20%.”
- j. Summary: “A validation study was conducted to determine the accuracy of three computer programs, DOE-2.1B, EMPS 2.1, and TARPS4 in predicting the hourly energy use of residential structures. A validation data set was developed that consisted of previously conducted measurements of energy use and interior space temperatures for residential buildings. It was required that the buildings be unoccupied, have measured on site weather and measured infiltration for a range of weather conditions, and have the thermal properties of the building thoroughly documented. The measured data base consisted of NBS Test Houses, the ORNL ACES Control House, and the NBS Houston Test House. Each of those houses met these criteria, and the thermal properties of the walls, roof, and floor slab were measured for the NBS Test Houses. A comparison of computed and measured values of the hourly energy consumption, indoor temperature and attic temperature is made for a winter and summer period. Overall agreement is satisfactory, however, DOE-2.1B overpredicts the cooling energy required for the high mass NBS Test Houses and EMPS 2.1 underpredicts the required heating energy in some cases. Agreement is excellent for low mass frame structures, such as attics.” Figure 8.1 shows measured and simulated results of air temperature and electric energy consumption for one of the NBS test houses.

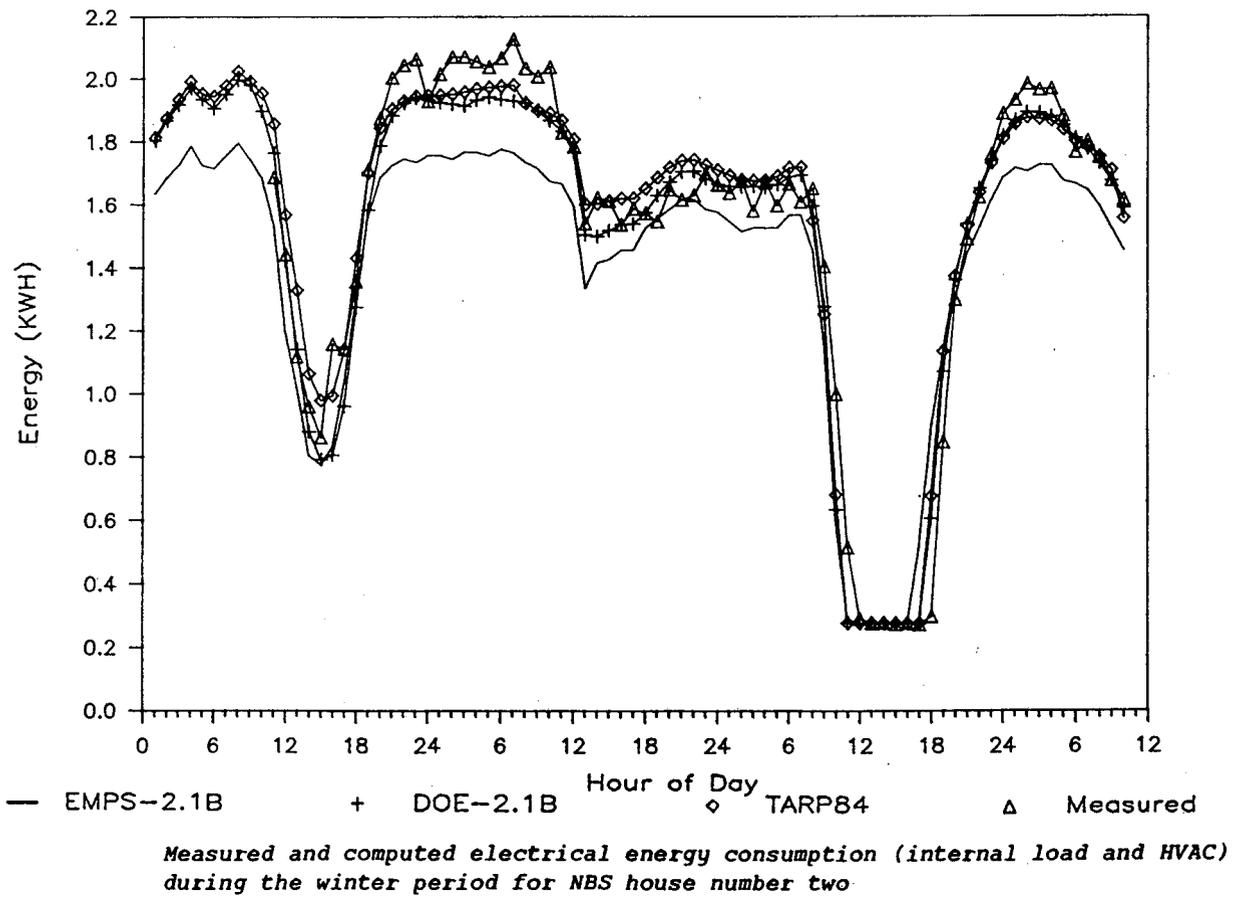
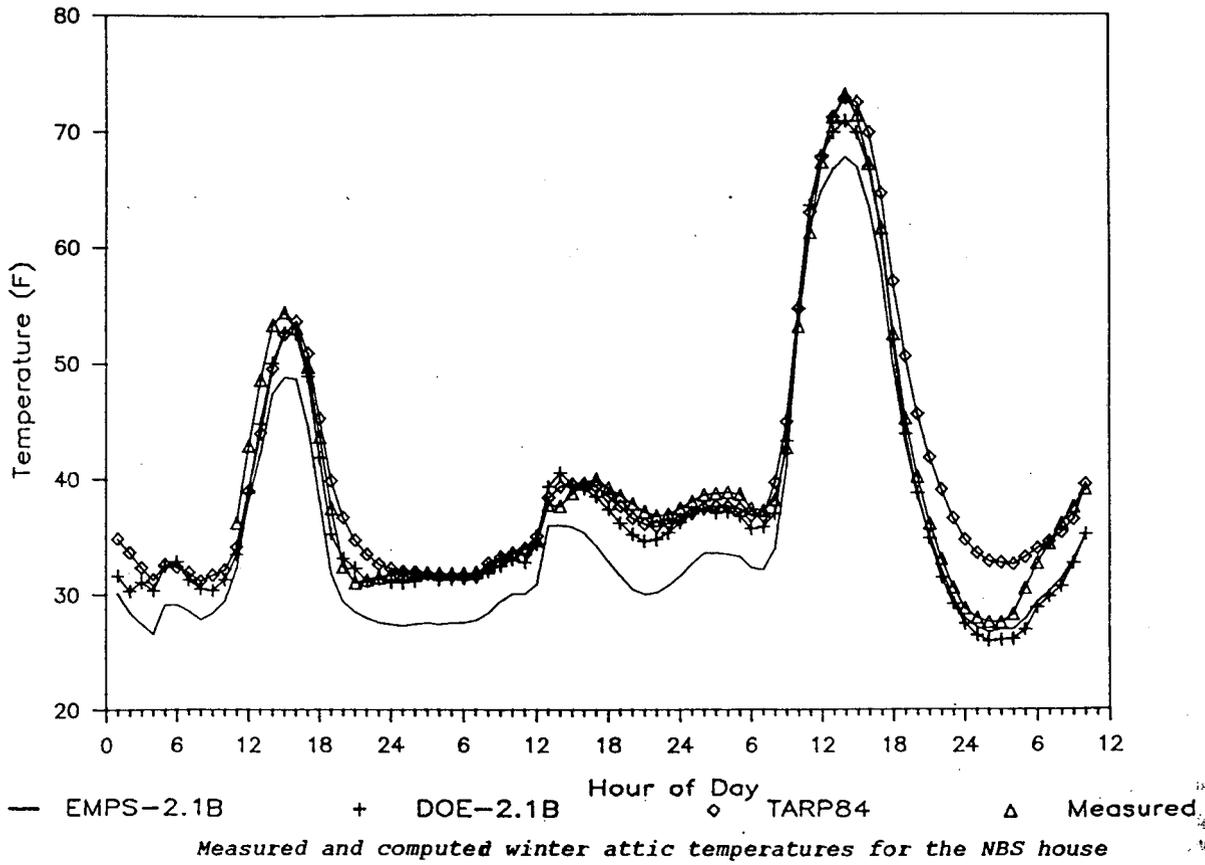


Figure 8.1

9. DOE-2.1, 2.1A: "DOE-2 Verification Project Phase 1 Final Report." Los Alamos Laboratory Report LA-10649-MS, February 1986. Diamond, S.C., Cappiello, C.C., and Hunn, B.D.

Compilation of studies. The complete Executive Summary from this report is presented. Results from this work are also reported in References 10, 13, and 16.

"This report presents the results of the DOE-2 Verification Project Phase 1 task that were not completed when the Phase 1 Interim Report [Ref. 17] was prepared in April 1981. Phase 1 of the project is an analytical and empirical verification of the DOE-2 building energy analysis computer program as a computational unit rather than as subprograms or as separate algorithms. The Phase 1 Interim Report addressed verification of the DOE-1.3, 1.4, and 2.0 versions of the program; this final report addresses verification of DOE-2.1 and 2.1A.

A major portion of this verification effort was an intensive user-effect sensitivity study to quantify the effects of the DOE-2 user under typical design conditions. Users were provided with three sets of increasingly refined input data specifications, which they used in comparing monthly and annual fuel, electrical, and total energy-use predictions for four commercial buildings. In addition, DOE-2 SYSTEMS program simulations were compared with laboratory test data and DOE-2 predictions were compared with those of other programs, with measured data, and with analytical results. Finally, the custom weighting factors (CWF) sub-program, used in passive solar and high thermal-mass building analysis, was rigorously tested. The results of these comparisons and tests are presented."

User-Effect Tests (Ref. 10)

"The user-effect tests show how user judgement and/or interpretation of data affected the dispersion (scatter) of results obtained by DOE-2 users. Four different types of buildings were used for the study: a bank in Santa Clara, California; a three-story office in Dayton, Ohio; an apparel store in Albuquerque, New Mexico; and a family restaurant in Downers Grove, Illinois. Six contractors and consultants, all experienced DOE-2 users, were selected to participate in our studies. Each contractor was provided with an identical set of general data packages, specifications, and drawings for the four buildings. The users were not given any measured data with which to compare their results. Three levels of input control were run in three successive tests.

1. Uncontrolled Input: Users were provided with "as is" building data packages that contained several ambiguities. None of their questions concerning input were answered, and the problem of ambiguities was left to their discretion.
2. Refined Input: Users were supplied with missing data, their questions regarding input were answered and gross ambiguities were eliminated.
3. Standard Evaluation Technique (SET) Input: Users were provided with the three sets of input specifications. SET is a prescribed method of using DOE-2 to calculate design energy use. Portions of the input were prescribed as fixed parameters.

Each contractor simulated each of the four buildings in succession, using the three sets of input specifications. The results were plotted in terms of monthly energy consumption for fuel, electrical, and total energy use. The monthly deviations among multiple users were compared with the monthly energy consumption averaged over all users and were then coplotted to compare the scatter for the three input sets. The following is a summary of the results of these comparisons.

1. As the DOE-2 user's input specifications became more complete and less ambiguous, the scatter in their monthly predictions of total energy consumption was successively reduced. The scatter reductions ranged from a factor of 1.2-2.7 when going from uncontrolled to refined input, thus eliminating errors and gross ambiguities. The scatter reductions ranged from a factor of 1.3-1.9 when going from refined input to SET input.
2. In most of the cases studied, scatter was greater for fuel energy consumption than for electrical energy consumption. Furthermore, as the user's input specifications became more controlled,

the reduction in scatter generally was greater for fuel energy consumption than for electrical energy consumption.”

