ENERGY ANALYSIS OF THE TEXAS CAPITOL RESTORATION

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ABSTRACT

This paper presents the methodology and results of a detailed energy analysis of the Texas Capitol Restoration. The purpose of this analysis was two-fold: 1) to determine the projected energy cost savings of a series of design alternatives for the Capitol Restoration, and 2) to calibrate the simulation model of the Capitol in its prerestored condition (in September 1991) using monitored energy use data from the Texas LoanSTAR program.

The Capitol in its proposed restored condition was simulated using the DOE-2 building energy analysis computer program with long-term Austin weather data to project the annual energy use, peak electric demand, and annual energy cost. Then a series of 13 energy efficient design alternatives was simulated. The results were compared to those of the base case to determine the projected annual energy and energy cost savings for each measure, and for combinations of several of the measures.

Finally, the paper documents the calibration of the DOE-2 model for the Capitol in its prerestored condition, using monitored hourly whole-building electric data (excluding heating and cooling energy).

INTRODUCTION

In October 1991 construction began on the restoration of the Texas State Capitol to its original 1880s condition. The restoration is being coordinated with the construction of the underground Capitol Extension building that is being built adjacent to the Capitol to its north. Because of its historic nature the Capitol is exempt from the *Texas Energy Conservation Design Standard for New State Buildings* (4). However, it was the desire of the State Preservation Board and the Governor's Energy Office to incorporate as many energy efficient features as were feasible.

Thus, the Center for Energy Studies at The University of Texas at Austin was contracted to conduct a detailed energy analysis of the Capitol Restoration design so as to determine the projected energy cost savings and payback periods of a proposed series of 13 design alternatives and several combinations of these alternatives. The payback periods were then used in retrofit funding decisions for the LoanSTAR program. We used the DOE-2.1D building energy analysis computer program (IBM PC version) to simulate the building (5). Because of the complex building configuration and its diverse functional use pattern, the energy analysis challenged the limits of the building energy simulation program.

A secondary objective of the study was to calibrate the simulation model of the Capitol in its prerestored condition using monitored energy use data from the Texas LoanSTAR program (8). A lack of reliable measured heating and cooling data limited the calibration to non-plant electric energy. The results of the calibration were not used in the restored Capitol analysis.

This paper describes the DOE-2 input data gathering process for the Capitol and the assumptions made in the model. Simulation results, using long-term average Test Meteorological Year (TMY) weather data, are presented for the Capitol Restoration design originally proposed by the contract architects and engineers. These results are presented in terms of annual energy use (gas and electricity), peak electric demand, and estimated annual energy cost. Then energy cost savings results are presented for a series of energy efficient design alternatives, including envelope, lighting, and HVAC system measures, as compared to the original design base case. Finally, we document the calibration of the DOE-2 model using monitored hourly whole-building electric data for the Capitol in its prerestored condition. A detailed discussion of the analysis and results is presented in Reference 3.

BASE CASE DESIGN MODEL FOR THE RESTORED CAPITOL

Occupancy Assumptions and Zoning Configuration

The Legislature was assumed to be in session for the full year, with no recesses. The building is accessible 24 hours a day with public spaces fully lighted and open at all times, but with offices closed, except for cleaning staff, from 10 PM to 8 AM. Occupancy of the Senate and House chambers and hearing rooms follows typical in-session patterns for sessions, hearings, and tours.

The restored Capitol, which consists of 318,095 gross useable square feet of floor area (all of which are conditioned), was divided into 28 thermal zones for the DOE-2 analysis. The approach adopted was to aggregate similar areas vertically so as to minimize the number of zones to be considered. This aggregation took into consideration orientation (solar differentiation), occupancy and use patterns, and exterior wall geometry. Figure 1 shows the zoning adopted; see Reference 3 for a detailed description.

