ESL-TR-94/12-11

ANALYSIS OF ENERGY CONSERVATION OPTIONS FOR U.S.D.O.E. CHILD DEVELOPMENT CENTER

FINAL
SUMMARY REPORT

Prepared by:

T. E. Bou-Saada,
J. S. Haberl, P.I.

Energy Systems Laboratory
Mechanical Engineering Department
Texas A&M University

Research sponsored by

U. S. Department of Energy through
Sandia National Laboratory,
Contract No. AK-8010

December 1993

Revised December 1994

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The U.S.D.O.E. Forrestal Child Development Center (CDC) was designed to be a "showpiece" model building. Its construction included energy efficient features such as efficient lighting, a photovoltaic system, an energy management system, lighting controls, envelope improvements, clerestory windows, energy efficient heat pumps, and a solar hot water system. The architect's estimate of the energy savings from these measures totaled 31.6 million Watt-hours per year (MWh/yr), an annual savings of about $1,580 (at $0.05/kWh). This study calculated a total annual energy savings of 23.2 MWh per year for the CDC; a savings of $1,160.

This report presents the results of a study that verifies the energy savings due to the individual ECOs through the use of a calibrated DOE-2 simulation. The results show that roughly 73% of the savings estimated by the GSA architect can be accounted for by the calibrated simulation. This compares very well when one considers that the large differences were contributed by the envelope improvements and the clerestory windows. If these two ECOs were omitted, 90% of the savings can be accounted for by the calibrated simulation.

PREFACE

The U.S.D.O.E. Child Development Center was designed and built to serve as an example of an energy efficient daycare center for federal employees and their children. As part of this effort the United States Department of Energy decided to verify the effectiveness of the Energy Conservation Options through the use of an analysis that utilized a calibrated DOE-2 simulation program. This report presents the preliminary findings of this effort.

This report has been prepared by Tarek Bou-Saada and Jeff Haberl, Ph.D., P.E.

Mailing address: Energy Systems Laboratory, Mechanical Engineering Department, Texas A&M University, College Station, Texas, 77843-3123, (409)845-1560, FAX (409)862-2762. Please address any comments to: Dr. Haberl via e-mail at jhaberl@loanstar.tamu.edu.

DISCLAIMER

EXECUTIVE SUMMARY

The U.S.D.O.E. Forrestal Child Development Center (CDC) was designed to be a "showpiece" model building. Its construction included energy efficient features such as energy efficient lighting, a photovoltaic system, an energy management system, lighting controls, envelope improvements, clerestory windows, energy efficient heat pumps, and a solar hot water system. The architect's estimate of the energy savings from these measures totaled 31.6 million Watt-hours per year (MWh/yr), an annual savings of about $1,580 (at $0.05/kWh). This study calculated a total annual energy savings of 23.2 MWh/yr for the CDC; a savings of $1,160.

This report presents the results of a study that verifies the energy savings from the individual ECOs through the use of a calibrated DOE-2 simulation. The results show that roughly 73% of the savings estimated by the GSA architect can be accounted for by the calibrated simulation which indicates a remarkably good overall estimate by the architect, although individual measures varied significantly.

DOE-2 has been extensively used over the years to simulate hourly building energy consumption in design considerations. In order to investigate the effects of ECOs on a building, a calibrated DOE-2 baseline model representing the existing building (including all the ECOs) was compared to simulations without individual ECOs and the difference tabulated.

Table 1 shows the energy conservation options calculated in this study versus savings predicted by the GSA architect. Currently, 34 W energy efficient fluorescent lights are installed which save 31.0% more than predicted. Photovoltaic generation saves 4.6% more than predicted. The energy management system saves 257.9% more than expected. Lighting controls and dimmers were not verified since the dimmers were not installed. Insulation, front entrance airlock, and south window shading save 72.0% less than predicted. The clerestory windows save 100.7% less. The simulation of the clerestory windows indicates that the windows actually caused the building to use more energy than would otherwise be necessary. Interviews with the USDOE staff revealed that automatic dimmers were not installed and the CDC staff only turned off lights when the children sleep for a few hours each afternoon. The improved EER heat pumps save 55.3% less than originally estimated. The solar domestic hot water system saves 4.2% less than predicted. Clearly, the solar domestic hot water system and the photovoltaic system came the closest to the savings estimates. Total simulated savings represent 73% of the GSA architect's proposals.

The bar chart in Figure 1 compares the simulated ECOs versus the original architect predictions. Part (a) is the verification of the seven individual energy conservation options. Part (b) is a breakdown of key energy using systems with and without the ECOs which includes interior lighting using 8.5% less, HVAC fans using 6.25% less, equipment and space heating using 1.17% less, space cooling using 10.32% less, and electric DHW (including the solar DHW) using 180.0% less. These systems are classified by energy use from largest to smallest. Finally, photovoltaic savings are shown for comparison purposes.

Table 1 Comparison of Energy Conservation Options to Savings Predictions.

	Energy Conservation Option	DOE-2 Basemodel "as-built" (kWh)	DOE-2 Predicted w/o ECO (kWh)	DOE-2 Predicted Savings (kWh)	Architect's Proposal (kWh)	Percent Difference (7)	Difference
1.	Energy Efficient Lights	157,116	161,477	4,361	3,328	31.0%	1,033
2.	Photovoltaic Generation (1)	-7,880	0	7,880	7,530	4.6%	350
3.	Energy Management and Control System (2)	157,116	160,695	3,579	1,000 (est)	257.9%	2,579
4.	Lighting Controls & Dimmers (3)	-	-	-	-	-	-
5.	Insulation, Airlock, South Shading	157,116	158,795	1,679	6,000	-72.0%	-4,321
6.	Clerestory Windows	157,116	157,075	-41	6,000	-100.7%	-6,041
7.	Improved Heat Pumps	157,116	158,590	1,474	3,300	-55.3%	-1,826
8.	Solar Hot Water (4)	2,345	6,565	4,220	4,407 (6,033 is incorrect)	-4.2%	-187
	All ECOs Combined (5)	151,581	168,042	16,461	-	-	-
	Total (6)			23,152	31,565	-26.7%	-8,413

(1) The calibrated difference was determined using a curve fit which compared photovoltaic generation as a function of global horizontal radiation. Global horizontal radiation was then extracted from a Washington, D.C. TMY weather tape. DOE-2 was not used for this verification.

(2) According to U.S.D.O.E. personnel, the HVAC system is manually operated each day. The 1,000 kWh savings by the GSA architect were based on engineering judgement.

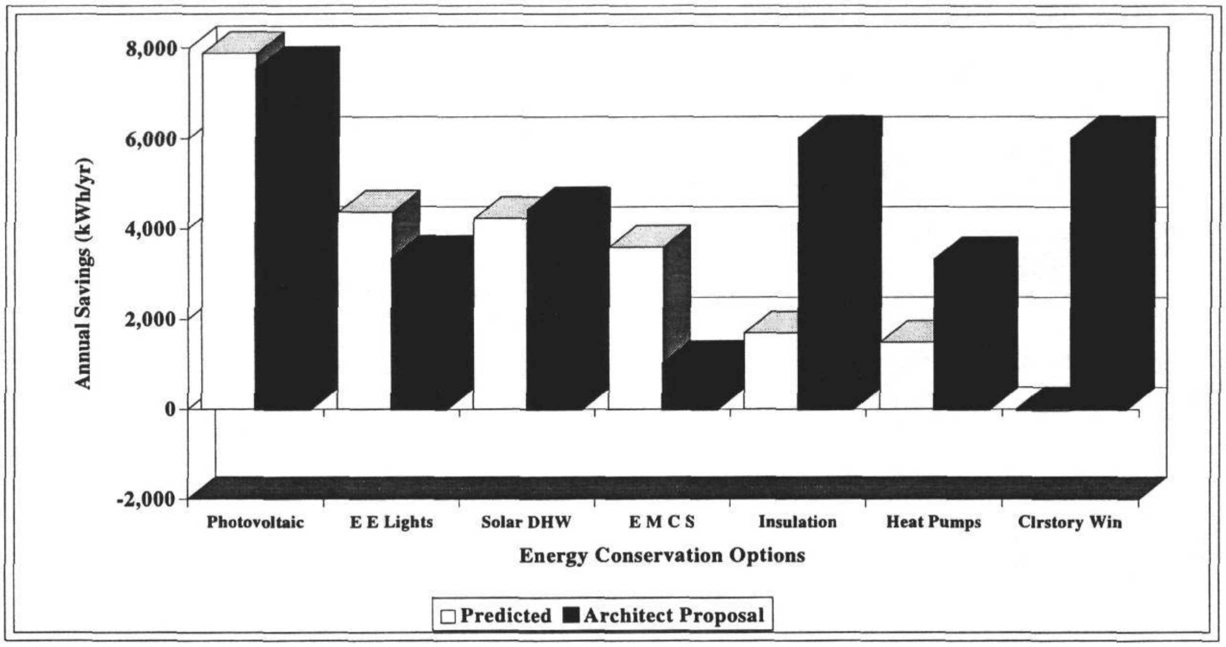
(3) According to U.S.D.O.E. personnel, the dimmers were not installed.

(4) Savings were determined by F-CHART. The value of 6,033 as specified in the original estimate is incorrect because the value used by GSA eroneously cited the total DHW requirements and not the solar DHW contribution.

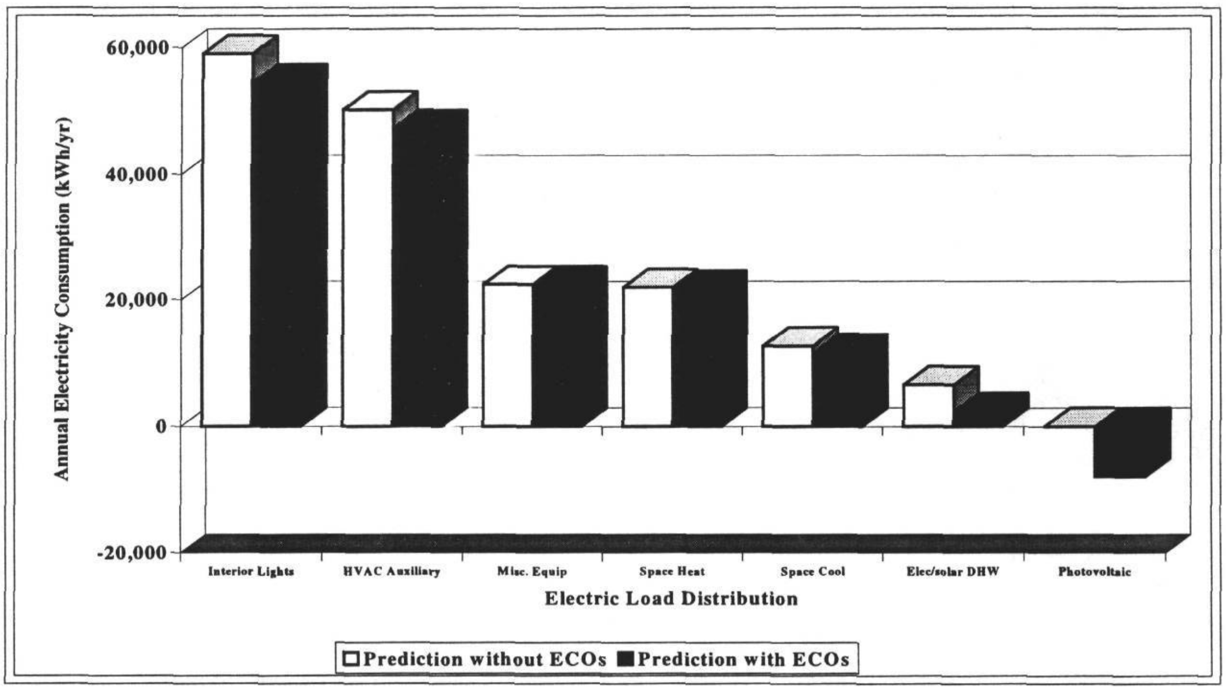
(5) Not part of original ECO list. Calculated by: (Basemodel + photovoltaic + dhw).

(6) Savings total does not include "All ECOs Combined."

(7) The percent difference was calculated as follows: [(DOE-2 savings - architect proposal) / architect proposal] x 100.



(a)



(b)

Figure 1 ECO Savings Comparisons. (a) Annual ECO Savings. (b) Annual Electric Load Distribution.

ANALYSIS OF ENERGY CONSERVATION OPTIONS FOR U.S.D.O.E. FORRESTAL CHILD DEVELOPMENT CENTER

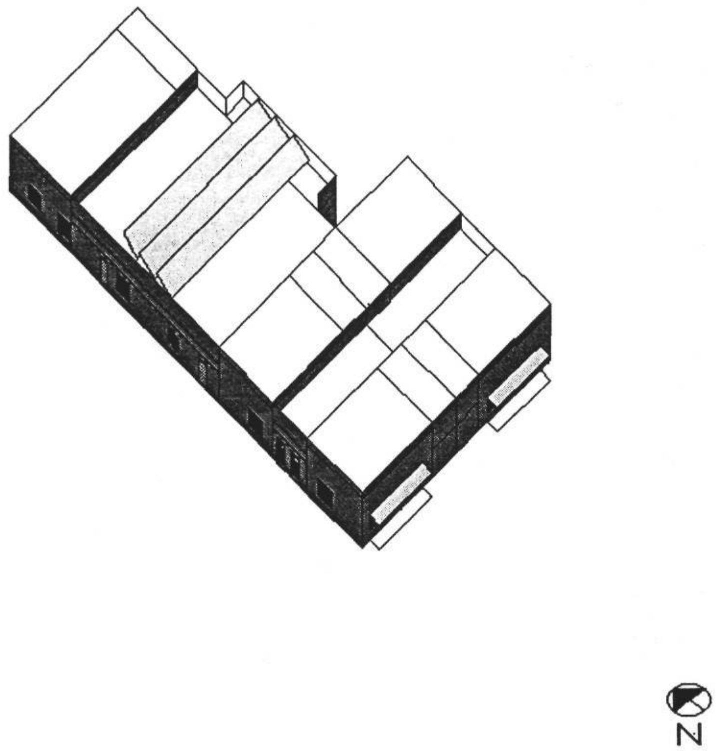
INTRODUCTION

This project intends to verify the effects of various energy conservation options (ECO) at the USDOE Forrestal Child Development Center (CDC) by using a calibrated DOE-2 simulation program. Such simulations allow for energy use comparisons by running a base model simulation of the existing building and comparing it parametrically to simulations for each ECO. The savings can then be calculated by comparing the annual energy use with the ECO to baseline annual energy use without the ECO.