“It was concluded that when the input is uncontrolled, considerable scatter in monthly results can be expected among expert users of building energy analysis computer programs such as DOE-2. The most significant reduction in scatter can be obtained by having an independent observer check the input for errors and by eliminating gross ambiguities in the input.” Figure 9.1 presents the user-effect tests for the monthly total energy consumption in a single-story office building with a floor area of 624 m² (6723 ft²) located in Santa Clara, California. Results are shown for the uncontrolled and refined input building descriptions. Table 9.1 summarizes the complete set of user-effect tests.

DOE-2.1A: Construction Engineering Research Laboratory (CERL) Studies (Ref. 16)

“The United States Army CERL conducted laboratory test of various types of heating, ventilating, and air conditioning (HVAC) systems. W.S. Fleming and Associated, Inc., compared the results of these tests with the system and plant performance tests calculated by DOE-2.1A for two major system types. The systems were first simulated using DOE-2 in its standard form with few changes to the default values for system parameters. The performance curves were then used for the actual equipment being simulated. Twenty-one of the test cases were compared for the variable-air-volume system and twenty-eight for the reheat fan system. The results showed that although the difference between predicted and measured daily electrical or fuel energy consumption in some tests was fairly large, the average difference, using the DOE-2.1A default values was about plus or minus 12%. The use of actual equipment performance curves improved the electrical energy consumption predictions within plus or minus 5% of the measured values.”

DOE-2.1: Lawrence Berkeley Laboratory (LBL) Studies

“LBNL compared NBSLD, BLAST-2, and DOE-2.1 simulations for a lightweight residential building in six climates. Their comparison indicated close agreement in predicting heating and cooling loads. However, when the standard weighting factors (SWF) rather than the CWF were used, DOE-2.1 consistently predicted heating loads that were lower than those predicted for the other two programs. When either the CWF or SWF were used, DOE-2 predicted higher cooling loads. The differences were attributed to the direct and diffuse solar radiation processing algorithms in DOE-2.1. A parametric study that used the CWF to compare only BLAST-2 and DOE-2.1 showed good agreement for heating and cooling loads for all parametric variations. Finally, a comparison of design-day predictions of the three programs showed good agreement in the peak loads predicted, the time-of-day occurrence of the peak, and the hourly profile. It was concluded that when the CWF are used in DOE-2.1, the prediction of loads for a lightweight building are more consistent.”

DOE-2.1: Solar Energy Research Institute (SERI) Studies (Ref. 13)

“Two major studies were conducted by SERI. The first compared heating and cooling load predictions of four building energy analysis computer programs, including DOE-2.1, for a low-mass and a high-mass residence. The programs showed substantial agreement for the heating loads and low-mass cooling loads but differed markedly for the high-mass cooling loads. An error was subsequently discovered and corrected in one of the programs.

In the second SERI study, temperature and energy flows for three programs, including DOE-2.1, were compared with analytical solutions for simplified test buildings, both with and without solar radiation effects. Although the steady-state tests showed slight, but explainable, differences among the three programs, they showed generally good agreement with the analytical solution. Results of the transient tests showed close agreement among the programs and the analytical solution for air temperature and thermal mass temperature histories.”

DOE-2.1: National Bureau of Standards (NBS) Studies

“The NBS compared DOE-2.1, a modified degree-day method, and the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) TC 4.7 modified bin method. The

comparison showed a 15% agreement in predicted annual energy consumption for four residences in ten localities.

ASHRAE compared seven building energy analysis computer programs, including DOE-2.1, with ASHRAE TC 4.7 simplified procedure for energy calculations. For their study, they used an office building in Washington, DC that had four different HVAC systems. The results, which showed large differences among the predicted annual energy consumption, suggested that the differences resulted from the user effect rather than from the calculation techniques.

A test summary of the DOE-2.1 solar simulator was prepared. The summary compared DOE-2's predicted performance with predictions of the TRNSYS program, which is the recognized standard for active solar-system simulation. In the four climates studies, predicted annual solar fractions and collector efficiencies showed nearly identical results for the two programs.

The NBS studies include several comparisons of DOE-2.1 predictions with measured data. Under the DOE-2 Passive Solar Class A Performance Evaluation program, one-week sets of measured data from three passive solar buildings were compared with DOE-2.1 predictions. Root-mean-square differences between predicted and measured hourly space temperatures typically were plus or minus 0.8°C-1.1°C (1.5F-2.0°F) over the test period. However, for the NBS Direct-Gain Test Cell, DOE-2 overpredicted the space temperature on cloudy days. Predictions of peak heating loads for fixed thermostat settings were within 9% of the measured values for the SERI Validation Test House." Figure 9.2 presents a comparison of measured and DOE-2 simulated air temperature and heat extraction rates from this NBS study.

DOE-2.1: Electric Power Research Institute (EPRI) Studies

"The EPRI study tested five building energy analysis computer programs against hourly and annual metered energy use for a conventional residence in Columbus, Ohio. All the computer programs, including DOE-2.1, predicted total energy use within 8% of the metered annual data." Figure 9.3 presents a comparison of measured and DOE-2 simulated total energy use from this study.

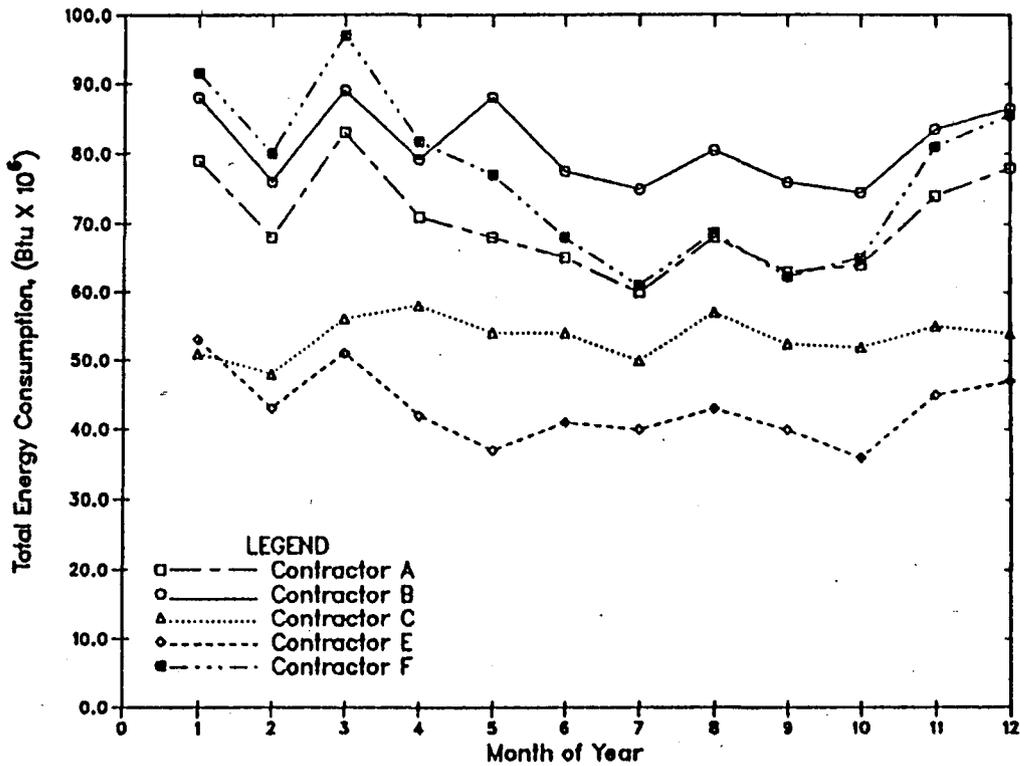
DOE-2.1A: Los Alamos CWF Accuracy Verification Tests

"Los Alamos National Laboratory conducted studies to verify the accuracy of the CWF routines in DOE-2.1A. The first test series used the Los Alamos Direct Gain Test Cell. During a one-week test period, with the cell temperature floating, agreement between DOE-2.1A predictions and measured hourly cell air temperatures were quite good. The second series of tests were conducted on four passive solar buildings. Tests on two buildings, a direct-gain residence and a small office/warehouse building, showed only fair agreement between DOE-2.1A and measured space temperatures, with differences of 3.9°C (7.0°F) during the peak solar hours. However, these differences were attributed to unmodeled effects in DOE-2.1A (such as manually operated storage vents). Tests were conducted in the NBS High-Mass Test House in the NBS environmental chamber on a simulated sunny day. These tests showed close agreement between measured and predicted space temperatures and heat-extraction rates. Measured and calculated heat-extraction rates for a low-mass, conventional test house in Houston, TX were in reasonably good agreement." Figure 9.4 presents a comparison of measured and DOE-2 simulated air temperature from this study.

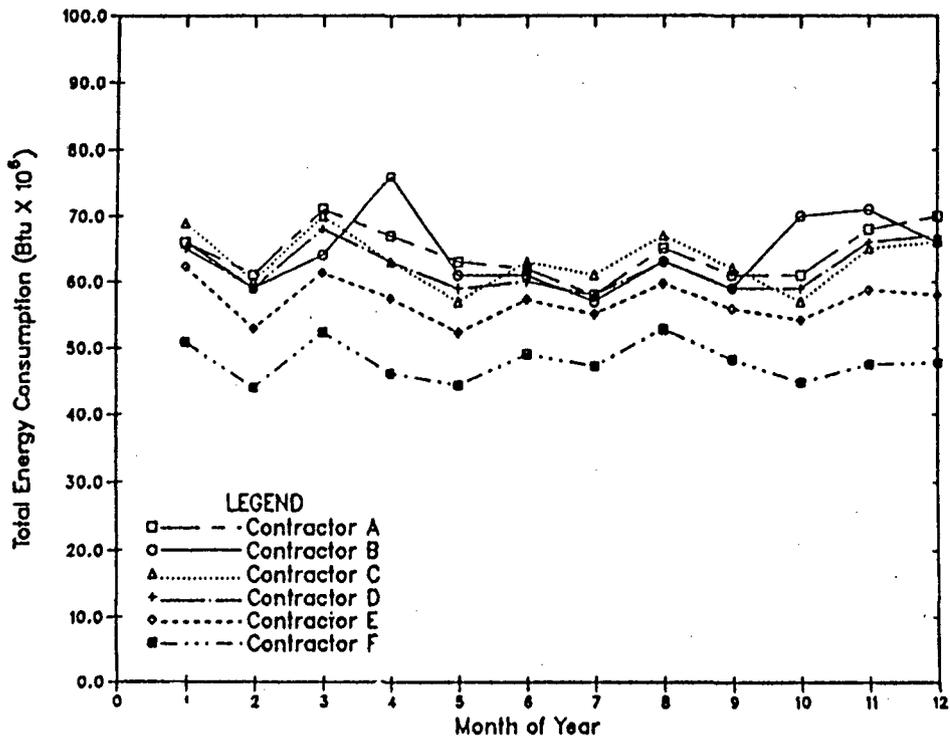
"We concluded from our studies that when the CWF were used, the DOE-2.1 predictions usually agreed well with measured laboratory and field data and with predictions of other building energy analysis computer programs. We also concluded that significantly more differences result from user effects than from differences in calculation techniques."