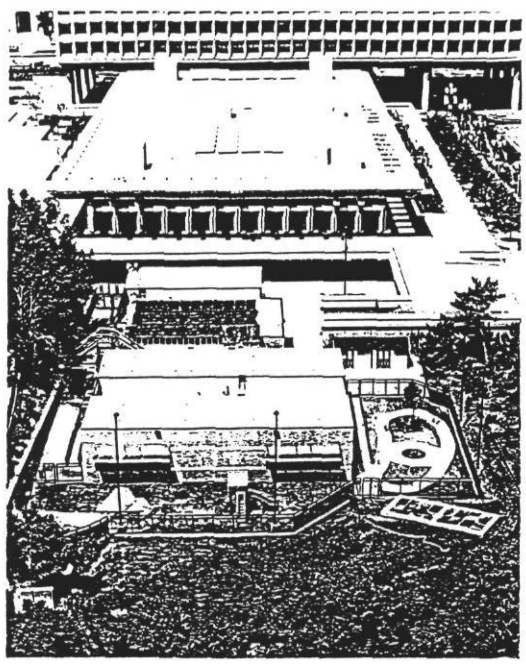
Figure 2 (a) is a model of the building as seen by DOE-2. This figure was generated with an architectural rendering package called DrawBDL (Huang 1993) which reads building dimensions directly from the DOE-2 BDL input code. The most beneficial feature of this viewing package is that it provides a means to eliminate inevitable errors in dimensioning of the building. Figure 2 (b) is a photograph of the building. Figure 3 shows the location of the Child Development Center building with respect to the neighboring buildings and shows its north-south orientation.

The DOE-2 Simulation Program

DOE-2 is divided into four main sections: LOADS, SYSTEMS, PLANT, and ECONOMICS. The LOADS sub-program calculates the heating/cooling loads on a building based on architectural specifications, interior loads, ambient conditions from a weather tape, and shading surfaces. Once hourly loads are calculated, the information is passed on to the SYSTEMS sub-program which then simulates the influence of internal equipment and HVAC secondary systems on electricity consumption, including all HVAC equipment, lights, and appliances. It allows the user to specify various system types such as single or dual duct systems, packaged residential systems, and heat pumps; as a result of these factors SYSTEMS simulates interior conditions such as temperature and relative humidity control. After receiving the information from SYSTEMS, the PLANT sub-program then calculates all primary energy-using equipment in the building such as chillers, condensers and domestic hot water systems. Finally, the ECONOMICS sub-program calculates utility costs and life cycle costs for a prescribed period of time.

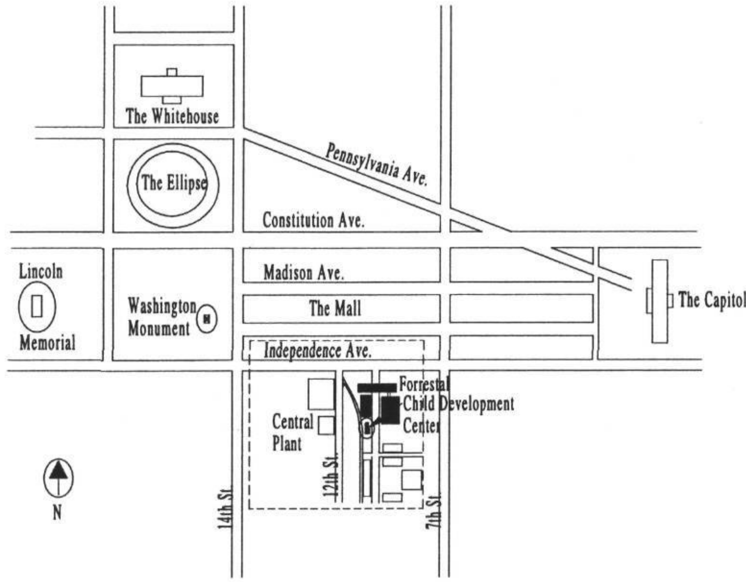


(a)

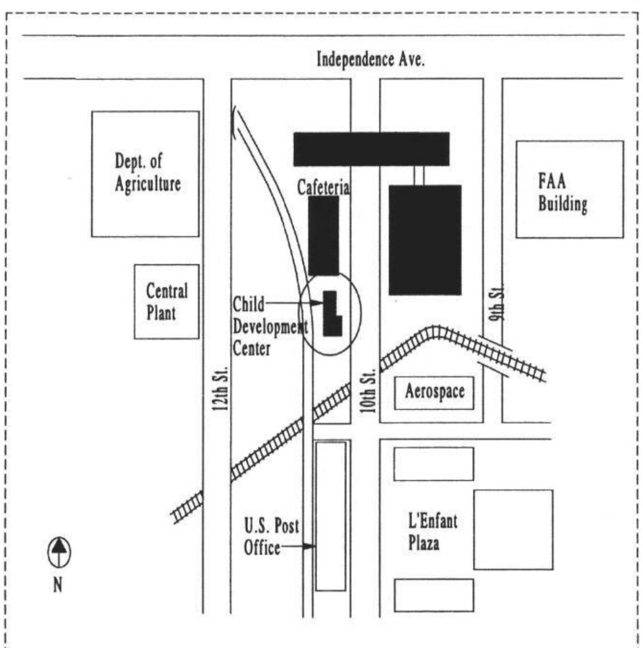


(b)

Figure 2 DOE-2 Child Development Center Model.



(a)



(b)

Figure 3 CDC Location. (a) Overview of Washington, D.C. (b) USDOE Forrestal Complex.

Measuring the Energy Use and Environmental Parameters

Data collection was performed using electronic data loggers located in the Forrestal building and CDC. Figure 4 shows the relative locations of each logger. Figure 5 is an electrical monitoring diagram for logger #905 detailing the original lights and equipment monitoring points for the Forrestal Building. Figure 6 shows a thermal monitoring diagram for logger #906 detailing the Child Development Center whole-building electricity, the cooling and heating energy points as well as ambient weather parameters from the National Weather Service. Also shown in Figure 6 is a monitoring diagram for the logger located in the CDC (#907) which monitors the photovoltaic system, solar radiation, and ambient temperature. Pertinent data were recorded and inspected weekly. Figures 7 and 8 are examples of weekly summary plots that show which data were collected. Figure 7 shows data from the Forrestal building and Figure 8 shows data from the CDC. These weekly inspection plots provide a means of verifying logger operation so that data loss is kept to a minimum in the event of logger or power failure.

On a weekly basis, the data are added to a contiguous database which allows for an analysis to be made over the entire dataset. Figure 9 shows a summary of the entire nine month measured ambient weather data. It includes NWS relative humidity, NWS ambient dry bulb temperature, NWS peak hourly wind speed, and site-measured global horizontal solar radiation. Figure 10 (a) is a plot of the monitored whole-building electricity use for the CDC. Figure 10 (b) shows the electricity produced by the photovoltaic array. Since the first draft of this report was submitted, two additional months of weather and energy use data were added to the original seven month calibration period extending well into the heating season. This dataset allows for a more accurate calibration which includes data from the cooling season, the heating season, and an intermediate season (Fels 1986; Kissock et al. 1993). The DOE-2 model was then re-tuned and the results reported here.

In order to calibrate the DOE-2 simulation to the existing building, several tasks needed to be accomplished. First, an accurate description of the building was created using the DOE-2 Building Description Language (BDL). This included a careful assessment of all architectural features and shading from nearby objects. Second, measured weather data were processed or "packed" into a format that DOE-2 can read. This included dry bulb temperature, relative humidity, solar radiation, and peak wind speed. Finally, numerous iterations were made to match the simulated output to the measured whole-building electricity data. With DOE-2 using ambient weather conditions from a weather tape, the user may choose either to employ standard weather tapes available from the National Weather Service or to pack a site-specific Test

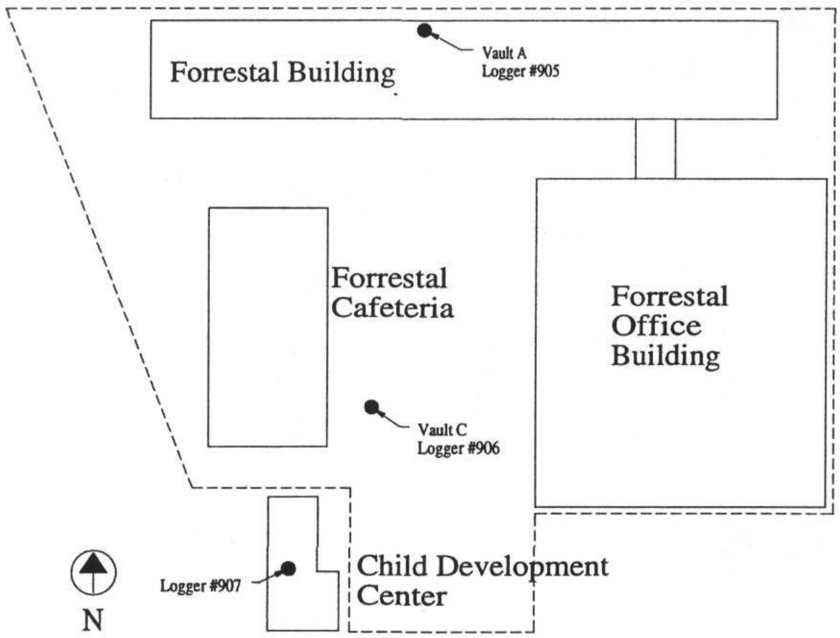


Figure 4 Forrestal Complex and Logger Locations.

ELECTRICAL MONITORING DIAGRAM

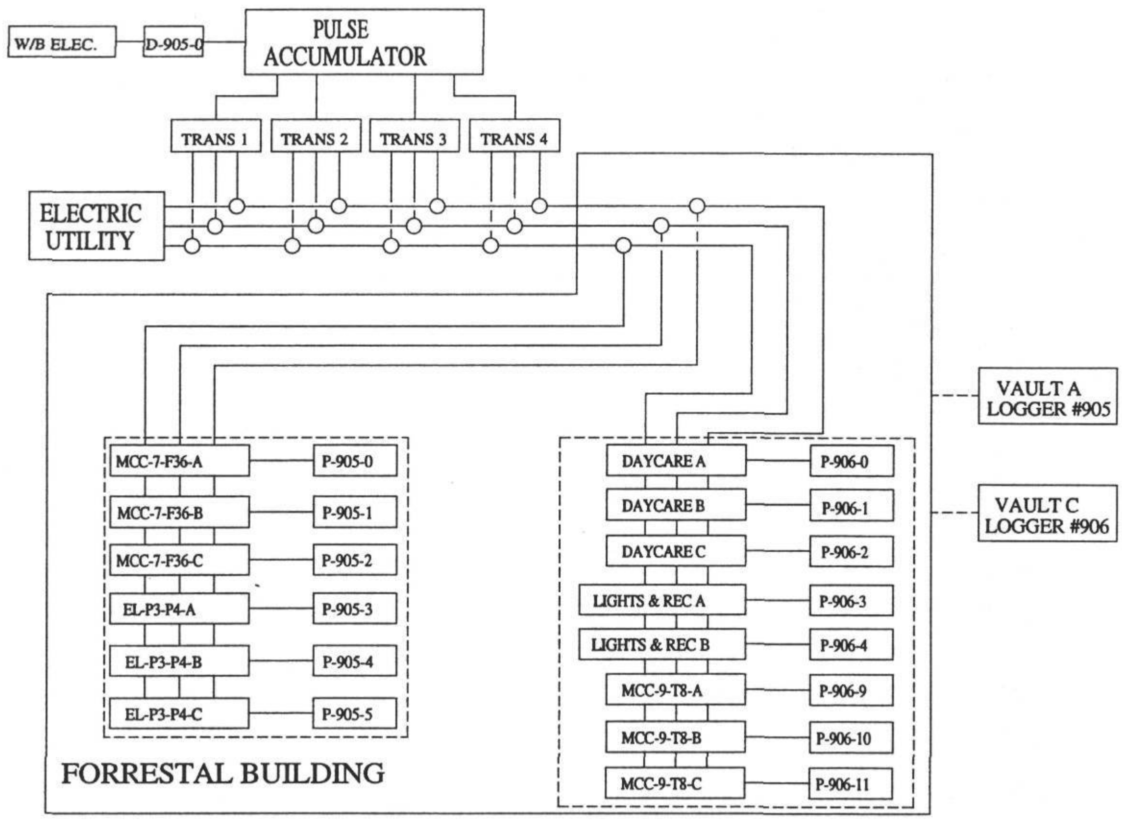
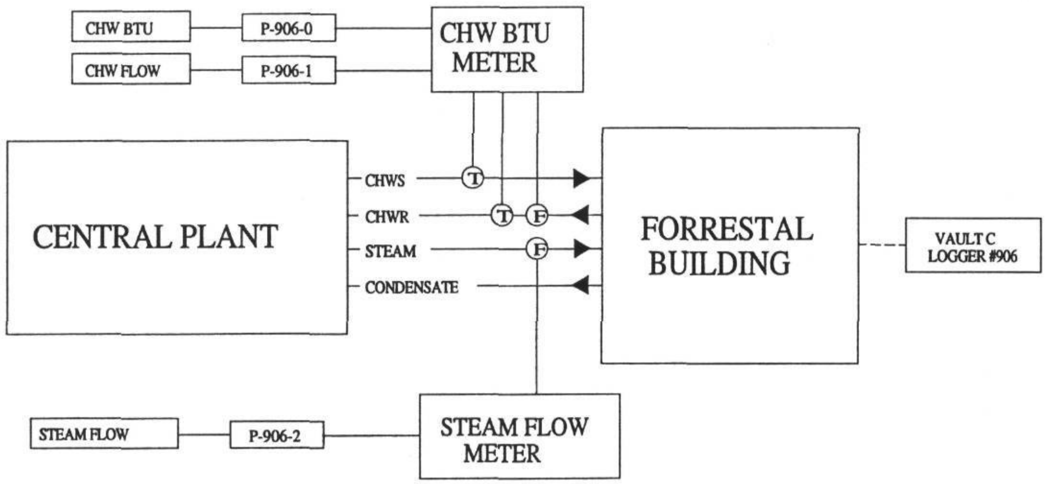


Figure 5 Forrestal Electrical Monitoring Diagram.

THERMAL MONITORING DIAGRAM



MONITORING DIAGRAM

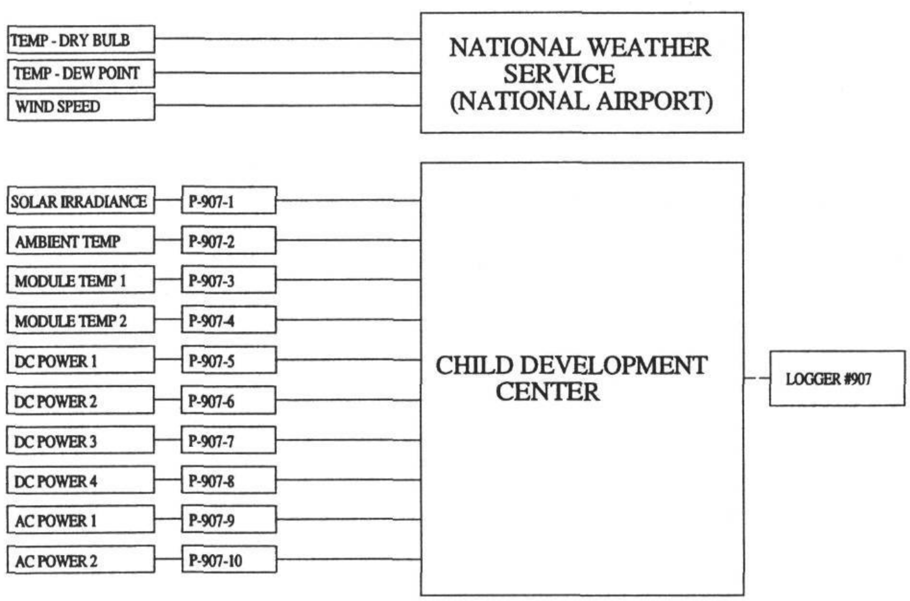


Figure 6 Forrestal Thermal and CDC Monitoring Diagrams.