Table 9.1

| USER-EFFECT COMPARISONS | | | |
|--|-------------------------|-------------------------------|--------------------------|
| <u>Monthly Standard Deviation (Btu x 10⁶)</u> | | | |
| <u>Building</u> | <u>Fuel Consumption</u> | <u>Electrical Consumption</u> | <u>Total Consumption</u> |
| Single Floor | | | |
| Uncontrolled | 11.3 | 1.4 | 14.9 |
| Refined | 3.9 | 1.0 | 6.4 |
| SET | 3.3 | .9 | 5.0 |
| Multifloor | | | |
| Uncontrolled | 350.2 | 49.2 | 498.7 |
| Refined | 94.4 | 47.0 | 184.0 |
| SET | 97.1 | 14.1 | 104.9 |
| Retail Store | | | |
| Uncontrolled | 139.9 | 21.8 | 162.0 |
| Refined | 145.1 | 13.5 | 131.9 |
| SET | 98.5 | 4.6 | 68.6 |
| Restaurant | | | |
| Uncontrolled | 213.5 | 9.1 | 222.6 |
| Refined | 128.8 | 10.5 | 137.1 |
| SET | 118.3 | 9.9 | 106.3 |

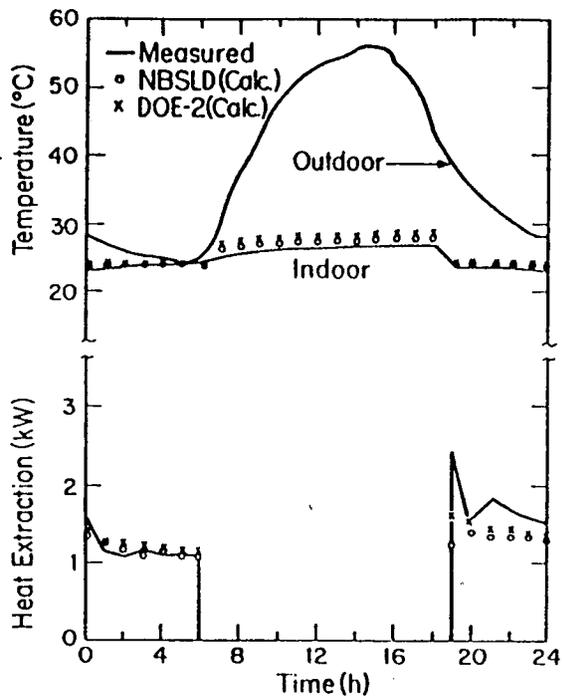


User-effect test with uncontrolled input: total energy use in single-floor office building.

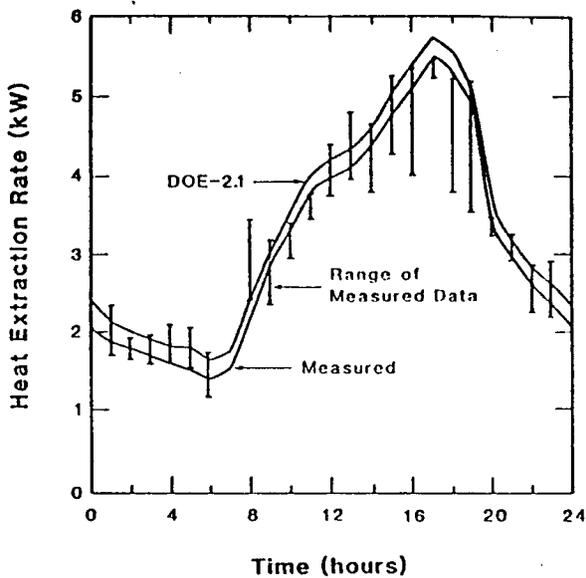


User-effect test with refined input: total energy use in single-floor office building.

Figure 9.1

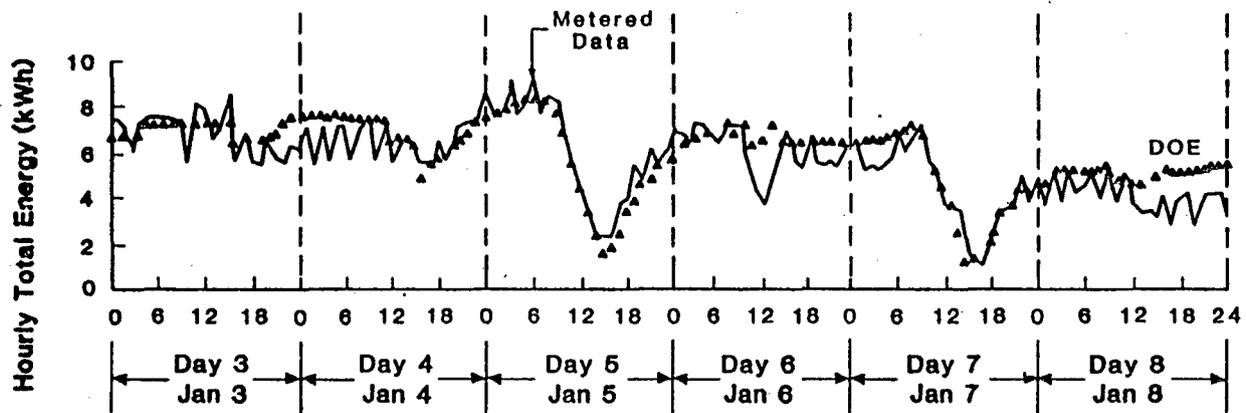


Comparison of DOE-2 and NBSLD predictions and measured air temperatures and heat-extraction rates for the NBS High-Mass Test House in Houston, Texas.



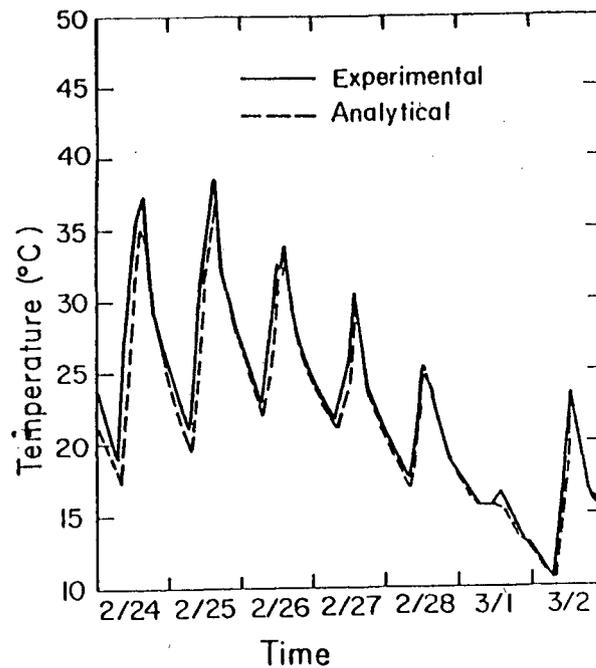
Comparison of DOE-2 predictions and measured heat-extraction rates for the NBS High-Mass Test House in Houston, Texas.

Figure 9.2



DOE-2.1A predictions vs measured hourly total energy use for a residence in Columbus, Ohio.

Figure 9.3



Comparison of DOE-2.1A predictions and measured air temperatures for the Los Alamos direct-gain test cell.

Figure 9.4

10. **DOE-2.1A: "User Effect Validation Tests of the DOE-2 Building Energy Analysis Computer Program."** *ASHRAE Transactions* 91(2) 1985. Diamond, S.C.; Cappiello, C.C, and Hunn, B.D. (See Reference 15; quoted floor areas are not the same.).

See Reference 15 for Energy Comparison tests; however, the quoted floor areas are not the same.

a. Version of DOE-2 Program: DOE-2.1C

b. Building Type:

- (1) Single-floor office building: Bank branch office built in 1974. Net floor area is 625 m² (6723 ft²). Construction is insulated frame walls, built-up roof, and concrete floor. Windows are 1.3cm (1/2in) solar-grey glass. Maximum occupancy is 120 people and the maximum internal equipment load is 18.2 kW. The building has three thermostatically controlled zones served by three constant-volume reheat systems. Plant equipment consists of hot-water boiler and a reciprocating chiller.
- (2) Multifloor office building: Headquarters for a steak house chain. Three-story, 6507 m² (70,000 ft²) rectangular office complex. Has a glassed-in entrance way and a north-facing glass-curtain wall; the remaining envelop structure is grey granite block. Peak occupancy is 200 persons and the maximum equipment load is 20 kW, except for a computer room which is 58.6 kW. The mechanical system consists of two large and one small constant-volume reheat systems servicing 46 zones. The plant equipment consists of oil-fired boilers, electric boilers, centrifugal chillers, DHW heater.
- (3) Retail store: One-story apparel store with a floor area 3067 m² (33,000 ft²). The building exterior is precast concrete with a store front of face brick and glass. Maximum occupancy varies from 300 persons to 1300. The mechanical system is a multizone air system with six zone air-handling units. The plant equipment is a gas-fired, hot-water boiler, direct expansion chiller, and an indoor wet cooling tower.
- (4) Restaurant: A single-story building with a floor area of 1518 m² (16,330 ft²). The building has cooking and food storage facilities, private dining room, cocktail lounge, and management offices. The envelope is hollow-core concrete block with vermiculite-fill insulation. All windows are double-glazed and nonoperable. Occupancy varies from 400 to a maximum of 1400 per day. The HVAC system consists of two constant-volume, variable temperature, multizone air systems. The plant equipment includes two gas-fired boilers and two reciprocating electric chillers.

c. Verification Type: Iterative. "...Three levels of input control were defined: (1) Uncontrolled in which the buildings were described under normal field conditions as they would be to a consultant conducting an energy audit...; (2) Refined input in which missing data were supplied, gross ambiguities in the data were eliminated, and questions concerning the simulations were answered...; and (3) Standard Evaluation Technique in which the input for each building was defined by the SET that was used in conjunction with the BEPS (Federal Register 1979) proposed by the U.S. Department of Energy..."

d. Location:

- (1) Santa Clara, CA, latitude-37.4N, longitude-121.9W
- (2) Dayton, OH, latitude-39.9N, longitude-84.2W
- (3) Albuquerque, NM, latitude-35.0N, longitude-106.6W
- (4) Downers Grove, IL, latitude-41.9N, longitude-87.6W

e. Dates Monitored: Not applicable.

f. Configurations Monitored: Not applicable.

g. Data Monitored: Not applicable.

h. Monitoring Interval: Not applicable.

- i. Conclusions: "The comparison of predicted monthly energy use results for these four buildings using three different sets of input specifications indicates the following conclusions:
- (1) Scatter in the monthly total energy consumption predictions by multiple users of DOE-2 is successively reduced as the input is tightened by being made more complete and less ambiguous. The scatter reductions range from 19% to 63% in going from uncontrolled to refined input, where errors and gross ambiguities have been eliminated. However, in going from the refined input to the SET input, where many input parameters are specified, the scatter reductions are not as marked, ranging from 22% to 48%.
 - (2) In the vast majority of cases studied, the scatter is greater for fuel energy consumption than for electrical energy consumption. Furthermore, as the input specifications are tightened, the reduction in scatter generally is larger for fuel energy consumption than for electrical energy consumption.
 - (3) Considerable scatter in monthly results can be expected among expert users of building energy analysis computer programs such as DOE-2 when the input is uncontrolled. However, the most significant reduction in this scatter can be obtained by having an independent observer check the input for errors and by eliminating gross ambiguities in the input."
- As an example, see Figure 9.1 from the previous reference for the variation in total energy consumption of the single-story office building for the six different consultants in the study. See also Table 9.1 for a complete summary of the results.