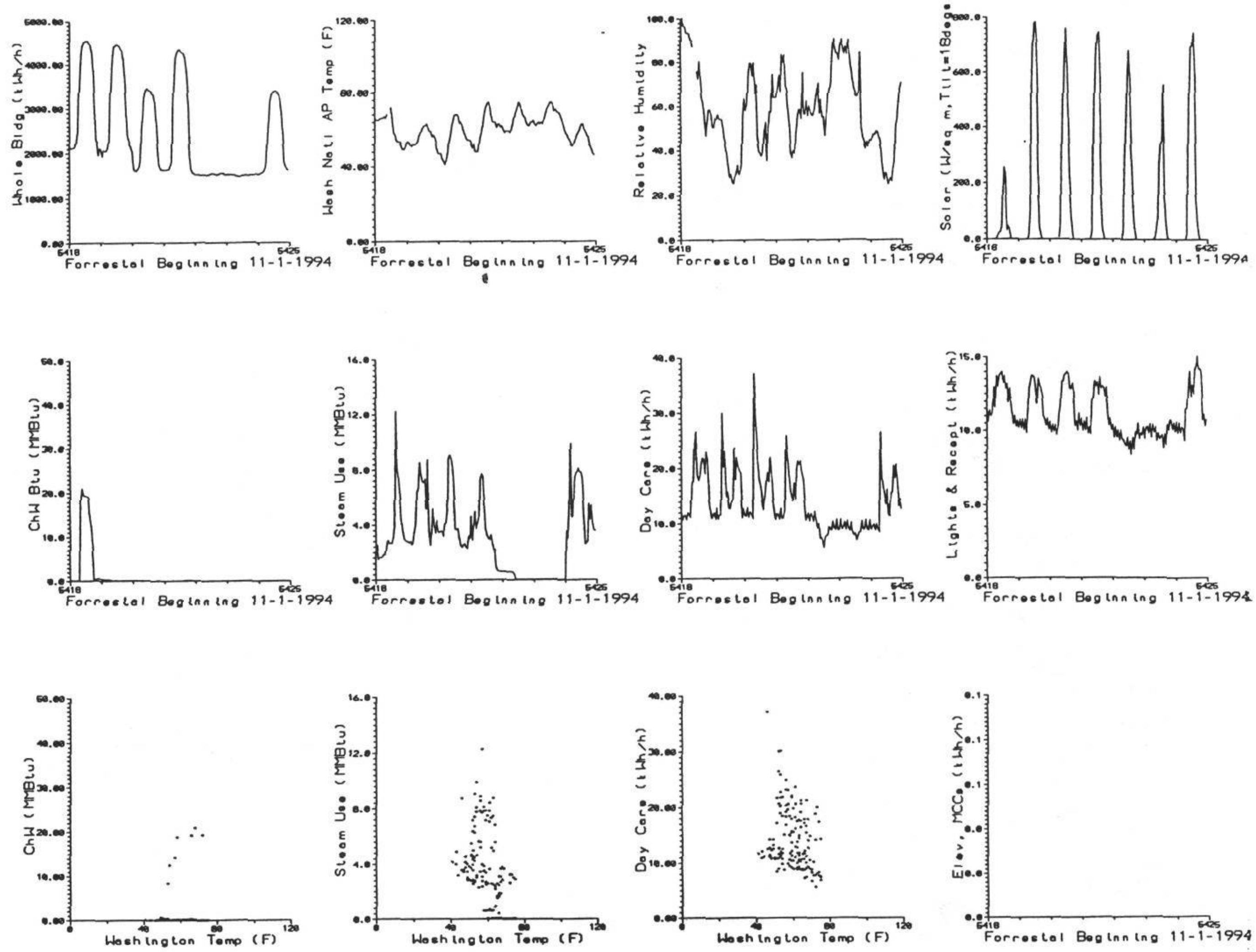


Figure 7 Forrestal Weekly Summary Plot.

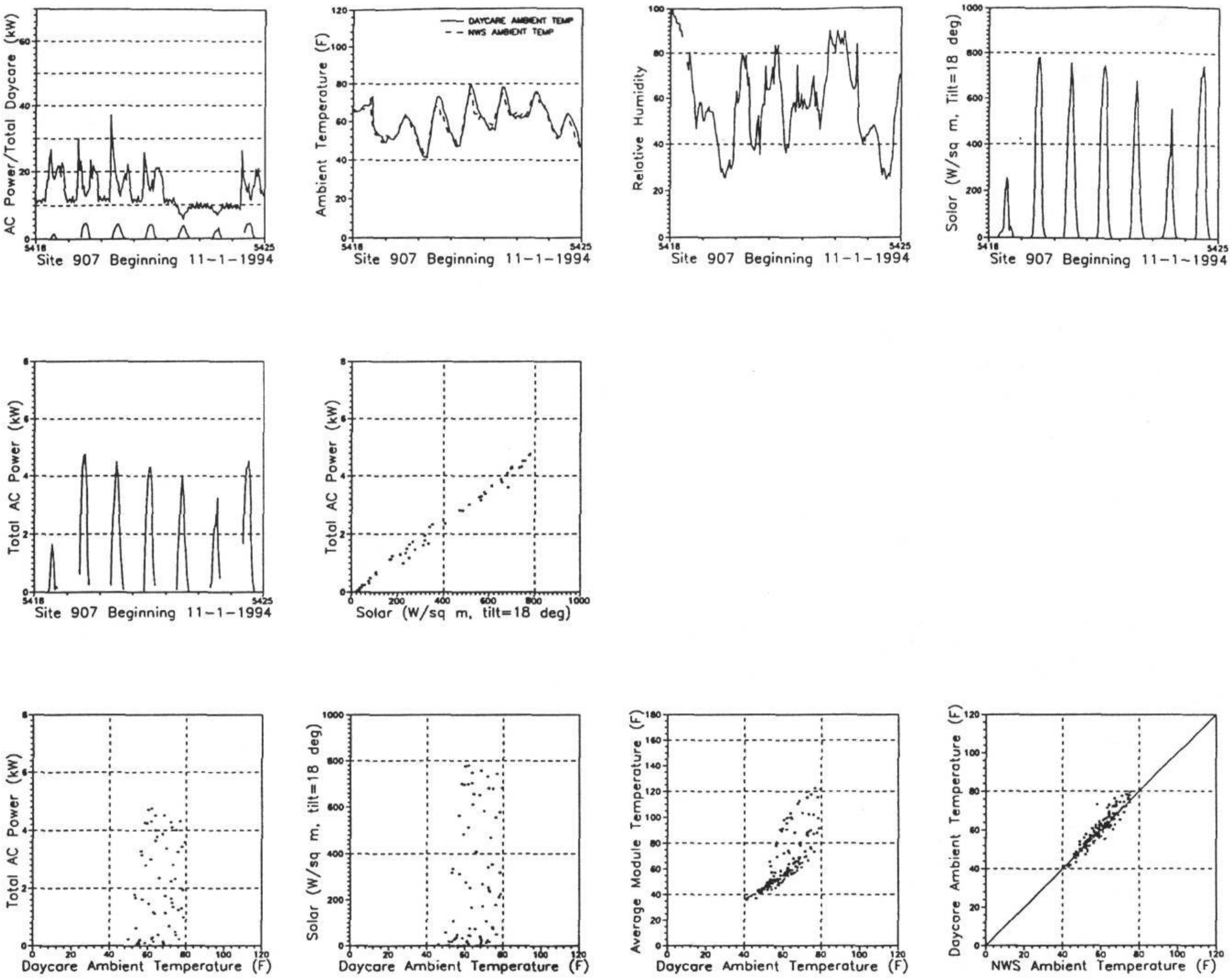


Figure 8 CDC Weekly Summary Plot.

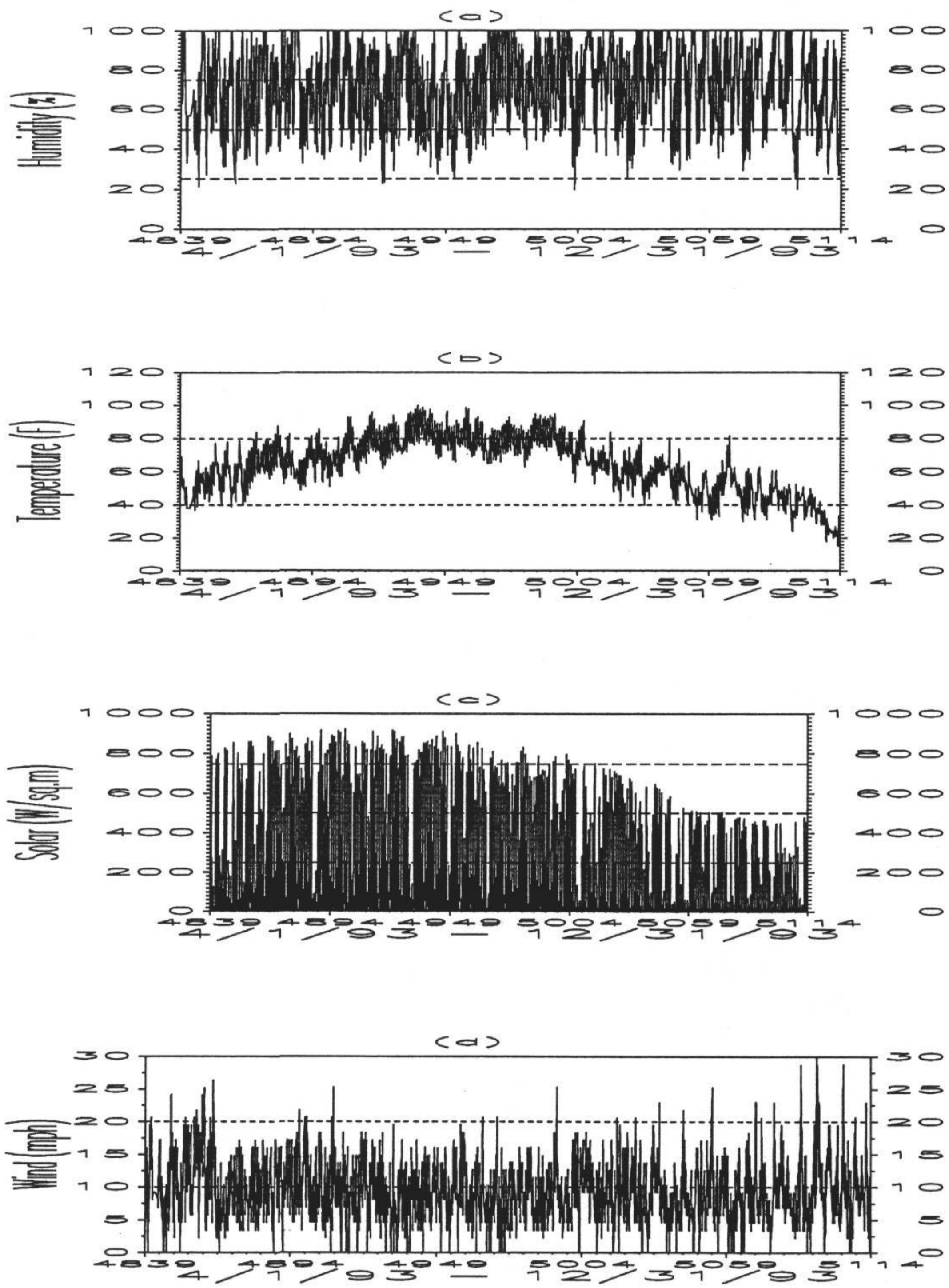
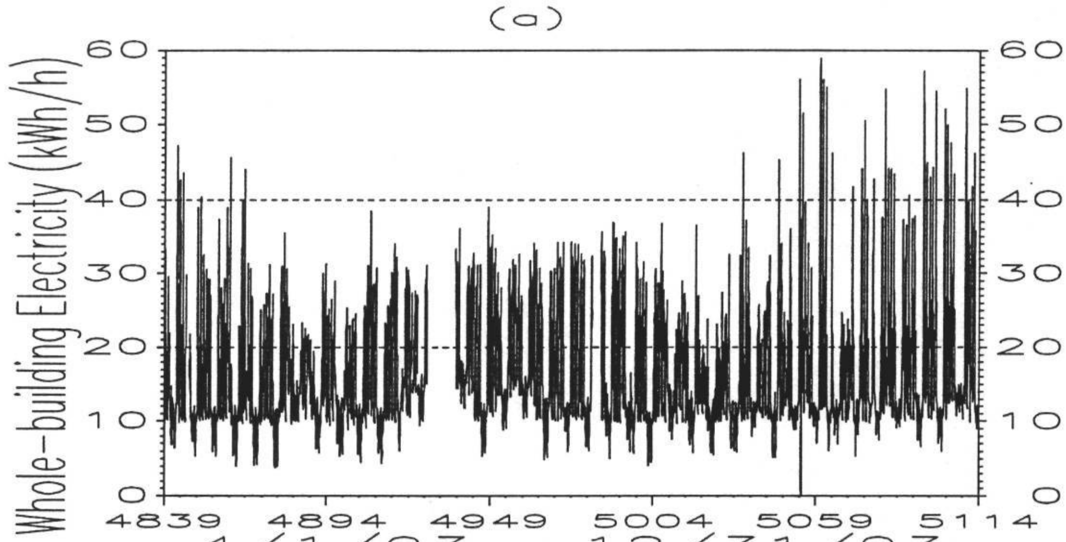


Figure 9 Measured Ambient Weather Data.



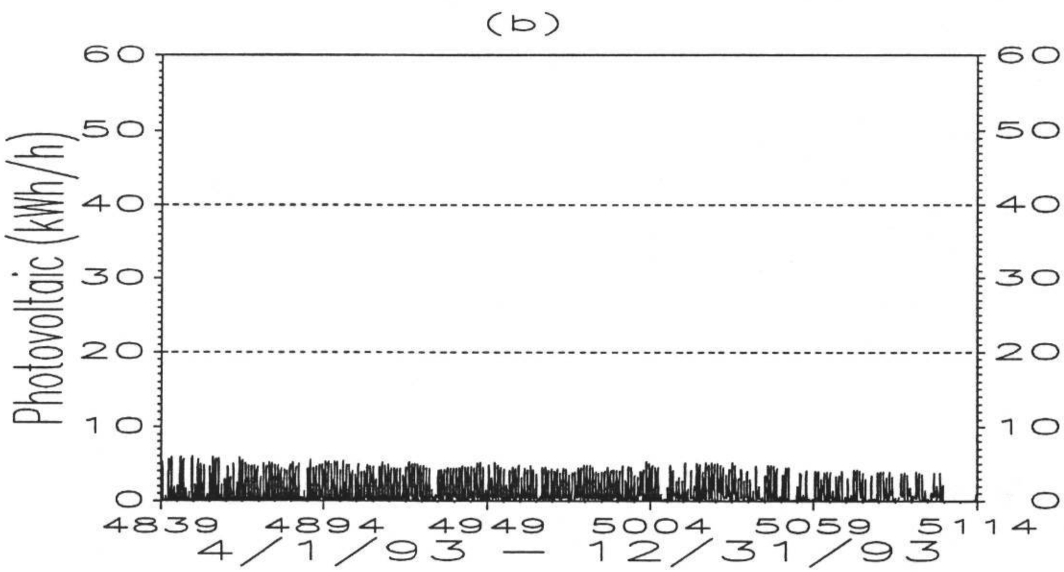


Figure 10 Measured Electricity Data. (a) Whole-building Electricity. (b) Photovoltaic.