- j. Summary: "In an earlier ASHRAE paper [Ref. 14], monthly and annual electric and fuel energy use predicted by the DOE-2 building energy analysis computer program was compared with measured energy use for five commercial buildings in a variety of climates. In each case, DOE-2 was run by an experienced analyst who was familiar with DOE-2 and the building analyzed.

As an extension of this study, a comprehensive experiment was conducted by the Los Alamos National Laboratory to test the effect that the user had on the predicted results. The objective was to obtain a quantified characterization of the effects of the user under typical design conditions where detailed input data are not available initially but are improved or refined as the design process progresses. The results indicate how the judgement of different experienced users, and/or their interpretation of the input data, affect the dispersion (scatter) of energy use calculations made in DOE-2.

In this experiment a round-robin of simulations of four commercial buildings was conducted; six contractors, each an experienced user of the program, ran DOE-2 for each of the buildings. Three levels of increasingly refined input data were used by each of the contractors. Results are presented, in terms of root-mean-square (rms) deviations from the predicted mean monthly and annual energy use for the cases of (1) uncontrolled input, (2) refined input, and (3) input constrained by the Standard Deviation Technique defined for the Building Energy Performance Standards proposed by DOE."

11. DOE-2.1A: "Comparisons of Predicted and Measured Energy Use in Occupied Buildings." *ASHRAE Transactions* 90(2B) 1984. Wagner, B.S.

Compilation of studies. Results are reported in References 12, 13, and 15.

"During the past decade, a series of studies have reported comparisons of building energy simulations to measured building performance. Over two dozen studies, comprising about 100 simulations of building energy use, have been compiled and categorized by quality of input and energy consumption data, type of study, model used, quality of input and consumption data, expertise of input preparer, and control and monitoring of occupancy. This paper summarizes results of studies of occupied buildings in which monitoring varied from very detailed to non-existent, the comparison interval from hourly to yearly, and the number of buildings from one to 200-plus. These results are briefly compared to results from unoccupied buildings and preliminary conclusions are presented about the use of building energy models for different types of field applications..."

"...Energy analysis models can be effectively used on occupied buildings. Differences between predictions and measurements in most of the studies compiled were within a range of plus or minus 20% on average for the monitoring period for simulations of individual occupied buildings or groups of occupied buildings. Cooling energy use and energy savings tended to be more difficult to predict than heating consumption. For all end-uses, the availability of accurate and sufficiently complete input data, especially occupant behavior, limits the ability of even detailed models to accurately predict energy use, in some cases, severely so. Two methods that successfully reduced errors were: (1) comparison of predicted and actual energy use for buildings with existing prior utility information and correction of verifiable input errors; and (2) for groups of buildings with limited building-by-building data, restricting predictions to the average of the group. The first should be standard practice for engineers and auditors recommending retrofits for individual buildings; the second is useful for utility programs for large numbers of buildings. For new buildings, or prototypical (hypothetical) buildings used in policy studies, when the energy use need not be predicted for a particular, actual occupant, the situation is similar to predictions for an unoccupied building or building with controlled (well-characterized) occupancy, for which predictions were generally less than 20% in error..."

12. DOE-2.1A: "The Validation of DOE-2 for Application to Single-Family Dwellings."
ASHRAE Transactions 90(2B) 1984. Colborne, W.G., Hall, J.D., and Wilson, N.W.

a. Version of DOE-2 Program: DOE 2.1A

b. Building Type:

- (1) Single-story, occupied house with a floor area of 93.6 m² (1007 ft²) with a full basement and gas-fired heating system. Most occupant related variables were known. All windows were single-glazed with exterior aluminum storms.
- (2) Single-story, occupied house with a floor area of 93.9 m² (1010 ft²) with a slab-on-grade construction and a gas-fired heating system. Most occupant related variables were known. All windows were single-glazed with exterior aluminum storms.
- (3) Seventy-five similar occupied houses in a subdivision (two-story with full basement and electric resistance baseboards) were averaged. The floor area of each floor as well as the basement was 44.66 m² (481 ft²). Windows were double-glazed with a random orientation distribution.
- (4) One zone with a floor area of 49 m² (527 ft²) of an unoccupied, passive solar house with heavy insulation. The house was electrically heated by resistance baseboards. The south-facing double-glazed window area in the zone was 11m² (119 ft²).

c. Verification Type: Iterative. Default data used for heating systems seasonal efficiencies and seasonal COPs of the cooling systems; blower-door test data used to determine the level of infiltration; TRY weather data modified using a degree-day correction based on actual weather; thermostat settings defined by occupant behavior; below-grade heat losses determined by ASHRAE methods; internal heat gains defined by actual appliance data and occupancy scheduling.

d. Location:

- (1)-(2) Windsor, Ontario, Canada; latitude-42.3N, longitude-83.0W.
- (3)-(4) Unknown

e. Dates Monitored:

- (1)-(4) Unknown

f. Configurations Monitored:

- (1)-(4) Base configurations with no changes. Tests DOE-2 ability to determine overall heating energy consumption and air temperature given basic data inputs.

g. Data Monitored:

- (1)-(2) Natural gas consumption of the heating system.
- (3) Electric consumption of the heating system.
- (4) Electric consumption of the heating system, space air temperature.

h. Monitoring Interval:

- (1)-(3) Annually.
- (4) Hourly for several different one-day periods.

i. Conclusions:

- (1) "...The DOE-2.1A prediction of annual energy use for heating was within 5% of the measured value. The major items of uncertainty were the method of making corrections for weather data by a degree-day ratio, the below-grade heat losses, and the part-load efficiency of the heating system..." Table 12.1 presents a comparison of measured and predicted natural gas consumption.

- (2) "...The DOE-2.1A prediction of annual energy use for heating was within 1% of the measured value. As with study #1, the major items of uncertainty were the accuracy of the degree-day correction method, the heat loss to the ground by the slab, and the part-load efficiency of the heating system..."
- (3) "...The simulated result that was considered to most nearly represent the actual houses used the higher internal gains and allowed for 35% basement heating...This simulated condition gave an energy consumption for heating...which was 5% below the measured value..."
- (4) Good agreement was obtained between measured and predicted space temperature variations. For the testing period when the day was clear and sunny with low winds, the maximum measured value was 27.2C (81F), whereas the maximum predicted value was 27.8C (82F). "...The energy consumption was also in reasonable agreement until about 1800 hours; at this point one of the heaters came on in spite of the fact that the space temperature was still above the thermostat setpoint. Leakage air was entering the space in such a manner that the heater thermostat was activated..." Figure 12.1 shows a comparison of measured and simulated results from this study.

j Summary: "A computer simulation of any complex system must be validated in some way to ensure that the computer is, in fact, simulating the actual system. This paper makes use of the building energy program DOE-2.1A with the objective of validating it for use with single-family dwellings. The major concern is, therefore, the loads portion of the program. Four studies were carried out, each with a different set of conditions.

The first involved a single-story house with full basement, while the second involved a single-story house on a slab. In both cases occupant-related variables were known and blower-door tests were run to assist in the estimation of infiltration. Utility-measured energy use was compared to simulated energy use. On a bimonthly basis, simulated heating energy differed from the measured value by up to 11%. These houses had gas-fired furnaces for which seasonal efficiencies could only be estimated.

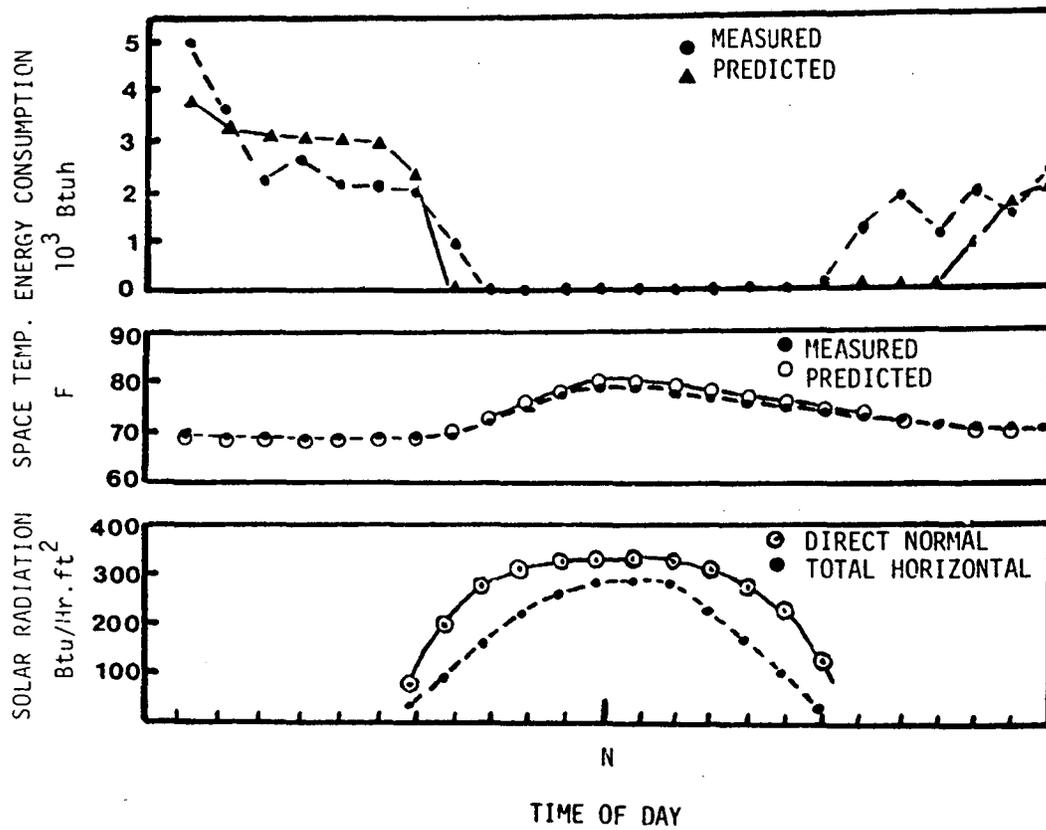
The third study involved 75 similar houses, which used electrical resistance heating. By using the average utility-measured consumption from the 75 houses, any abnormalities in construction or occupant behavior would be averaged out. Electric heating also eliminated the necessity of estimating a seasonal efficiency of a fossil-fired system. The simulated heating agreed within 5% of the measured for the total heating season.

The final study used an unoccupied house with electric heating, and all measurements were made on an hourly basis. Under certain selected conditions, good agreement was shown between simulated and measured space temperatures and heating energy..."

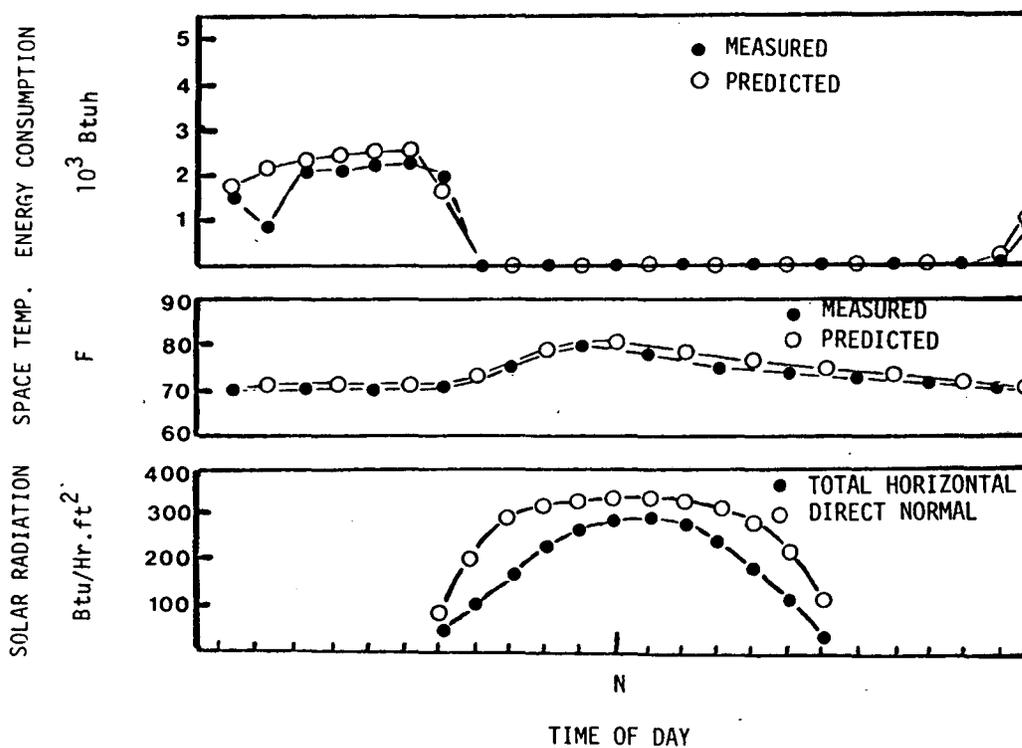
Table 12.1

A Comparison of the Adjusted Utility-Measured
 Natural Gas Consumption to the DOE-2.1A Predictions
 for Validation Study #1

| Billing Period | Natural Gas Consumption (MBtu) | | Variation (%) |
|-------------------|-----------------------------------|-----------------------|------------------|
| | Adjusted Measured | DOE-2.1A Predicted | |
| Oct./Nov. | 17.6 | 16.0 | -9 |
| Dec./Jan. | 39.4 | 42.2 | 7 |
| Feb./Mar. | 33.5 | 37.2 | 11 |
| Apr./May | 14.7 | 15.1 | 3 |
| Jun./Sept. | 10.6 | 10.6 | |
| Total | 115.6 | 121.1 | 5. |



Hourly comparisons of simulated and measured energy consumptions and space temperatures for a clear day with light winds



Hourly comparisons of simulated and measured energy consumptions and space temperatures for a clear day with strong northerly winds and a large temperature variation

Figure 12.1

13. **DOE-2.1A: "Measured Versus Predicted Performance of the SERI Test House: A Validation Study."** Solar Energy Research Institute Report SERI/TP-254-1953, May 1983. Judkoff, R.; Wortman, D.; and Burch, J.
- a. Version of DOE-2 Program: DOE-2.1A
 - b. Building Type: Unoccupied, unfurnished single-story ranch-style slab-on-grade residential building with a floor area of 92.9 m² (1000 ft²) instrumented with approximately 200 data recorders. The front of the residence is facing south and has 8.4 m² (90 ft²) of storm windows. Storm windows are also approximately equally distributed on the other three facades (sizes not available). Heating is provided by electric heaters; no cooling system is present.
 - c. Verification Type: Iterative. Changes made to several input variables to improve the accuracy of the simulations (see Configurations Monitored below).
 - d. Location: Golden, CO, latitude-39.8N, longitude-104.9W.
 - e. Dates Monitored: April 20-26, 1982
 - f. Configurations Monitored: Results are presented for nine configurations, each representing a different level of input and variable accuracy. They test DOE-2 ability to accurately determine room air temperature and heating load.
 - (1) Base Case: Handbook or assumed values used for all thermophysical inputs. Meteorological and geometric inputs are measured.
 - (2) Infiltration: Same as base case except hourly zonal infiltration rates were measured and used to generate the infiltration input..
 - (3) Ground Temperature: Same as base case except measured ground temperature was used as input to the ground coupling subroutines in the codes.
 - (4) Ground Albedo: Same as base case except measured ground albedo was used in the calculation of radiation incident upon glazed surfaces.
 - (5) Thermostat Setpoint: Same as base case except a correction was made to the thermostat setpoint based on the average temperature of air in the zone when the heater was actually on.
 - (6) Wall and Roof Conductance: Same as base case except measured wall and ceiling conductances were used.
 - (7) Window Conductance: This case was not run because measured window conductances were the same as those given by the ASHRAE Handbook of Fundamentals.
 - (8) Absorptivity: This case was not run because the measured solar spectrum absorptivity on opaque surfaces was not significantly different than assumed values.
 - (9) Measured: All the measured values in cases 2 through 6 were used. This case represents the highest degree of control over external error sources..."
 - g. Data Monitored: Interior air temperature in several zones and whole-house heating load.
 - h. Monitoring Interval: Hourly for seven days.
 - i. Conclusions: "This work is part of a multiyear, multilaboratory effort on the part of DOE to improve calculational methods for building energy analyses by collecting high quality detailed data and applying rigorous validation techniques. Although this work is far from complete, several conclusions can be drawn:
 - (1) Input assumptions based on standard engineering references can cause predictive errors of approximately 60% even when using measured meteorological data.
 - (2) Accurate temperature prediction does not guarantee accurate load prediction, nor does it guarantee an accurate temperature prediction on the next building studied."
 - (3) The heating load predictions for the three codes for all cases were within about 7% of each other.

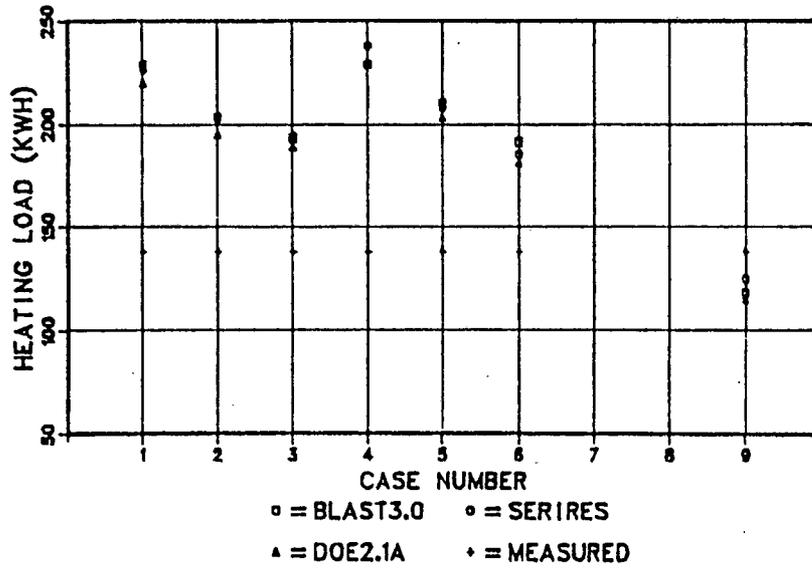
- (4) Even when most input errors are eliminated using measured thermophysical input data, prediction errors ranging from 10% to 17% have still been found.”

Figure 13.1 shows a comparison of measured and whole-house heating and peak loads during the monitoring period for the seven configuration variations studied.

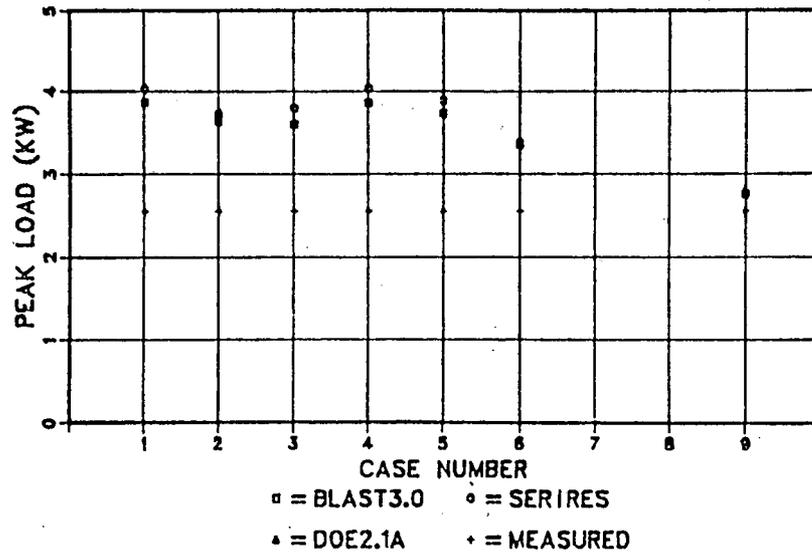
j. Summary: “For the past several years the United States Department of Energy (DOE) Passive and Hybrid Solar Division has sponsored work to improve the reliability of computerized building energy analysis simulations. Under the auspices of what has come to be called the Class A Monitoring and Validation program, the Solar Energy Research Institute (SERI) has engaged in several areas of research that includes:

- (1) developing a validation methodology;
- (2) developing a performance monitoring methodology designed to meet the specific data needs for validating analysis/design tools;
- (3) constructing and monitoring a 1000 ft², multizone, skin-load dominated test building;
- (4) constructing and monitoring a two-zone test cell; and
- (5) making sample validation studies using the DOE-2.1, Blast-3.0 and SERIRES-1.0 computer programs.

This paper reports the results obtained in comparing the measured thermal performance of the building to the performance calculated by the building energy analysis simulations. It also describes the validation methodology and the Class A data acquisition capabilities at SERI.”



Weekly Whole-House Heating Loads



Whole-House Peak Load

Figure 13.1

14. DOE-2.1A: "A Summary Report of Building Energy Compilation and Analysis (BECA) Part V: Validation of Energy Analysis Computer Programs." Lawrence Berkeley Laboratory Report LBL-14838, January 1983. Wagner, B.S. and Rosenfeld, A.H..

Compilation of studies. Results are reported in References 12 and 15.

"BECA compiles and reviews comparisons of building energy analysis techniques to measured building energy use. This paper summarizes preliminary results for the 12 studies reviewed to date. For commercial buildings, detailed computer programs were accurate to within 10% when correct input data were available. For residential buildings, accuracy of building energy analysis programs was generally better than 19% when the buildings analyzed were intensively instrumented and monitored to eliminate errors in input...Accuracy of predictions for groups of buildings, as expected, tended to be better than individual predictions. Accuracy tended to decrease as quality of input data decreased..."

"...We note that:

- (1) The number of comparisons cited is still small, as is the total building sample size.
- (2) Comparisons of predicted vs. measured cooling consumption are scarce, and, to date, not encouraging on an individual building basis.
- (3) We know of no experimental results from tests of the accuracy of auditor inputs.
- (4) Published studies tend to reflect comparisons in which accuracy was relatively good. It would be useful to know when and why computer predictions fail..."

15. DOE-2.1A: "Comparison of DOE-2 Computer Program Simulations to Metered Data for Seven Commercial Buildings." *ASHRAE Transactions* 87(1) 1981. Diamond, S.C. and Hunn, B.D.