Reference Year, or TRY, weather tape (TRY 1983) for a more accurate weather dependent calibration.

Packing a tape entails collecting hourly outdoor dry bulb temperature, outdoor relative humidity, wind speed, and global horizontal solar radiation. Routines were used to lay these data onto a TRY tape for the prescribed time for up to one year (Bronson 1992). For this building a tape was packed for available data from April through December 1993. Hourly dry bulb temperature, dew point temperature, and peak wind speed data were obtained from the National Weather Service which has a weather station located nearby at the Washington National Airport. Dew point temperature was used along with dry bulb temperature to calculate relative humidity using a psychrometric conversion routine (Sparks et al. 1993). Global solar radiation was measured on-site at an 18° angle titled from the horizontal toward the south, the same tilt angle of the photovoltaic solar panels located on the roof. The solar data were converted into global horizontal solar radiation (0° tilt) using a correlation developed by Erbs et al. (1982). All four weather parameters were combined into one data file and run through a FORTRAN weather packing program. The routine overlaid dry bulb temperature, relative humidity, and wind speed onto the TRY tape. The Erbs correlation was then used again to synthesize direct and diffuse solar radiation from global horizontal radiation and also packed onto the TRY tape. Missing data were labeled as "-99.0" and data interpolated according to the method reported in a more detailed report (Bronson 1992).

Simulation Method

The DOE-2 simulation involved encoding the building into an "input file" to be read by the DOE-2 BDL. The information was fed into the LOADS sub-program based on architectural data such as the building location, building elevation, orientation of each wall, window, door, roof panel, shading surface, and building construction materials and thermal properties. The heating ventilating and air conditioning, or HVAC, equipment was detailed in SYSTEMS, for such factors as cooling and heating capacities, system efficiencies, fan sizes, and air volume requirements. Occupancy, lights, equipment, and system schedules were added to the input file on an hourly basis to control equipment and lights. Then, hourly estimates of the exterior lighting loads were encoded separately from interior lighting systems which were summarized for each internal zone. Exterior lighting was calculated separately from interior lighting because it was determined that they have no effect on interior heating or cooling loads. The exterior electricity load was then passed directly to the PLANT sub-program bypassing the LOADS and SYSTEMS calculations. Table 2 summarizes the input variables for the CDC. This brief description highlights the major points for the simulation. The reader is referred to the DOE-

Table 2 DOE-2 Input File Variables.

	Input Deck Summary Page		
Run Name:	Daycare33	**Remarks:**	Calibrated as-built baseline model

LOADS			**Weather File:**	Washngtndctmy.wth	
Exterior Envelopes					
Roof	Refl. membrane, metal deck, insulation: U=0.033, Absorp. = 0.5				
Walls	Face brick, sheathing, insulation, gyp. board: U=0.068, Absorp. = 0.85				
Window and Glass Doors					
SC= 0.71		External Shading Devices:		Shade over South windows; buildings; trees	
People	10/zone (2 children/adult)				
Sensible - (Btu/h-person)	250				
Latent - (Btu/h-person)	200				
Schedule:	7am - 0.1, 8am-7pm - 0.85, 8pm - 0.05, 9pm-6am - 0.0				
Infiltration					
Zone ->	**1**	**2**	**3**	**4**	
air changes per hour	0.6	0.6	0.6	0.6	
Lights (tot W)	3,002	3,383	5,704	1,790	
Recept. & Equip. (tot W)	500	750	5,100	1,350	
Floor Weight (lbs/ft^2)	30	30	30	30	

SYSTEMS		**TYPE:**	Package Single Zone Air Cooled Heat Pump		
Heating Capacity (Btu/h) :		**Cooling Capacity (Btu/h) :**		**EER (sum)**	**EER (win)**
Zone 1	85,000	Zone 1	90,000	10.6	10.2
Zone 2	85,000	Zone 2	90,000	10.6	10.2
Zone 3	85,000	Zone 3	90,000	10.6	10.2
Zone 4	42,000	Zone 4	46,000	10.0	8.3

CFM					
Zone ->	**1**	**2**	**3**	**4**	
Supply Air	2,381	2,582	2,985	1,645	
Exhaust Air	585	490	591	345	
Outside Air	580	500	700	315	
Thermostat Type:	Two position (controlled by EMS)				
Throttling Range:	2 F	**Setpoint:** 75 F (summer), 72 F (winter)			
Night Setback:	80 F (summer), 55 F (winter)				
			Sizing Option:	Adjust loads	
Humidity Control:	No				

	PLANT
Source:	Electricity

2.1D reference manual (LBL 1989) for further details. Additional details concerning the calibrated simulation are available in the reports by Bou-Saada (1994a; 1994b).

To verify the effectiveness of the energy conservation options, one DOE-2 model was created for each ECO. The first model was run in order to calibrate the simulation to measured whole-building electricity consumption for the nine month period of April - December 1993. This typically is the most difficult and time consuming task in modeling buildings. In this stage, incorrect assumptions in the input file must be detected, or one will always be unsure of what is being simulated. Once all the parameters were adjusted to what was believed to be as close as possible to actual building conditions, the model was declared "calibrated". Several methods were used to verify the calibration which are detailed in the reports by Bou-Saada (1994a; 1994b).

A monthly difference of 5% or less between the modeled energy use and actual measured data is considered acceptable. This DOE-2 simulation is within -0.7% mean bias error (MBE) of the monthly data when an overall nine month comparison is taken into account. The hourly CV(RMSE) over the nine month calibrated period is 23.1%. Tables 3 through 6 are monthly comparison summaries between actual and simulated values showing the CV(RMSE), MBE, and the percent difference. Table 3 shows the overall calibration period, Table 4 shows the weekday occupied period values, Table 5 shows the weekday unoccupied period values, and Table 6 shows the weekend period values. Additional details concerning the statistical results may be found in Bou-Saada (1994a; 1994b).

Figure 11 is a three-dimensional positive only hourly residual plot which shows the monitored data in part (a) and the base model simulation in part (b). Figure 11 (c) shows the measured data subtracted from the DOE-2 base model and indicates any over-predictions. Figure 11 (d) shows the DOE-2 base model subtracted from the measured data and represents the under-predictions. The last two plots (i.e., 11 (c) and 11 (d)) show positive residuals only. Figure 12 is also a three-dimensional residual plot, but shown from a rotated perspective. Figure 13 (a) through (c) show time-series plots of hourly measured data and hourly simulated data (April through June), and the hourly difference. Figure 14 (a) through (c) are the July through September comparisons and Figure 15 (a) through (c) show October through December.

Data Processing and Statistical Graphics

In order to report the calibration differences, several computer programs and graphical tools were used, including routines by Abbas (1993) and routines developed especially for this report (Bou-

Table 3 Total Period CV(RMSE), MBE, and Percent Differences.

Month	Total Measured (kWh)	Mean (kWh)	Total Simulated (kWh)	Mean (kWh)	Total Difference %	Hourly MBE %	Hourly RMSE (kWh)	Hourly CV(RMSE) %
April	10,606	15.5	10,243	15.0	-3.4	-3.4	4.2	26.9
May	11,507	15.5	10,948	14.7	-4.9	-4.9	3.4	21.8
June	11,568	17.4	11,313	17.0	-2.2	-2.2	3.5	20.2
July	11,247	19.9	11,052	19.6	-1.7	-1.7	4.9	24.7
August	12,621	18.6	12,531	18.5	-0.7	-0.7	4.0	21.7
September	11,885	16.5	12,012	16.7	1.1	1.1	3.7	22.5
October	11,216	15.1	11,413	15.3	1.8	1.8	3.5	23.2
November	11,944	16.7	12,202	17.0	2.2	2.2	4.0	23.7
December	9,220	18.3	9,337	18.5	1.3	1.3	4.2	22.8
Total	101,814	16.9	101,051	16.8	-0.7	-0.7	3.9	23.1

Table 4 Weekday Occupied Period CV(RMSE), MBE, and Percent Differences.

Month	Total Measured (kWh)	Mean (kWh)	Total Simulated (kWh)	Mean (kWh)	Total Difference %	Hourly MBE %	Hourly RMSE (kWh)	Hourly CV(RMSE) %
April	5,233	21.3	5,172	21.0	-1.2	-1.2	5.6	26.1
May	5,379	21.3	5,334	21.2	-0.8	-0.8	3.4	15.9
June	6,127	25.6	6,169	25.8	0.7	0.7	3.6	13.9
July	5,859	29.3	6,246	31.2	6.6	6.6	4.1	13.9
August	6,997	29.9	6,886	29.4	-1.6	-1.6	3.6	11.9
September	6,246	23.7	6,438	24.4	3.1	3.1	4.5	19.1
October	5,292	21.0	5,440	21.6	2.8	2.8	5.1	24.1
November	6,153	23.4	6,410	24.4	4.2	4.2	5.2	22.4
December	4,932	27.4	5,149	28.6	4.4	4.4	6.2	22.6
Total	52,217	24.5	53,244	25.0	2.0	2.0	4.6	18.9

Table 5 Weekday Unoccupied CV(RMSE), MBE, and Percent Differences.

Month	Total Measured (kWh)	Mean (kWh)	Total Simulated (kWh)	Mean (kWh)	Total Difference %	Hourly MBE %	Hourly RMSE (kWh)	Hourly CV(RMSE) %
April	3,486	13.9	3,210	12.8	-7.9	-7.9	3.7	26.8
May	3,404	13.5	3,140	12.5	-7.8	-7.8	3.6	26.3
June	3,168	13.5	3,037	13.0	-4.1	-4.1	3.6	26.6
July	3,133	15.8	2,807	14.2	-10.4	-10.4	5.4	33.8
August	3,128	13.8	3,147	13.9	0.6	0.6	4.5	32.3
September	3,504	13.3	3,543	13.4	1.1	1.1	3.5	26.6
October	3,285	13.0	3,463	13.7	5.4	5.4	2.8	21.4
November	3,628	13.9	3,732	14.3	2.9	2.9	3.5	24.9
December	2,695	14.9	2,633	14.6	-2.3	-2.3	2.9	19.5
Total	29,430	13.9	28,712	13.5	-2.4	-2.4	3.8	27.0

Table 6 Weekend Period CV(RMSE), MBE, and Percent Differences.

Month	Total Measured (kWh)	Mean (kWh)	Total Simulated (kWh)	Mean (kWh)	Total Difference %	Hourly MBE %	Hourly RMSE (kWh)	Hourly CV(RMSE) %
April	1,887	10.0	1,860	9.8	-1.5	-1.5	2.0	20.1
May	2,725	11.4	2,474	10.3	-9.2	-9.2	3.2	27.9
June	2,272	11.8	2,106	11.0	-7.3	-7.3	3.4	28.5
July	2,255	13.5	2,000	12.0	-11.3	-11.3	5.3	39.2
August	2,496	11.5	2,497	11.5	0.0	0.0	4.1	35.4
September	2,135	11.1	2,031	10.6	-4.9	-4.9	2.6	23.2
October	2,639	11.0	2,511	10.5	-4.9	-4.9	1.7	15.0
November	2,164	11.2	2,060	10.7	-4.8	-4.8	2.1	18.9
December	1,593	11.1	1,556	10.8	-2.4	-2.4	1.6	14.3
Total	20,167	11.4	19,095	10.8	-5.3	-5.3	3.1	27.0

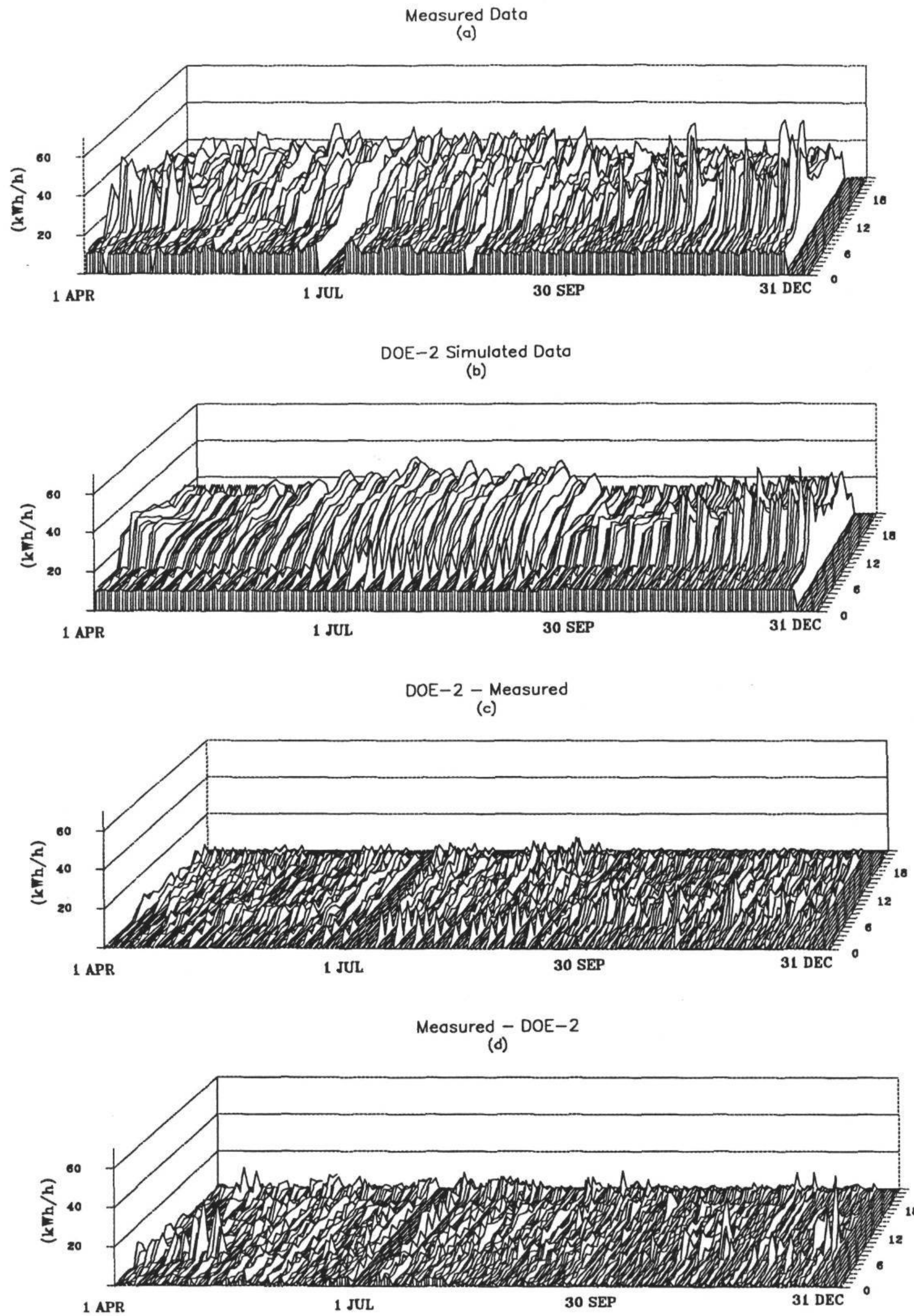


Figure 11 Comparative Three-dimensional Plots. (a) Measured Data. (b) Simulated Data. (c) Simulated - Measured Data. (d) Measured - Simulated Data.