See Reference 10 for User-Effect tests; however, the quoted floor areas are not the same.

a. Version of DOE-2 Program: DOE-2.1A

b. Building Type:

- (1) Single-floor office building: Bank branch office built in 1974. Net floor area is 600 m² (6500 ft²). Construction is insulated frame walls, built-up roof, and concrete floor. Windows are 1.3cm (1/2in) solar-grey glass. Maximum occupancy is 120 people and the maximum internal equipment load is 18.2 kW. The building has three thermostatically controlled zones served by three constant-volume reheat systems. Plant equipment consists of hot-water boiler and a reciprocating chiller.
- (2) Multifloor office building: Headquarters for a steak house chain. Three-story, 5980 m² (64,400 ft²) rectangular office complex. Has a glassed-in entrance way and a north-facing glass-curtain wall; the remaining envelop structure is grey granite block. Peak occupancy is 200 persons and the maximum equipment load is 20 kW, except for a computer room which is 58.6 kW. The mechanical system consists of two large and one small constant-volume reheat systems servicing 46 zones. The plant equipment consists of oil-fired boilers, electric boilers, centrifugal chillers, DHW heater.
- (3) Retail store: One-story apparel store with a floor area 3027 m² (32,580 ft²). The building exterior is precast concrete with a store front of face brick and glass. Maximum occupancy varies from 300 persons to 1300. The mechanical system is a multizone air system with six zone air-handling units. The plant equipment is a gas-fired, hot-water boiler, direct expansion chiller, and an indoor wet cooling tower.
- (4) Restaurant: Single-story building with a floor area of 1970 m² (21,200 ft²). The building has cooking and food storage facilities, private dining room, cocktail lounge, and management offices. The envelope is hollow-core concrete block with vermiculite-fill insulation. All windows are double-glazed and nonoperable. Occupancy varies from 400 to a maximum of 1400 per day. The HVAC system consists of two constant-volume, variable temperature, multizone air systems. The plant equipment includes two gas-fired boilers and two reciprocating electric chillers.
- (5) Hospital: Multistory building with a total floor area of 46,450 m² (500,000 ft²). The large building required the use of 90 zones. There were ten different wall constructions and five roof constructions. There were thirteen lighting profiles and five base loads. The HVAC system consists of four variable air volume systems, four variable air volume with reheat systems, ten constant volume single-zone systems, and six four-pipe fan coil systems.
- (6) School: Single-story elementary school with a total floor area of 3690 m² (40,000 ft²). The structure has masonry walls and a steel deck roof. Total window-to-wall area ratio is 50%. The HVAC system has unit ventilators in three rooms heated by a gas-fired boiler.
- (7) Solar-heated and -cooled building:

c. Verification Type: Non-iterative. Data provided describing the buildings and measured weather data.

d. Location:

- (1) Santa Clara, CA, latitude-37.4N, longitude-121.9W
- (2) Dayton, OH, latitude-39.9N, longitude-84.2W
- (3) Albuquerque, NM, latitude-35.0N, longitude-106.6W
- (4) Downers Grove, IL, latitude-41.9N, longitude-87.6W
- (5) Chattanooga, TN, latitude-35.0N, longitude-85.2W
- (6) Kennewick, WA, latitude-46.2N, longitude-119.1W
- (7) Los Alamos, NM, latitude-35.9N, longitude-106.3W

- e. Dates Monitored: Not available.
- f. Configurations Monitored: Comparison of non-iterative simulation results of seven different building configurations in a variety of climates with metered utility data tests DOE-2 ability to predict energy consumption.
- g. Data Monitored: Utility metered energy consumption (gas/fuel oil, electric).
- h. Monitoring Interval: Monthly.
- i. Conclusions: “Comparisons of DOE-2 simulations with measured utility data for a set of seven existing commercial buildings of various types in a variety of climate zones indicate the following conclusions:
 - (1) For the set of seven buildings tested, there is a standard deviation of less than 8% and a maximum difference of 12% between predicted and measured data for annual total energy use.
 - (2) For the set of seven buildings tested, the difference between predicted and measured data for annual gas/fuel and electric energy results in a standard deviation of 11% and 9.2% respectively. The range of differences is 1-19% and 1-15% respectively.
 - (3) The composite standard deviation for the set of seven buildings on a monthly basis is 16.7% for total energy use, 26.3% for gas/fuel oil use, and 18.7% for electric energy use. The range of differences is 2-24%, 10-35%, and 9-30% respectively.”

Figure 15.1 presents a comparison of the calculated monthly energy consumption with utility data for several of the building configurations and Table 15.1 summarizes the annual results.

- j. Summary: “As part of the DOE-2 Verification Project being conducted by the Los Alamos Scientific Laboratory, seven existing commercial buildings were simulated using the DOE-2 computer program. These buildings included a restaurant, single-floor office building, retail store, hospital, multifloor office building, school, and solar-heated and -cooled building.

This comparison test required each building to be simulated by a separate contractor or national laboratory. Predictions of the DOE-2 computer program were then compared to the utility company monthly metered data. Results of these comparisons for gas/fuel oil use, electric energy use, and total energy use are reported...”

“...The absolute difference between predicted and measured data for individual months ranged from 14 to 45% for gas/fuel oil, where the 45% difference was a single-month occurrence for the retail store. Absolute differences for individual months ranged from 13 to 37% for electricity. The 37% difference was a single-month occurrence for the school. Comparable differences for monthly total energy use were in the range 15 to 33%. Despite the occurrence of rather large differences for a few individual months, statistical analysis of all monthly results show composite standard deviations for the seven buildings of 26.3, 18.7, and 16.7% respectively... Comparisons of predicted and measured energy use on a monthly basis show significantly higher deviations than the annual comparisons. Probable causes of this phenomenon include the following:

- (1) Underpredictions in some months tend to compensate for overpredictions in other months resulting in an improved annual comparison.
- (2) Standard schedules for parameters such as occupants, lights, equipment, and DHW are used in the simulations. Effects of the variations in these schedules for the actual test year tend to average out, matching the standard schedules in the long-term annual results, but not in the shorter-term monthly results.
- (3) Short-term differences in weather between the building site and the weather data monitoring station appear in the monthly results, but tend to be averaged in the annual results.
- (4) Anomalies in the utility data used for the comparison cause higher monthly differences. For example, a small error in reading a gas meter could result in an overbilling one month and underbilling the next month that is not readily detected. Also, the date of measure (meter reading) and the date of prediction (end of calendar month) generally do not coincide. In

these cases, the utility data were interpolated for the end of the month, resulting in small errors in the monthly results. Again, this phenomenon tends to average out in the annual results.”

Table 15.1

Summary of Reference-Run Results (Annual)
DOE-2 Predictions vs Measured Data

| | Gas/Fuel | Electricity | Total | Predicted | | Measured | |
|--|----------|-------------|-------|---|---------------|---|---------------|
| | Oil | | | Energy | Energy Budget | | Energy Budget |
| | (%) | (%) | (%) | MJ/m ² .yr (Btu/ft ² .yr) | | MJ/m ² .yr (Btu/ft ² .yr) | |
| Restaurant | -1 | -2 | <-1 | 7959 | (701,300) | 8037 | (708,200) |
| Single-Floor Office | +4 | +12 | +8 | 1585 | (139,700) | 1467 | (129,300) |
| Retail Store | -19 | -4 | -12 | 1710 | (150,600) | 1949 | (171,700) |
| Hospital | -4 | -14 | -7 | 4813 | (424,100) | 5171 | (455,700) |
| Multifloor Office | -14 | <-1 | -4 | 1328 | (117,000) | 1376 | (121,300) |
| School | +5 | <-1 | +4 | 1075 | (94,700) | 1033 | (91,000) |
| NSRSC (Solar) | +15 | -15 | -12 | 492 | (43,400) | 562 | (49,500) |
| Standard Deviation (%) for Set of Seven Buildings | 11.0 | 9.2 | 7.9 | | | | |

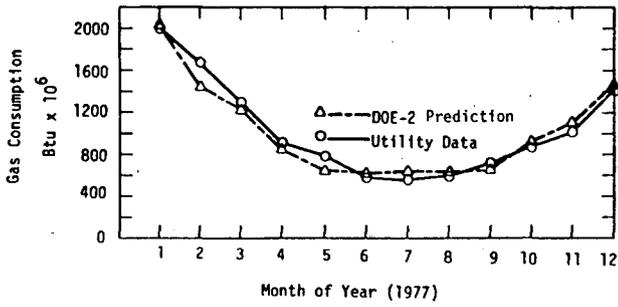


Fig. 1 Reference run - DOE-2 prediction vs gas utility data for restaurant

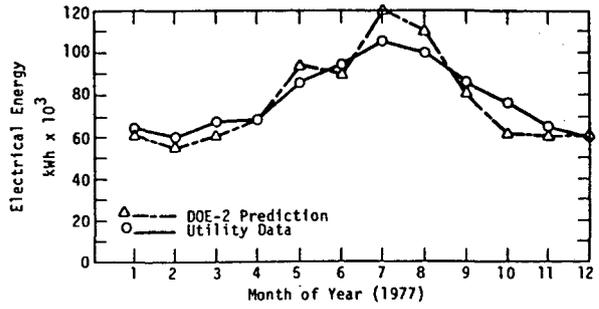


Fig. 2 Reference run - DOE-2 prediction vs electric utility data for restaurant

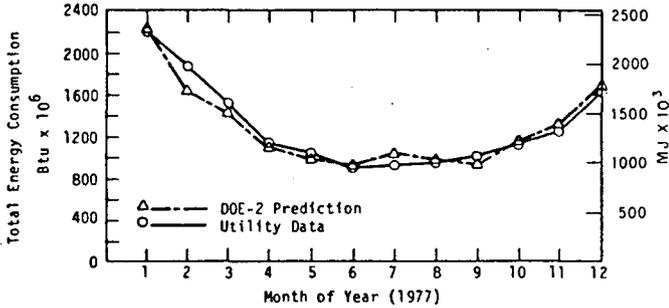


Fig. 3 Reference run - DOE-2 prediction vs total energy utility data for restaurant

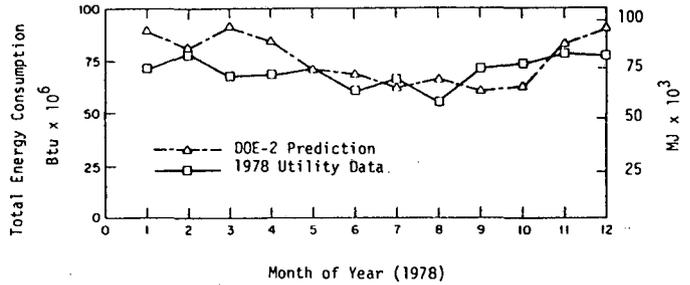


Fig. 4 Reference run - DOE-2 prediction vs total energy utility data for single-floor office building

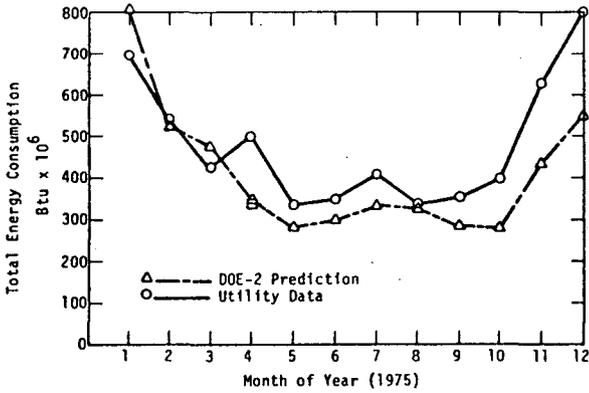


Fig. 5 Reference run - DOE-2 prediction vs total energy utility data for retail store