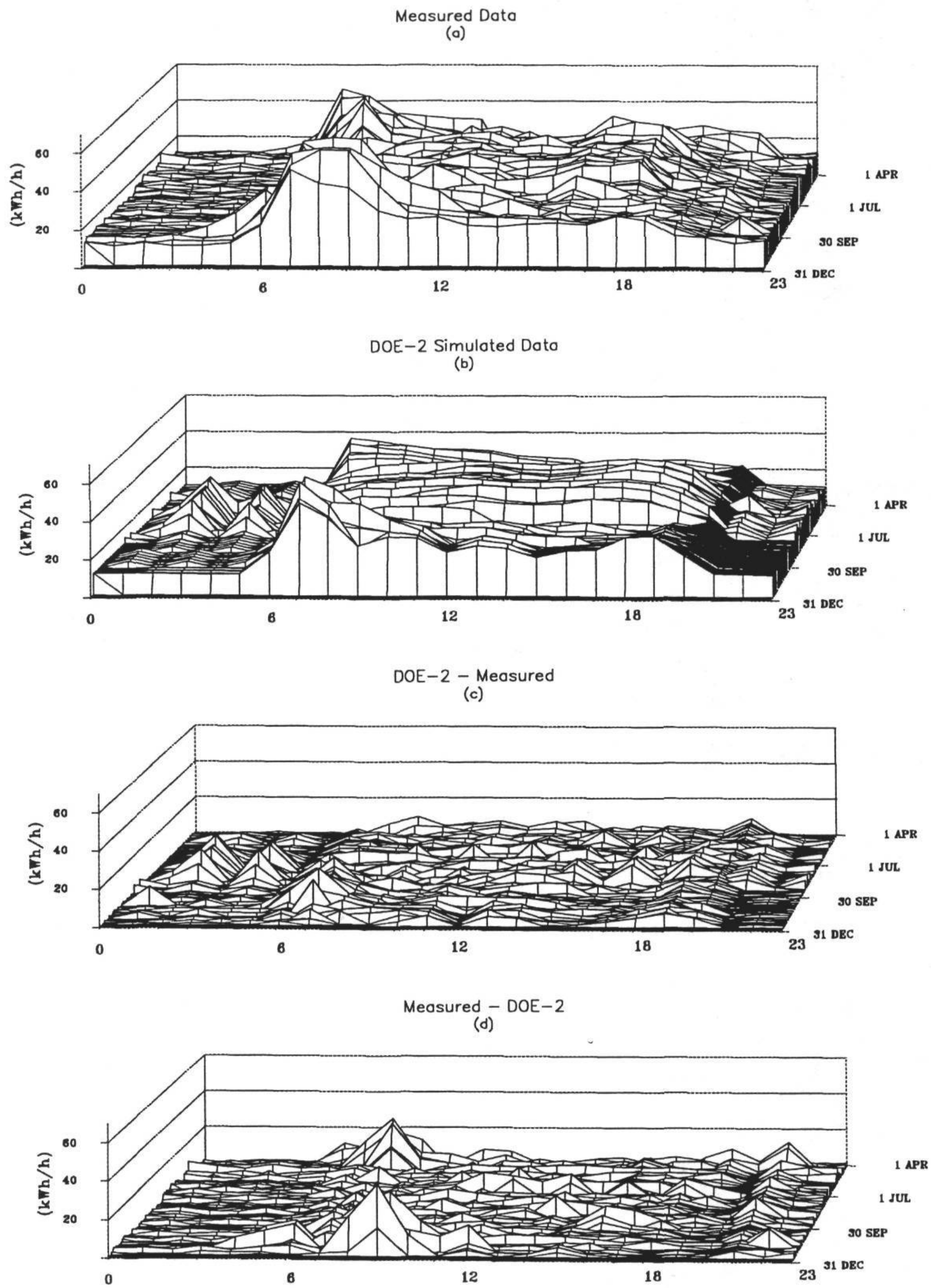


Figure 12 Rotated Comparative Three-dimensional Plots. (a) Measured Data. (b) Simulated Data. (c) Simulated - Measured Data. (d) Measured - Simulated Data.

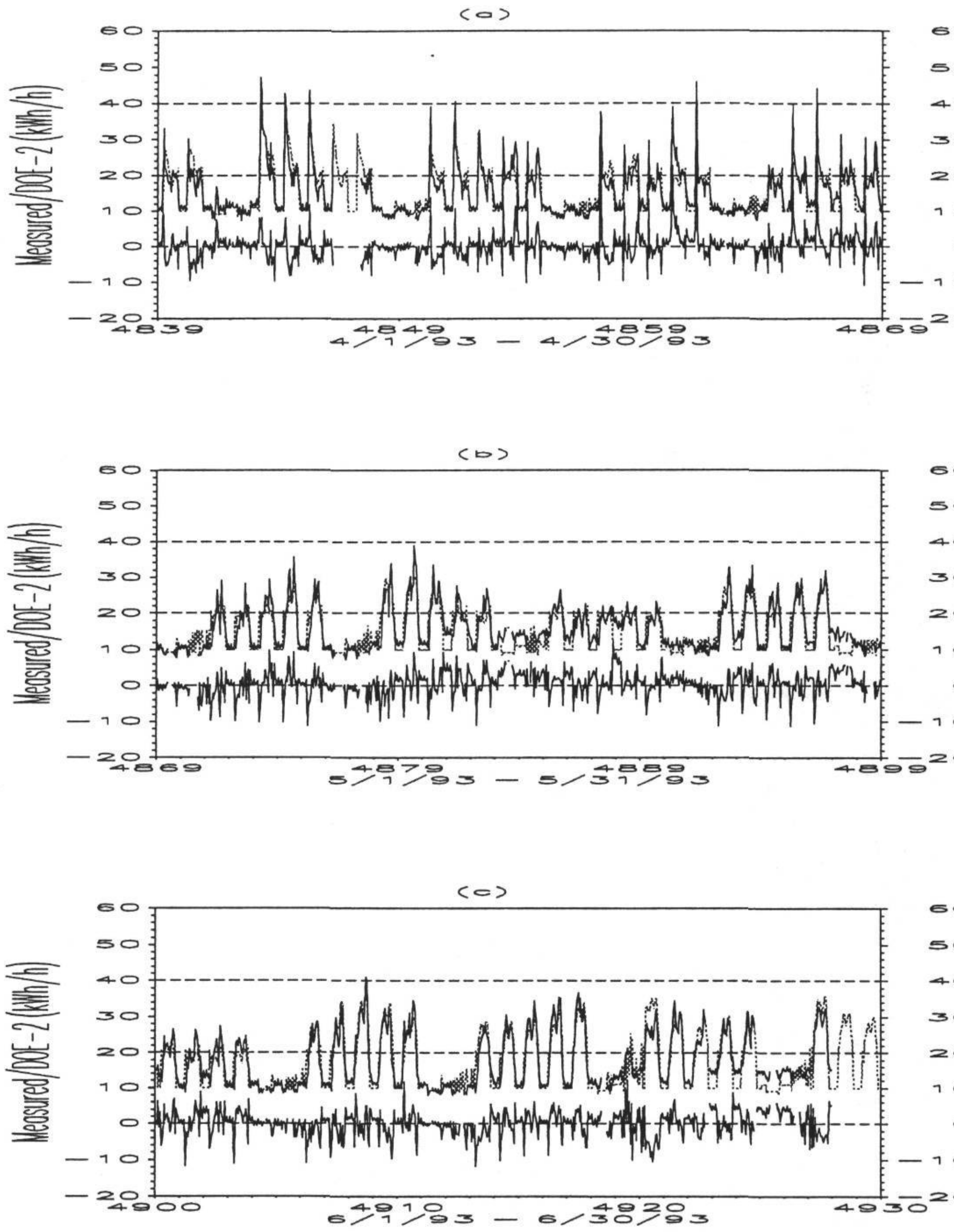


Figure 13 Time-series Plots of CDC Electricity Use: April - June 1993. (a) April. (b) May. (c) June. The dashed line is the DOE-2 simulation. The solid line is the measured data. The bottom trace represents the residuals or the measured - simulated difference.

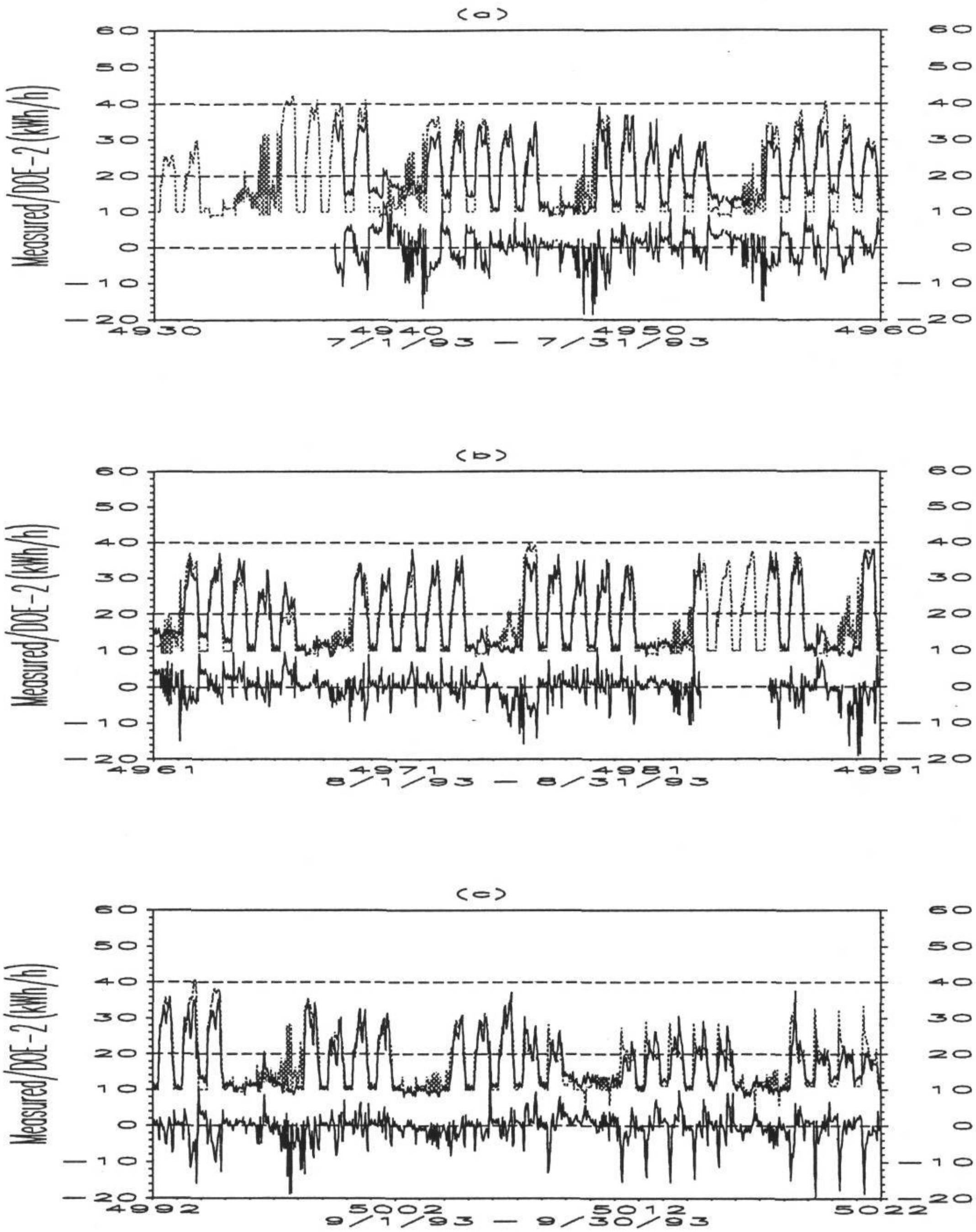


Figure 14 Time-series Plots of CDC Electricity Use: July - September 1993. (a) July. (b) August. (c) September. The dashed line is the DOE-2 simulation. The solid line is the measured data. The bottom trace represents the residuals or the measured - simulated difference.

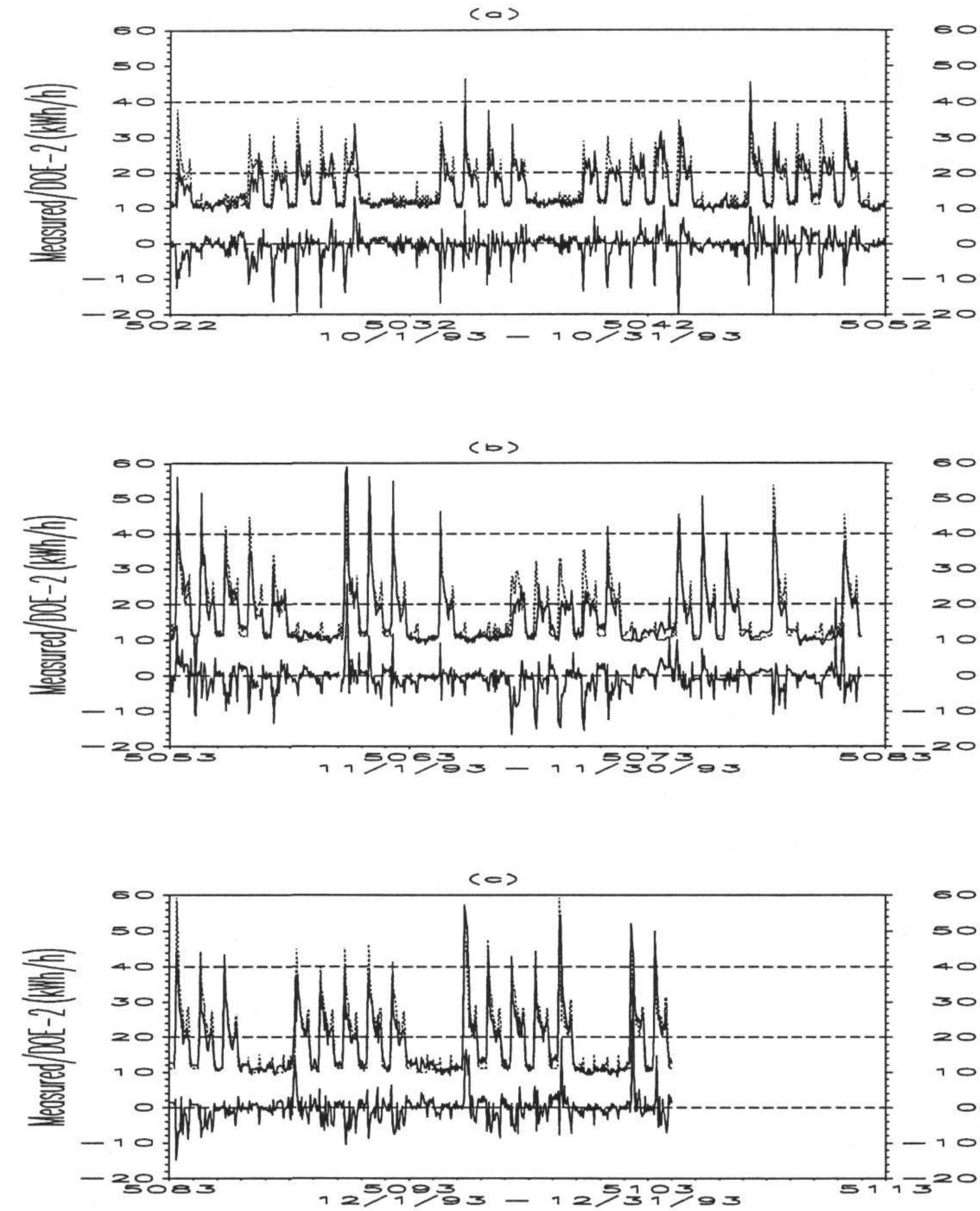


Figure 15 Time-series Plots of CDC Electricity Use: October - December 1993. (a) October. (b) November. (c) December. The dashed line is the DOE-2 simulation. The solid line is the measured data. The bottom trace represents the residuals or the measured - simulated difference.