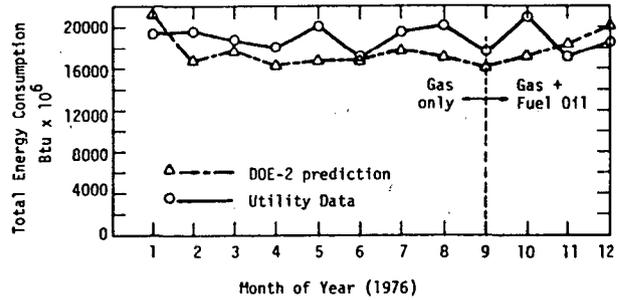


Fig. 6 Reference run - DOE-2 prediction vs total energy utility data for hospital

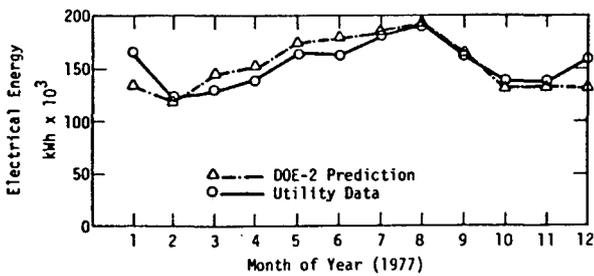


Fig. 7 Reference run - DOE-2 prediction vs electric utility data for multifloor office building

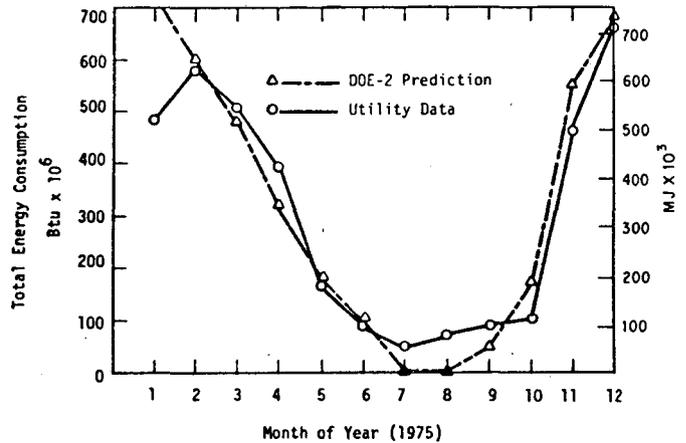


Fig. 8 Reference run - DOE-2 prediction vs total energy utility data for school

16. **DOE-2.1A: "A DOE-2.1A Comparison with CERL Data for VAV and REHEAT Systems."**
Report by W. S. Fleming and Associates, Inc., November 1981.
- a. Version of DOE-2 Program: DOE 2.1A
 - b. Building Type: Four 0.91m x 1.22m x 1.22m (10ft x 15ft x 10ft) test chambers were located within a conditioned laboratory. The walls were stud construction with 10.1cm (4in) fiberglass insulation. Floor and ceiling were of similar construction. Outer and inner surfaces were plywood and wall board respectively. A fan coil unit was installed in each zone to provide a cooling load; a unit ventilator supplied a heating load. There were no other internal loads and ambient temperatures in the laboratory varied from 18.3C (65F) in winter to 26.6C (80F) in summer. The HVAC systems were connected to the chambers with flexible ducting and included boilers and chillers.
 - c. Verification Type: Iterative. The initial comparison of measured and simulated performance was done using DOE-2.1A default equipment performance data; in the second test, actual performance data curves were used in the simulation using the curve-fitting routines.
 - d. Location: United States Army Construction Engineering Research Laboratory (CERL), Champaign/Urbana, IL, latitude-40.0N, longitude-88.3W
 - e. Dates Monitored: Not available.
 - f. Configurations Monitored: Basecase default performance curves for Variable Air Volume (VAV) and Reheat Fan (RHFS) systems compared to actual performance data. Provides an indication of the expected differences between default and actual data. Also shows the differences to expect between an novice user of DOE-2 and an experienced user.
 - g. Data Monitored: Space temperature, total cooling and heating, total electric energy and gas consumption.
 - h. Monitoring Interval: Hourly for one day.
 - i. Conclusions: "The results of these tests indicate that the DOE-2.1A simulations for VAVS and RHFS systems close adequately with carefully monitored and instrumented tests as prepared and reported by CERL. Even when using the default values and curves stored in the program, the reports were satisfactory. Using the DOE-2.1A program curve-fit routines, the agreements on component electric energy improved. However, the interpretation of DOE-2.1A hourly reports for auxiliaries such as the cooling tower fan and pumps was difficult..." Table 16.1 presents a summary of the deviations obtained during the testing. Although the difference between measured and predicted fuel and electric energy use in some test cases was large, the average using the default DOE-2.1A performance curves was 10%. Using actual performance data, the predictions improved to within 5% of the measured energy use.
 - j. Summary: "This report describes a comparison of DOE-2.1A computer simulation runs to measured data collected by the Construction Engineering Laboratory (CERL) located in Champaign, Illinois...The Department of Energy's Analysis Program DOE-2.1A was used to simulate two HVAC system types; namely, VAV with Reheat, and Terminal Reheat (Constant Volume). Forty-nine CERL test cases were prepared as input to DOE-2.1A and the simulation results were then compared to the test data collected by CERL..."

Table 16.1

VAV Deviations (21 Test Cases)

| | Maximum Range | Average |
|-------------|---------------|---------|
| Cooling | -13% to +16% | +2% |
| Heating | -100% to +89% | +4% |
| Electrical | -54% to +7% | -10% |
| Natural Gas | -19% to +61% | +9% |

REHEAT Deviations (28 Test Cases)

| | Maximum Range | Average |
|-------------|---------------|---------|
| Cooling | -4% to +10% | +3% |
| Heating | -100% to +26% | - 4% |
| Electrical | -14% to +16% | +3% |
| Natural Gas | -12% to +74% | +12% |

17. DOE-1.3, 1.4, 2.0: "DOE-2 Verification Project Phase 1 Interim Report." Los Alamos Laboratory Report LA-8295-MS, April 1981. Diamond, S.C., Cappiello, C.C., and Hunn, B.D.

Compilation of studies. The complete Executive Summary from this report is presented. Results from this work are also reported in References 11, 14, and 15.

"This report details nearly all of the results of Phase I of the DOE-2 Building Energy Analysis Computer Program Verification Project. The project was planned and implemented by the Los Alamos National Laboratory. Phase I of the project was an analytical and empirical verification of DOE-2 as a computational unit rather than as separate algorithms.

Phase I included work conducted by the Los Alamos National Laboratory and several contractors and consultants. A crosscheck of DOE-2 with the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) loads calculative procedures, as well as a line-by-line check of program constants and flag-setting algorithms, was performed. Also, a comparison of plant equipment performance default values with manufacturers' data was made, and results of the DOE-2 active solar system simulator were compared with results of other solar system simulation computer programs. Empirical tests of the full DOE-2 program, including comparisons with measured monthly and annual energy consumption for seven commercial buildings located in seven different cities and for nine elementary schools were conducted. In addition, comparisons of energy use predicted by several building energy analysis computer programs, including DOE-1.4 and DOE-2.0, and the results of the manual calculative method developed by ASHRAE Technical Committee 4.7 (Energy Calculations) were made.

The present study addresses all verification work done with the DOE-2.0A program and its predecessor versions (DOE-1.3, 1.4, and 2.0). Ongoing verification work involving DOE-2.1 and subsequent versions will be presented in a later report.

The ASHRAE/DOE-2 LOADS crosscheck included comparisons of DOE-2 predicted cooling loads with those of the 1972 and 1977 ASHRAE Handbook of Fundamentals for four cooling load components: conduction through sunlit walls, solar, lights, and occupants. The results show that DOE-2 predicts peak loads that differ by 4, 15, 29, and 5 per cent, respectively, from the 1972 ASHRAE "computer" method, and by 2, 15, 20, and 0 per cent, respectively, from the 1977 ASHRAE "manual" method. The primary reason for the differences, which are quite significant sometimes, is that DOE-2 and the ASHRAE methods are based on different weighting factor sets. Furthermore, the ASHRAE 1972 computer and 1977 manual methods do not use consistent sets of weighting factors. The usefulness of these results is obscured because no measured field data exist that indicate which of the three sets of weighting factors is the most accurate.

The plant equipment subroutine check...indicated that in the majority of comparisons, good agreement between manufacturers' data and the equipment performance default curves was obtained. Poor agreement occurred only in the models for waste heat from diesel-engine and gas-turbine generators. These discrepancies have been resolved.

A series of software-software comparisons of results from the DOE-2 solar simulator, running in the stand-alone mode, with those of other commonly used solar system simulation computer programs (for example TRNSYS) has been made within the framework of the Systems Simulation and Economic Analysis Working Group, sponsored by DOE. Simulation comparisons have been made for space heating and domestic hot water, heat pump, and industrial process heat systems. The comparisons of hourly and monthly results show excellent agreement for both liquid and air systems. The small discrepancies result primarily from the slightly different treatment given the components in each of the programs. Discrepancies in the industrial process heat runs indicated a need for improvement of the compound parabolic concentrator collector model in DOE-2. Improvements in this model have been made.

A set of five contractor/test building pairs was selected by competitive bid to conduct the empirical tests of the full DOE-2 program. In addition, two national laboratory/building pairs were involved. These seven pairs are

Single-floor office building/Control Data Corporation;
Multifloor office building/Galehouse and Associates;
Retail store/New Mexico Energy Institute;
Restaurant/Ganze, Korobkin, and Caloger;
Hospital/Bickle Division of CM, Incorporated;
School/Lawrence Berkeley Laboratory (LBL); and
National Security and Resources Study Center/ Los Alamos National Laboratory.

In these monthly-energy-use field tests, the seven participants simulated their respective buildings using the DOE-2.0A program. These simulations were conducted using historical knowledge of the buildings and their operation during the one-year test period. The period of simulation, metered data, and weather data used were all for the same calendar period. DOE-2 energy consumption predictions for gas or fuel-oil energy, electricity, and total energy consumption were compared with metered data (monthly utility bills).

A statistical analysis of these comparisons produced the following results.

- (1) For the set of seven buildings tested, on an annual basis, the standard deviation of predicted from measured results was 7.9 per cent for total energy consumption, 11.0 per cent for gas/ fuel oil use, and 9.2 per cent for electrical energy use.
- (2) For the set of seven buildings tested, on a monthly basis, the deviations were somewhat higher: 16.7, 26.3, and 18.7 per cent, respectively, for total energy consumption, gas/fuel oil use, and electrical energy.

The comparison of annual energy use predictions of DOE-1.4 and measured utility data for 10 elementary schools across the US, conducted by LBNL, showed good agreement. Standard deviations of DOE-1.4 predictions from the measured data were 9.1 per cent for total energy consumption, 9.5 percent for gas/fuel oil use, and 7.6 per cent for electrical energy for the set of schools simulated." Figures 17.1 and 17.2 show a comparison of measured and simulated gas/fuel oil consumption and electric energy use for two of the schools analyzed as part of this project and Table 17.1 presents a summary of the whole study.

"The comparison of annual energy use predictions of DOE-2.0 and measured utility data for the Boston Marriott Hotel, conducted by William S. Fleming and Associates (WSFA), showed a deviation of 3 per cent." Figure 17.3 shows results from this study.