Saada 1994). First, the building was simulated with DOE-2 on an hourly basis for a nine month period. The resulting whole-building electricity reports were extracted from the DOE-2 output reports and processed with SAS, the Statistical Analysis Software (SAS 1989). Three-dimensional daily and box-whisker-mean plots were found to be helpful during the fine tuning process. The box-whisker-mean plots display the maximum, minimum, mean, and median points for a given period of data. The upper and lower tips of the whiskers are the 90th and 10th percentiles respectively representing outliers. The upper and lower box ends are the 75th and 25th percentiles, respectively, with the line in between them being the median, or the 50th percentile. The line connecting each box represents the statistical mean, or average. X-Y scatter plots were also used to display the electricity consumption. The combined x-y scatter plot/box-whisker-mean plot were found to be helpful in characterizing weather-dependent behavior.

In the next two figures (16 and 17), the data are divided into weekday/weekend temperature bin box-whisker-mean plots corresponding to weekly building occupancy patterns. Weekdays were defined to begin on Mondays at 7:00 a.m. and end on Fridays at 9:00 p.m. Weekends began on Fridays after 9:00 p.m. and ended on Mondays at 7:00 a.m. These figures contain four types of data. In the upper left graph the measured electricity use is shown plotted against average ambient temperature. In the upper right graph, the DOE-2 simulated data are shown. Below each scatter plot (parts (a) - monitored and (c) - calibrated) are box-whisker-mean bin plots in parts (b) and (d) showing the whole-building electricity consumption as a function of temperature bins divided into 10° F segments. The measured data box-whisker-mean average in part (b) (the line connecting the boxes) is superimposed onto the calibrated base model box-whisker-mean plot in part (d) to indicate the difference between the two means, and hence how well the model is calibrated.

Figure 18 is similar to the Figure 11 (a) and (b) three-dimensional graph, but breaks down the energy usage using weekly box-whisker-mean plots instead of temperature bins with the measured data in Figure 18 (a) and the base model simulation in Figure 18 (b).

BUILDING DESCRIPTION

The 8,100 sq. ft. modular building is divided into four conditioned zones: two main classroom zones; one kitchen, office, and utilities zone; and one play area zone. An unconditioned plenum and an unconditioned crawl space are located above and below the four zones respectively. The daycare building is oriented on a north-south azimuth (the east walls face due East, the north wall faces due North, etc.) Figure 19 (a) shows the building orientation with shading surfaces

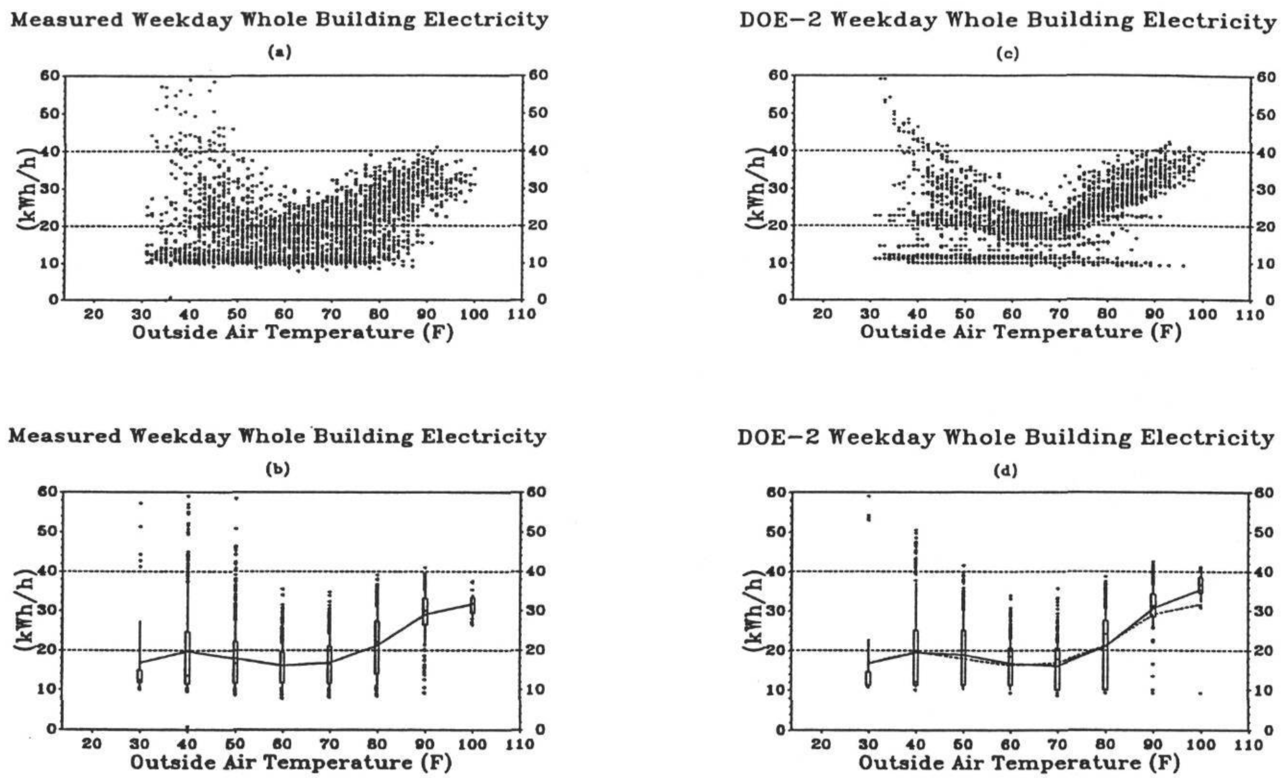


Figure 16 Weekday Temperature Bin Calibration Plots. (a) Measured Whole-building Scatter Plot. (b) Measured Whole-building Box-whisker-mean Plot. (c) DOE-2 Whole-building Scatter Plot. (d) DOE-2 Whole-building Box-whisker-mean Plot.

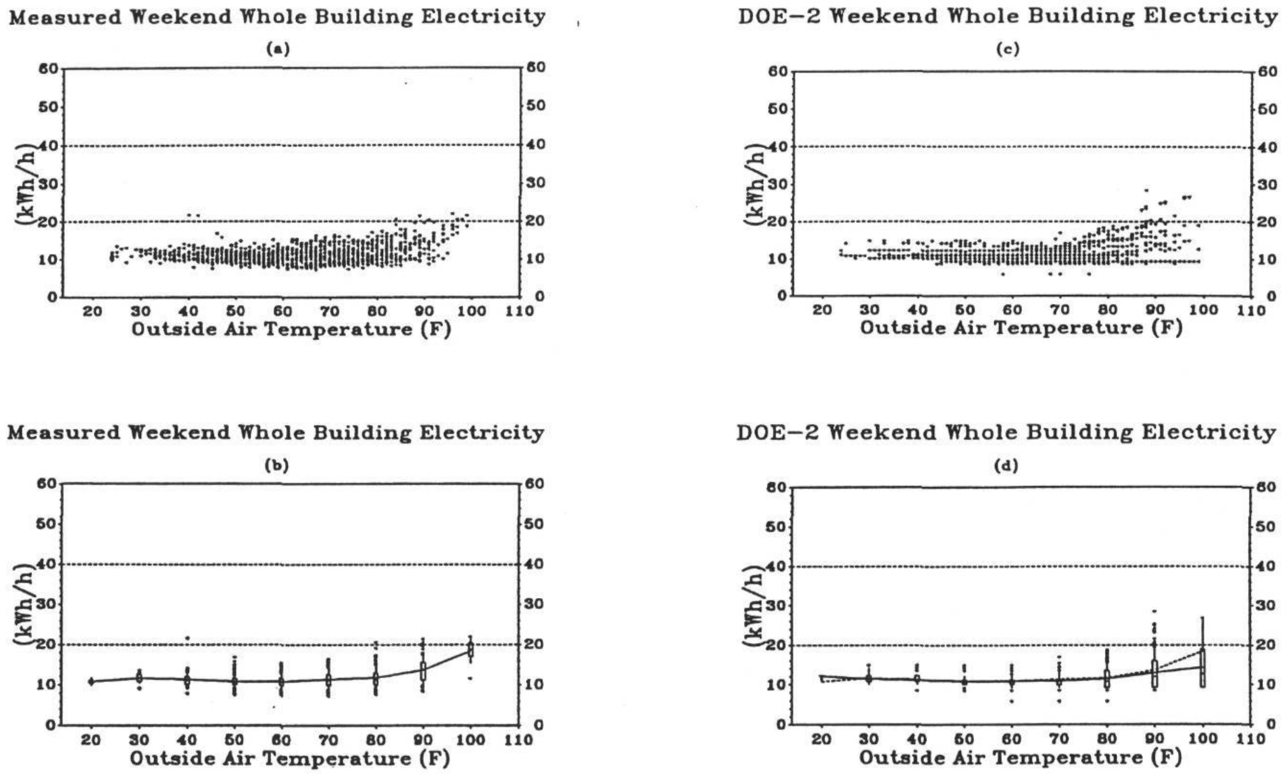


Figure 17 Weekend Temperature Bin Calibration Plots. (a) Measured Whole-building Scatter Plot. (b) Measured Whole-building Box-whisker-mean Plot. (c) DOE-2 Whole-building Scatter Plot. (d) DOE-2 Whole-building Box-whisker-mean Plot.

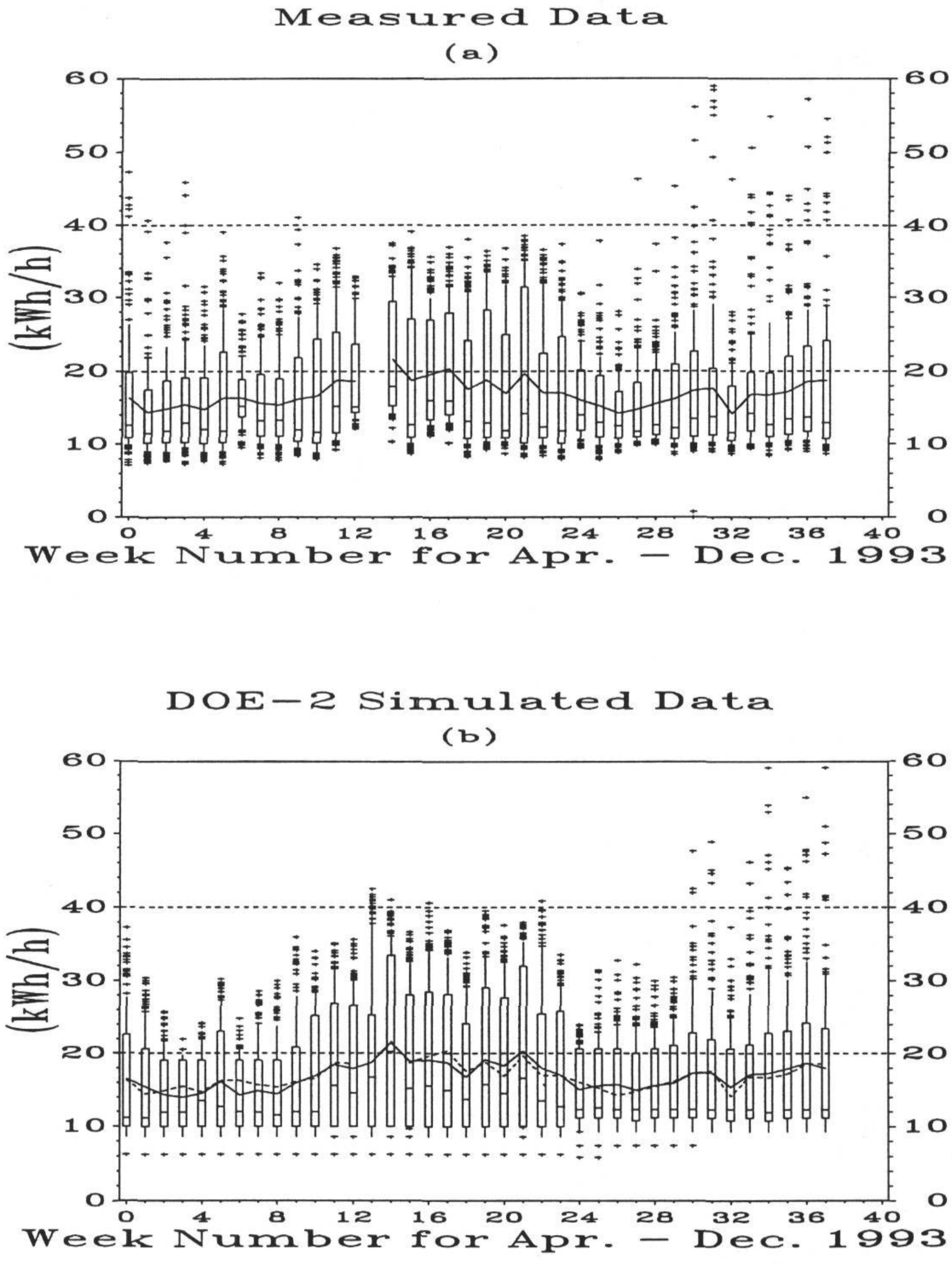
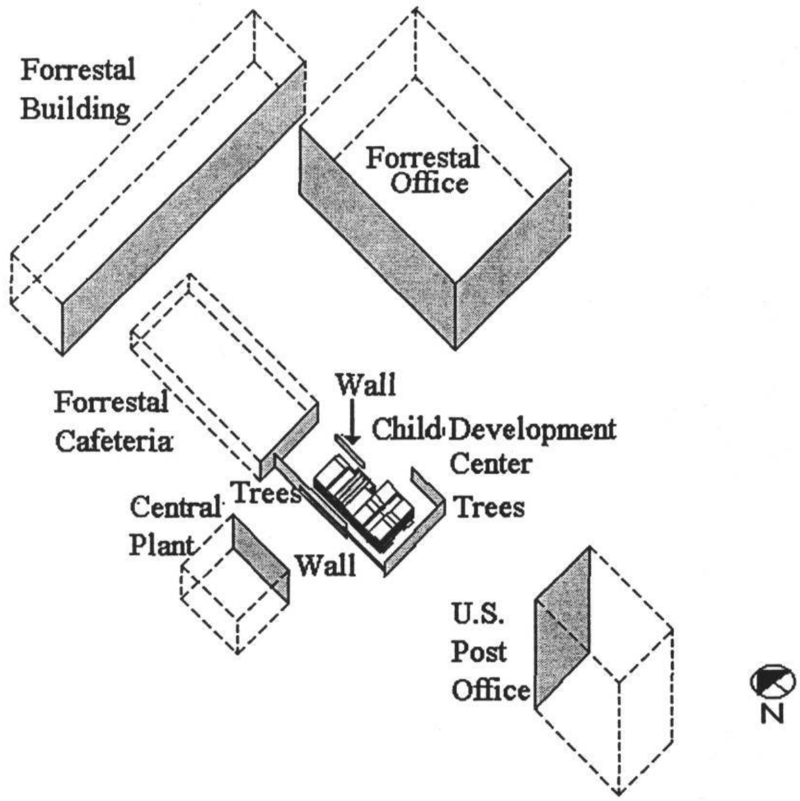
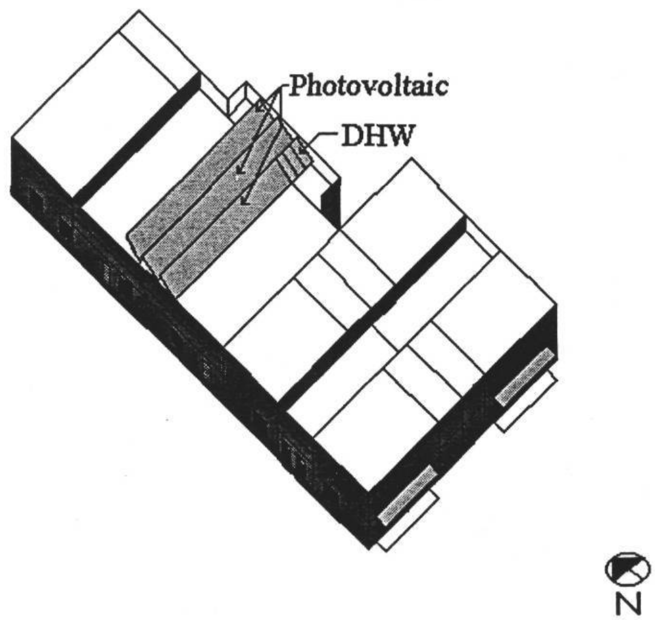


Figure 18 52-Week Measured and Simulated Binned Box-whisker-mean Plots.