"Comparisons of several building energy analysis computer programs, including DOE-1.4 and 2.0, were made in two separate American Institute of Architects Research Corporation (AIA/RC) studies. The first study involved comparative simulations of four buildings: a warehouse, an office building, a hospital, and a retail store. The simulation methods used were DOE-1.4, ACCESS, BLAST, and the ASHRAE Technical Committee 4.7 hand-calculative method. DOE-1.4 predicted annual energy budgets within 17, 6, 1, and 2 per cent, respectively, of the average results of the methods compared (no measured energy use data were available). However, large variations in interpretation of building drawings and specifications occurred among the four participants. These variations cast some doubt as to the validity of the results.

The second comparison study performed by AIA/RC involved only the DOE-2.0 and ACCESS computer programs in which simulations were made for a retail store and an office building. The difference in annual total energy predictions between the two programs was 7.7 per cent for the retail store and 9.5 per cent for the office building.

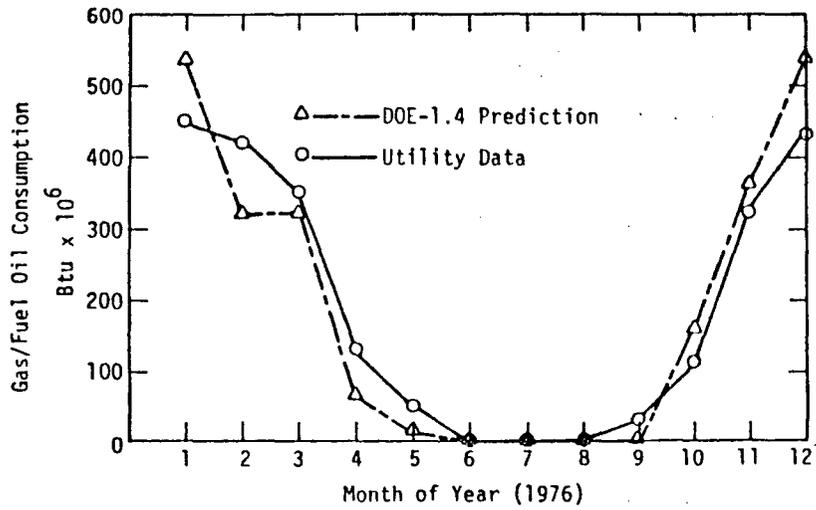
Two additional comparison studies were conducted by LBNL and the California Energy Resources, Conservation, and Development Commission (ERCDC) for single-family residences. These studies compared results from DOE-2.0, NBSLD, and BLAST. The maximum variation in predicted annual energy consumption was 12 per cent for heating and 7 per cent for cooling.

With a few exceptions, the DOE-2.0 predictions agree well with ASHRAE calculation methods, manufacturers' data, and measured annual building energy consumption. DOE-2.0 predictions also agree well with predictions of several other building energy analysis computer programs."

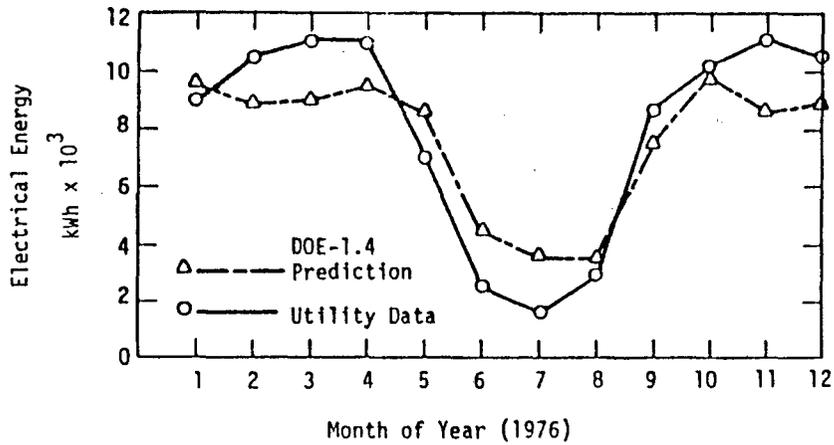
Table 17.1

LBNL SCHOOLS PROJECT
DOE-1.4 PREDICTED ENERGY USE VERSUS MEASURED UTILITY DATA (ANNUAL)

| School | Gas/Fuel Oil (Btu x 10 ⁶) | | | Electric Energy (kWh x 10 ³) | | | Total (Btu x 10 ⁶) | | |
|-------------------|--|----------|------------------------|---|----------|------------------------|-----------------------------------|----------|------------------------|
| | DOE-1.4 | Measured | Per Cent Difference | DOE-1.4 | Measured | Per Cent Difference | DOE-1.4 | Measured | Per Cent Difference |
| Warwick, RI | 2 388 | 2 681 | -11 | 97 | 112 | -13 | 2 719 | 3 063 | -11 |
| Lincoln, NB | 2 336 | 2 270 | +3 | 92 | 95 | -3 | 2 650 | 2 594 | +2 |
| Glen Rock, NJ | 6 000 | 5 645 | +6 | 157 | 164 | -4 | 6 535 | 6 205 | +5 |
| Sioux Falls, SD | 2 963 | 3 506 | -15 | 102 | 104 | -1 | 3 311 | 3 861 | -14 |
| Langhorn, PA | 4 922 | 4 560 | +8 | 157 | 162 | -3 | 5 458 | 5 113 | +7 |
| Stevens Point, WI | 2 667 | 2 950 | -10 | 325 | 364 | -11 | 3 776 | 4 192 | -10 |
| Hindman, KY | 2 350 | 2 544 | -8 | 76 | 84 | -8 | 2 609 | 2 831 | -8 |
| Columbus, OH | 6 876 | 6 716 | +2 | 170 | 162 | +4 | 7 456 | 7 269 | +3 |
| Lubbock, TX | 2 653 | 3 075 | -14 | 92 | 82 | +11 | 2 967 | 3 355 | -13 |

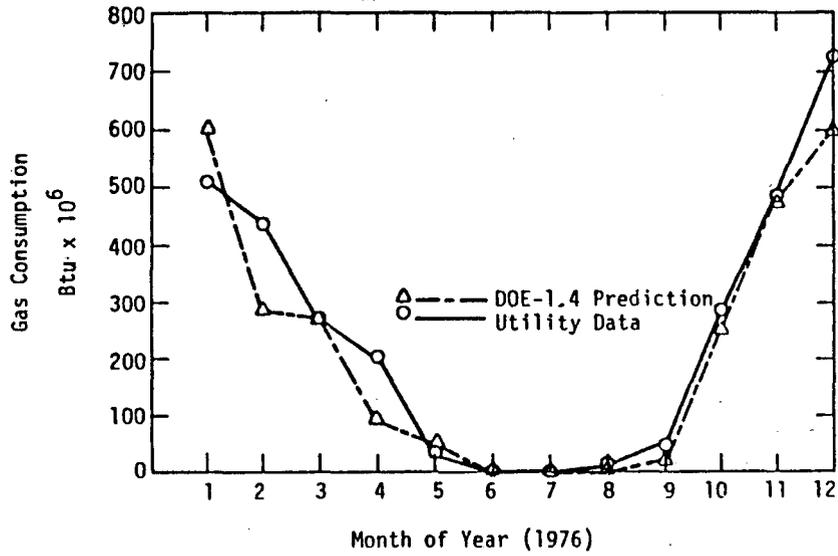


DOE-1.4 prediction versus gas/fuel oil utility data for Eastridge School, Lincoln, Nebraska.

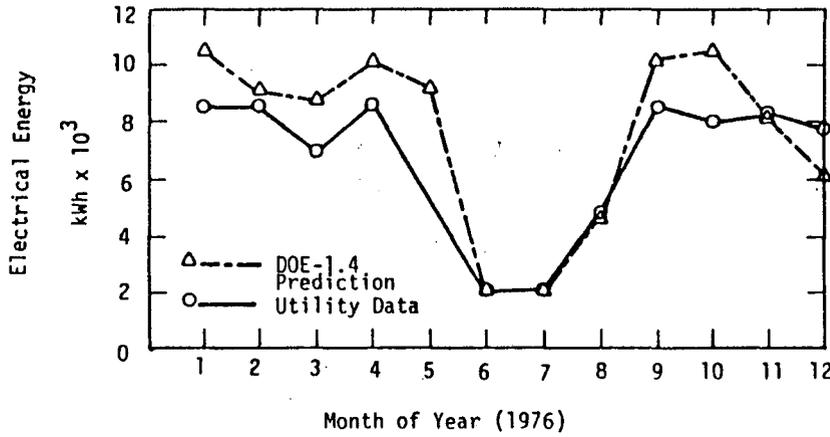


DOE-1.4 prediction versus electric utility data for Eastridge School, Lincoln, Nebraska.

Figure 17.1

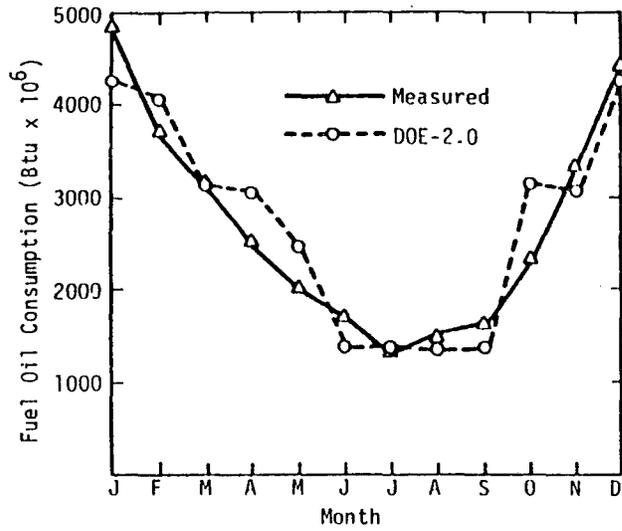


DOE-1.4 prediction versus gas utility data for Brown School, Lubbock, Texas.

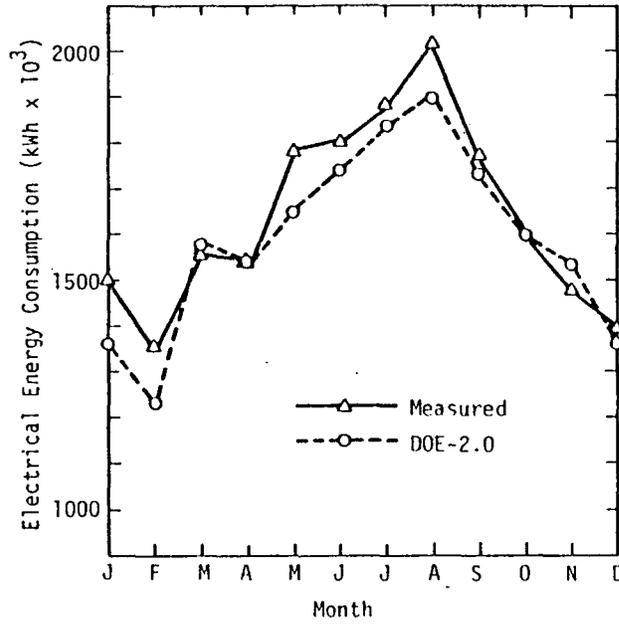


DOE-1.4 prediction versus electric utility data for Brown School, Lubbock, Texas.

Figure 17.2



Monthly heating fuel oil consumption for the Marriott Hotel, Boston, Massachusetts.



Monthly electrical energy consumption for the Marriott Hotel, Boston, Massachusetts.

Figure 17.3

**ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720**