(a)



(b)

Figure 19 CDC Building. (a) Forrestal Complex and Surroundings. (b) Daycare Center. The solid planes represent shading from buildings, walls, or trees.

provided by trees and buildings and Figure 19 (b) shows the building without shading. A row of trees surrounds the building on the east, south, and west sides. A wall is located on the west and north side. Three photovoltaic solar collector arrays are mounted on the roof which also provide some shading. Two horizontal window shades, one above each row, shade the south side windows. For shading simulation purposes, flat opaque horizontal planes represent shading devices and vertical walls were used to represent buildings, walls, and trees.

Construction

The building walls are composed of typical prefabricated construction materials consisting of 5/8" interior gypsum board, R-13 batt insulation in the middle, 5/8" exterior gypsum board sheathing, and 1/2" light brown exterior face brick. Limited daylighting is provided by 1" tinted double pane insulated windows with venetian blinds on the ground level. The classroom side of the building has a raised ceiling with the upper north-facing walls containing 1" clerestory untinted insulated windows for daylighting purposes. The roof is constructed with a reflective white roofing membrane, 1-½" metal decking on steel beams, and R-30 batt insulation. The floor consists of carpeting and padding, 4" mesh reinforced lightweight concrete, and R-15.4 rigid insulation over a 3' crawl space. The crawl space floor contains gravel on top of a polyethylene vapor barrier.

Systems

The heating, ventilating, and air conditioning (HVAC) system includes four packaged, single zone high efficiency air-cooled heat pumps, one for each zone (three - 7-½ ton units and one - 4 ton unit). Each heat pump is equipped with its own air-handler located in an equipment room. Conditioned air is distributed by supply and return ducts located in the plenum. Outside air is blended with conditioned air at each air-handler. Several exhaust fans are located throughout the building to maintain an air balance. A computer-controlled Energy Management System (EMS) controls the heat pumps and air handlers based on pre-programmed operating schedules and zone temperature night setbacks. The heat pumps are supplemented with electric baseboard heaters which are used when the heat pumps reach their maximum heating capacity.

According to the DOE staff, the EMS periodically failed to set back the thermostats. Therefore, a manual night set-back is being implemented during evening/morning lockup inspections. Since this is accomplishing the same thing that the EMS night set-back was designed to do the DOE-2 simulation included the set back.

The kitchen is equipped with two refrigerators, two freezers, one ice maker, a range, and several other typical kitchen appliances. Domestic hot water (DHW) is primarily supplied by a roof mounted solar DHW system which is capable of handling most of the hot water load. An electric DHW heater is available as a backup unit to meet the balance of the hot water load. Both the solar DHW storage tank and the electric DHW heater are located in an equipment room connected to the kitchen. The photovoltaic system solar panels are located on the roof which supplements the whole-building electricity energy requirements by up to 6 kW at peak periods (at solar noon). The classrooms, kitchen, hallways, and offices are equipped with energy efficient 34 W fluorescent lights. Several emergency lights and exit signs are located throughout the building and remain on continuously. Exterior lighting is provided by four - pole-mounted 400 W and twelve - wall-mounted 175 W high intensity discharge fixtures controlled by photocell sensors.

Occupancy

Typically, the building is occupied on weekdays by approximately twenty staff members and sixty children. A characteristic day begins at 7:00 a.m. and ends at 6:30 p.m., Monday through Friday. The HVAC system remains on until 9:00 p.m. to allow for after-hours work and a nightly walk-thru inspection by maintenance crew. During afternoon hours, most classroom lights are turned-off during the children's nap time and are turned back on late in the afternoon.

RESULTS

Table 7 is a list of the baseline installed ECO features provided by the GSA architect and standard (w/o ECO) comparisons. A calibrated DOE-2 simulation was used to test each individual ECO over a one year period using the Washington, D.C. TMY (Typical Meteorological Year) weather tape (TMY 1988) and compared to original architectural savings estimates. A one year base model was run and used as a baseline energy consumption starting point. This model used the same DOE-2 BDL input file that was calibrated to the nine months of measured data. In effect, the calibrated model represents the "as-built" building with all the ECOs. The DOE-2 input file was then modified, one ECO at a time, to determine what the energy use would have been without the ECOs. For each comparison, the ECO parameter in question was changed to the non-ECO value provided by either the architect, or the PEPCO reference value. The annual energy consumption was then measured against the base model and the difference compared to the original estimates. A percent difference was then calculated and tabulated in Table 8 (which was also reported as Table 1).

ECO Description

Figure 20 (a) is a bar graph of all the ECO comparisons with architectural savings estimates. Figure 20 (b) shows the electricity end use with and without ECOs, as simulated by DOE-2 (both graphs are reported from Figure 1).

The first energy-efficient feature is the installation of 34 W efficient fluorescent lighting instead of standard 40 W fluorescent lamps. The 34 W lamps are located in each zone for main lighting and used in the base model. The number of fixtures was based on the architectural plans and a total wattage was calculated per zone. For the comparison model, the equivalent electricity that would have been consumed by 40 W lamps using metal-core 40 W ballasts was substituted for the 34 W lamps and an annual simulation performed. According to DOE-2, the lights are actually saving 31.0% more than the GSA architect predicted.

The next conservation measure evaluated was the installation of a photovoltaic system to supplement whole-building electricity usage. This savings verification did not utilize DOE-2. In order to calculate the annual savings from the photovoltaic array, several processing steps were undertaken. First, hourly electricity produced by the photovoltaic array was recorded and compared to the measured global horizontal solar radiation data. Then, a quadratic curve-fit was calculated as shown in Figure 21. In a separate procedure, one year of hourly global horizontal radiation was extracted from the Washington, D.C. TMY weather tape. This radiation data, in turn, was used in conjunction with the curve-fit equation to calculate photovoltaic generation for

Table 7 Baseline and Standard ECO Features.

ENERGY CONSERVATION OPTION	BASELINE	STANDARD W/O ECO	COMMENTS
Energy efficient lighting	Energy efficient 34 W lamps (fluorescent) architect proposed value	Standard 40 W lamps (fluorescent) PEPCO recommended baseline	1 DOE-2 run with either option
Photovoltaic	Use measured data, curve-fit to TMY weather	No photovoltaic	Verification independent of DOE-2
EMCS	Schedule heat pumps according to on/off period and temperature	Thermostat control only (fans on 24 hrs/day)	1 DOE-2 run with either option
Lighting controls	Dimmers (not installed according to DOE personnel)	No dimmers	No DOE-2 simulation performed
Insulation, airlocks, South window shading	Roof - R-30 Walls - R-13 Tight building - 0.6 ach Shading over south windows	Roof - R-18 Walls - R-11 Loose building - 1.0 ach No shading over south windows	1 DOE-2 run with options combined
Clerestory windows	Add to BDL	Replace with equivalent walls	1 DOE-2 run with either option
Heat pumps	3 @ 10.6 EER summer 1 @ 8.9 EER summer 3 @ 10.2 EER winter 1 @ 10.0 EER winter	3 @ 8.3 EER summer 1 @ 8.3 EER summer 3 @ 8.3 EER winter 1 @ 8.3 EER winter	Baseline values based on manuf. data/Stndrd values from PEPCO rebate form
Solar DHW system	Solar prediction with F-CHART	No solar; 80 gal/day	F-CHART prediction
All ECOs combined	All above features installed	No ECOs installed	1 DOE-2 run with either option

Table 8 Comparison of Energy Conservation Options to Savings Predictions.

	Energy Conservation Option	DOE-2 Basemodel "as-built" (kWh)	DOE-2 Predicted w/o ECO (kWh)	DOE-2 Predicted Savings (kWh)	Architect's Proposal (kWh)	Percent Difference (7)	Difference
1.	Energy Efficient Lights	157,116	161,477	4,361	3,328	31.0%	1,033
2.	Photovoltaic Generation (1)	-7,880	0	7,880	7,530	4.6%	350
3.	Energy Management and Control System (2)	157,116	160,695	3,579	1,000 (est)	257.9%	2,579
4.	Lighting Controls & Dimmers (3)	-	-	-	-	-	-
5.	Insulation, Airlock, South Shading	157,116	158,795	1,679	6,000	-72.0%	-4,321
6.	Clerestory Windows	157,116	157,075	-41	6,000	-100.7%	-6,041
7.	Improved Heat Pumps	157,116	158,590	1,474	3,300	-55.3%	-1,826
8.	Solar Hot Water (4)	2,345	6,565	4,220	4,407 (6,033 is incorrect)	-4.2%	-187
	All ECOs Combined (5)	151,581	168,042	16,461	-	-	-
	Total (6)			23,152	31,565	-26.7%	-8,413

(1) The calibrated difference was determined using a curve fit which compared photovoltaic generation as a function of global horizontal radiation. Global horizontal radiation was then extracted from a Washington, D.C. TMY weather tape. DOE-2 was not used for this verification.

(2) According to U.S.D.O.E. personnel, the HVAC system is manually operated each day. The 1,000 kWh savings by the GSA architect were based on engineering judgement.

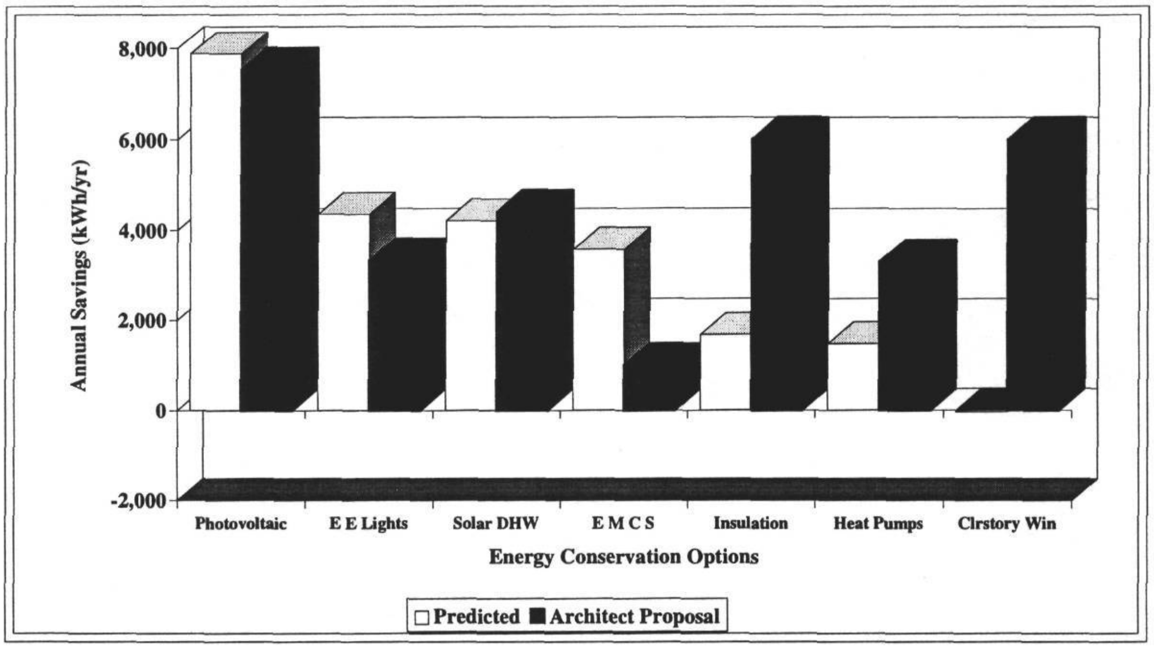
(3) According to U.S.D.O.E. personnel, the dimmers were not installed.

(4) Savings were determined by F-CHART. The value of 6,033 as specified in the original estimate is incorrect because the value used by GSA eroneously cited the total DHW requirements and not the solar DHW contribution.

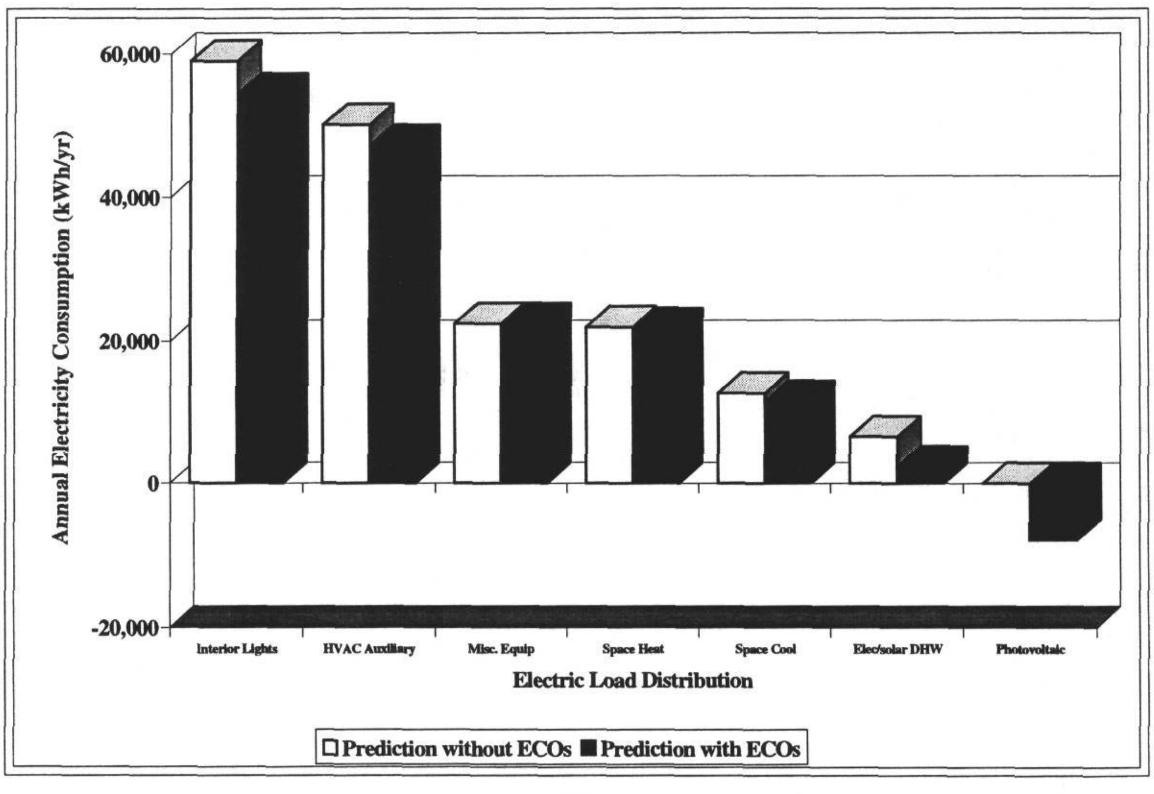
(5) Not part of original ECO list. Calculated by: (Basemodel + photovoltaic + dhw).

(6) Savings total does not include "All ECOs Combined."

(7) The percent difference was calculated as follows: [(DOE-2 savings - architect proposal) / architect proposal] x 100.



(a)



(b)

Figure 20 ECO Savings Comparisons. (a) Annual ECO Savings. (b) Annual Electric Load Distribution.

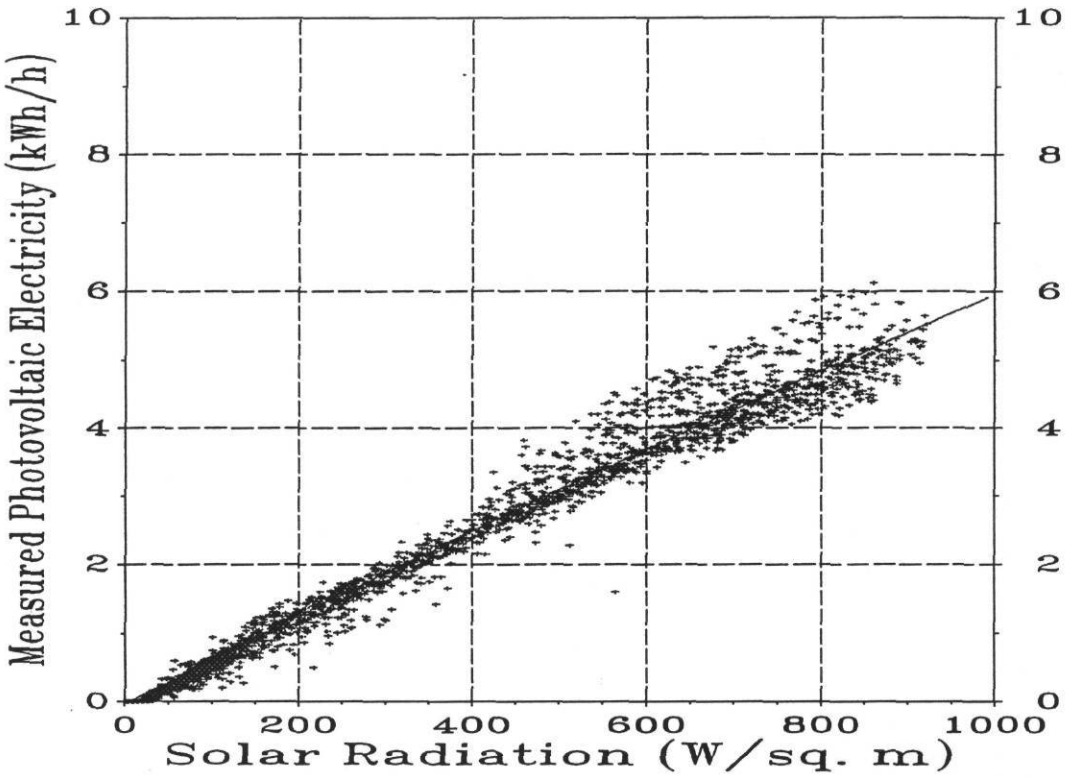


Figure 21 Photovoltaic Generation as a Function of Solar Radiation.

one year which was then compared to the proposed photovoltaic savings estimates. The installed photovoltaic system, according to this procedure, produces 4.6% more electricity than the Sandia estimates. Two interesting features were noted about the photovoltaic system. First, prior to March 1993, half of the photovoltaic system electricity production was not occurring because one of the electrical breakers had tripped on the inverters. Second, shading by nearby trees seems to decrease the output during the afternoons. This effect diminishes in the fall when the leaves drop off the trees. Hence, the bimodal pattern in Figure 21.

A computerized Energy Management System was put in place to optimize heat pump operation and air handlers. The base model was run with the parameters such as set-point temperatures, and operations schedules made available from a computer print-out from the EMS system. The DOE-2 standard verification run assumed that the HVAC system is allowed to operate under thermostat control at any time of the year (i.e., 24-hour-per-day operation). DOE-2 predicts that the Energy Management System actually saves 257.9% more that originally stated (only an annual savings estimate was available from the GSA architect; no indication was given as to what conditions the architect assumed).

The original savings calculations for the lighting controls and dimmers were based on the dimmers theoretically reducing light levels by 30-40%. This ECO could not be verified since DOE personnel confirmed that dimmers had not been installed. The occupancy sensors, on the other hand, have been installed, but could not realistically be simulated due to unpredictable utilization.

The fifth energy conservation option is the installation of additional insulation in the roof and wall, an air-lock at the main entrance, and shading devices at the south-side windows to improve the building envelope. Roof insulation, as installed, is R-30 batt insulation. This was compared to standard R-18 batt insulation. Wall insulation was improved from R-11 batt insulation to R-13 batt insulation. The effect of the main entrance airlock was estimated by simulating for infiltration by setting the base model to 0.6 air changes per hour per zone representing a "tight" building. The non-ECO savings were simulated by assuming a "loose" building and setting the air leakage to 1.0 air change per hour per zone. The south-side windows are shaded by overhangs which are accounted for in the base model with shading planes. To simulate the savings, the overhangs were omitted from the input file for the non-ECO option. The savings comparison shows that these combined features save 72.0% less than originally predicted.

Clerestory windows were added to the north-side raised ceiling walls above the classroom areas to provide daylighting. The base model included them as per architectural and manufacturer specifications. They were removed from the model and replaced with equivalent walls to simulate savings. The results revealed that the building actually looses energy as a result of the windows being there to the tune of 100.7% less than the GSA architectural calculations. One of the reasons that this varied so much is that the daylight sensors were never installed; therefore, no lighting reduction took place.

The seventh feature is the installation of high efficiency air-cooled heat pumps with a higher EER than standard heat pumps. Manufacturer catalogs were obtained and EER values were detailed in the input file for the base model. For the standard comparison model, the standard EER reference values provided by PEPCO were used. The difference shows that the installed higher efficiency heat pumps saved 55.3% less than originally calculated. This may be due in part to the large amount of electric baseboard heaters.

The solar DHW system savings was verified using the F-CHART program (F-CHART 1989) instead of DOE-2. By applying the solar DHW system manufacturer specifications, the program estimated annual DHW energy consumption as well as annual solar system contribution. This was then compared to estimated savings calculated by the National Renewable Energy Laboratory (NREL) using F-CHART. The initial GSA savings estimate was inaccurate since an incorrect value was extracted from the NREL F-CHART analysis and published as potential savings (i.e., the original estimate incorrectly used the total DHW requirements in place of the solar system contribution). A verification F-CHART run was compared to the original F-CHART run, however the corrected value was used for comparison and tabulated. The results (when compared to the corrected F-CHART run) were quite good with the solar system providing only 4.2% less than originally predicted by NREL. The operation of the solar DHW was confirmed by the DOE personnel.

Finally, the base model was compared to a run made with all ECOs removed simultaneously. The total energy consumption revealed that the existing building saves 73.3% of what was originally anticipated. This is somewhat skewed, however, by the large under-estimations originally made for ECOs number 5 and 6. With these ECOs removed the calculated savings are 90.0% of the GSA architect's estimates.

Improvements to the Input File

Since the 12/93 draft report was written, a few modifications were made to the DOE-2 input file. In order to improve the simulation, two additional months of data were added to the measured dataset extending well into the cold weather period. This addition represents a more accurate simulation since data are now available for cold weather, intermediate weather, and hot weather as opposed to having only intermediate and hot weather data from the draft report. As a result, it became necessary to recalibrate the model to account for the winter weather. Unfortunately, this had a significant change in the savings calculations. Table 9 compares the ECO savings results for the current model along with savings results reported in the draft report. The current model is believed to be close to the truth.

Table 9 Comparison of Current Savings Predictions to Draft Savings Predictions.

	Energy Conservation Option	Current Percent Difference	12/93 Draft Percent Difference
1.	Energy Efficient Lights	31.0%	40.8%
2.	Photovoltaic Generation	4.6%	4.6%
3.	Energy Management and Control System	257.9%	460.1%
4.	Lighting Controls & Dimmers	-	-
5.	Insulation, Airlock, South Shading	-72.0%	-41.9%
6.	Clerestory Windows	-100.7%	-120.6%
7.	Improved Heat Pumps	-55.3%	-42.4%
8.	Solar Hot Water	-4.2%	-4.2%
	All ECOs Combined	-	-
	Total	-26.7%	-15.9%

CONCLUSION

The CDC building was simulated and calibrated to a nine month period which included measured whole-building electricity consumption, ambient dry bulb temperature, dew point temperature, wind speed, and global horizontal solar radiation. After data processing which included merging data from two loggers and the NWS into a single file and converting global solar radiation measured at an 18° south facing tilt into global horizontal, diffuse, and direct radiation, a TRY weather tape was packed with on-site measured data and fed to DOE-2. Multiple annual DOE-2 models were run, one for a calibrated base model and one for each ECO. The differences were calculated and compared to the architect's original energy savings estimates. Several statistical viewing aides were developed to show the calibration's robustness including time-series plots, box-whisker-mean plots, three-dimensional plots, and scatter plots as a function of both temperature bins and weekly bins. The photovoltaic system and the solar hot water system showed the best results comparing closely with original architect's estimates. The building envelope improvements and clerestory windows were found to have the least accurate design predictions.

RECOMMENDATIONS

1. Maintenance of the ECOs appears to be a major consideration. It is recommended that routine inspections be implemented to confirm the operation of the photovoltaic, solar DHW, and other energy consuming systems.

2. Due to budget constraints, the current effort did not measure infiltration or solar DHW performance. Additional measurements would provide more insight into these measures.

3. Side-by-side comparisons are recommended between the DOE Child Development Center in Germantown and the CDC at the Forrestal building.

4. A detailed analysis of the thermal energy savings from the Forrestal lighting retrofit is recommended. As shown in this report total lighting savings (lighting plus thermal savings) can be 20-40% more than lighting savings. This 20-40% additional savings has been confirmed by simulations reported in Rundquist et al. (1993).

ACKNOWLEDGMENTS

This work was supported the U.S.D.O.E. under Sandia contract number AK-8010. We would like acknowledge significant contributions by Mr. E. James Vajda, Mr. Louis D'Angelo, Mr. Mark Ginsberg, Mr. Richard King, Mr. Roger Hill, Mr. Mike Shincovich, Mr. Norm Branca, Ms. Ona Whitfield, and Mr. Paul Moyer. Their help with questions regarding the calibration process and information gathering was invaluable. Also, we wish to thank Mr. John Keczmerski, Mr. Shailesh Desai, Mr. Harish Kapur, and Mr. Godfrey Smith of the General Services Administration, Project Execution Branch for their aid in acquiring building architectural and systems information. Technical assistance from Mr. John McBride and Mr. Roger Lippman at the National Center for Appropriate Technology (NCAT) in Seattle, WA, and Mr. Andrew Rosenthal of the Southwest Technical Development Institute (SWTDI) in Las Cruces, NM are also gratefully acknowledged.

REFERENCES

Abbas, M. 1993. Development of graphical indices for building energy data, *M.S. Thesis*, Texas A&M University, College Station, TX, Energy Systems Report No. ESL-TH-93/12-02.

Bou-Saada, T.E. 1994a. An improved procedure for developing a calibrated hourly simulation model of an electrically heated and cooled commercial building, *M.S. Thesis*, Texas A&M University, College Station, TX, Energy Systems Report No. ESL-TH-94/12-01.

Bou-Saada, T.E. 1994b. Advanced DOE-2 calibration procedures: A technical reference manual. Energy Systems Report No. ESL-TR-94/12-01, Texas A&M University, College Station, TX,.

Bronson, J.D. 1992. Calibrating DOE-2 to weather and non-weather dependent loads for a commercial building. *M.S. Thesis*, Texas A&M University, College Station, TX, Energy Systems Report No. ESL-TH-92/04-01.

Erbs, D.G., S.A. Klein and J.A. Duffie. 1982. Estimation of diffuse radiation fraction for hourly, daily, and monthly-average global radiation. *Solar Energy*, Vol. 28, No. 4, pp. 293-302.

F-CHART. 1989. F-CHART Solar System Analysis Software. IBM PC Version 5.6. 4406 Fox Bluff Rd. Middleton, WI 53562

Fels, M. 1986. Special issue devoted to measuring energy savings: The scorekeeping approach. *Energy and Buildings*, Vol.9, Nos.1 and 2.

Huang & Associates. 1993. DrawBDL user's guide. 6720 Potrero Ave., El Cerrito, CA, 94530.

Kissock, J.K., T.A. Reddy, D. Fletcher, and D.E. Claridge. 1993. The effect of short data periods on the annual prediction accuracy of temperature-dependent regression models of commercial building energy use. *Energy Systems Report No. ESL-PA-93/04-01*, Texas

A&M University, College Station, TX., Proceedings of the ASME-ASES-SED International Solar Energy Conference, Washington, DC.

LBL. 1989. DOE-2 Supplement, Ver 2.1D. Lawrence Berkeley Laboratory, LBL Report No. LBL-8706 Rev. 5 Supplement. DOE-2 User Coordination Office, LBL, Berkeley, CA.

Rundquist, R.A., K.F. Johnson, and D.J. Aumann. 1993. Calculating lighting and HVAC interactions. *ASHRAE Journal,* Vol.35, No.11, pp. 28-37.

SAS Institute, Inc. 1989. SAS reference manual. SAS Institute, Inc., SAS Circle, P.O. Box 8000, Cary, NC 27512-8000.

Sparks, R., S. Katipamula, J. Spadaro, J. Mahoney and J. Haberl. 1993. Documentation manual for Air, version 1.5β, *Energy Systems Laboratory,* Texas A&M University, College Station, TX, Aug.

TMY. 1988. Typical meteorological year (TMY) user's manual - TD-9734. National Climatic Data Center, Asheville, NC 28801-2696.

TRY. 1983. Test reference year (TRY) tape reference manual - TD-9706. National Climatic Data Center, Asheville, NC 28801-2696.