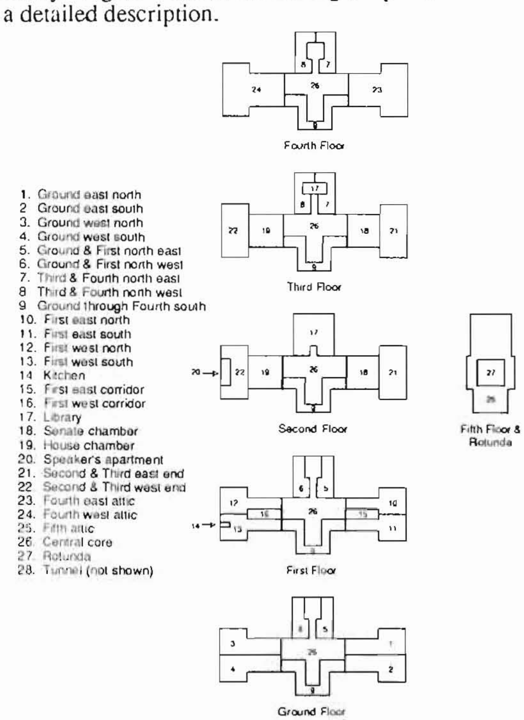

Figure 1. Zoning Configuration for Capitol Restoration Model

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Walls and Roof

Although the Capitol involves an elaborate exterior, simplifications were required for a workable computer model. In several places walls were moved outward to be flush with the entrances, giving a simpler rectangular form, and porticos and entrance setbacks were eliminated. Care was taken to keep the exterior wall area and enclosed floor area constant. Although self-shading of the building in the setbacks and notches was lost in the simplified outline, self-shading of exterior walls was maintained. A comparison of the simplified outline with a more detailed model showed a difference of only 1% in overall heating and cooling loads. Shading from exterior pilasters, columns, wall offsets, and cornices is also neglected, but shading from large nearby trees is not. The curved upper rotunda and dome were represented by a rectangular solid with equal surface area. The attic spaces were simplified into rectangular shapes with flat roofs, with the height of the side walls set to give equivalent volume.

Wall construction is of uninsulated limestone, with thickness varying from 2 ft at the top to 5-6 ft at the bottom; a granite facade covers most of the exterior area. The composite wall is modeled as a 4-ft thick masonry wall, the maximum thickness allowed for the DOE-2 weighting factors. Roof construction is uninsulated wood, with built-up roofing; the attic skylights are 3/8-in. textured glass in metal frames.

Windows

All windows are single-glazed with wood frames, modeled with a U-value of 0.98 Btu/h-ft^2-°F and a shading coefficient of 0.82 for 1/4-inch glass. The number of windows in the model is reduced by representing groups of similar windows by a single window located at the center of the group; a multiplier command increases the effective window area to equal that of the group, while maintaining essentially equivalent shading effects. Ground floor windows, which are partly below grade, have the top one-third of their area exposed to solar irradiation, with the remainder within light wells shaded by a metal grating covered by screen. This lower window section is assumed to receive no solar irradiation, but is exposed to outside temperatures.

Schedules

Schedules for occupancy, lighting, and equipment use, and for HVAC system operation, are assumed to follow daily, in-session patterns in the prerestored Capitol. For most schedules, the day is divided into the regular workday from 8 AM to 6 PM, an extended workday from 6 PM to 10 PM, and night from 10 PM to 8 AM. Typical occupancy and equipment schedules for offices (the majority of the floor space) are 100% of design values during peak occupied hours, and 2% during unoccupied hours. Similarly, the office lighting schedule is essentially 100% during peak occupied hours and 20-35% during unoccupied hours. Six basic schedules are used: public, night/emergency, office, Senate chamber, House chamber, and conference or hearing rooms. Other schedules apply to the library, the Speaker's apartment, the kitchen, storage areas, and attics. The night/emergency access areas are lighted at all times, as are the public areas.

Electrical Loads

Lighting: Lighting loads are calculated from a count of installed fixtures and their wattages as shown in the electrical drawings and specifications. Installed wattages in office and conference/hearing areas are reduced by 10% to account for rooms with the lights turned off; the lighting schedule is applied to this value. The overall lighting schedule for a zone is a weighted composite calculated by multiplying the hourly schedule factor for each use type by the proportion of wattage associated with that use, and summing over all use types.

On the basis of these calculations, the average diversified lighting load in the office spaces and adjacent corridors is about 2.0 W/ft^2, and in the library about 2.9 W/ft^2. Diversified lighting is higher in the Senate and House Chambers: 3.0 and 3.5 W/ft^2, respectively.

Equipment: The equipment electrical load in offices and hearing and conference rooms assumes a base plug load of 0.5 W/ft^2, which includes coffee makers, task lighting, answering machines, and other general office equipment. In addition, a computer is assumed to be on every desk, with one desk per 100 ft^2 in staff offices and one desk per office for legislators and aides. A power of 150 W is used as a typical computer electrical load, averaged over its operating cycle, which is roughly equivalent to an IBM XT or AT (6, 9). This amount is reduced by 10%, to account for diversity. Copy center equipment is an additional electrical load on the ground floor. When these loads are aggregated, the typical installed (diversified) load for the offices and adjacent circulation space is 0.8 to 1.0 W/ft^2.

In the library the diversified equipment load is 0.7 W/ft^2, which includes computers, copiers, microform readers, and other equipment. The Senate chamber equipment load is 0.1 W/ft^2, whereas the House chamber load is set at 0.2 W/ft^2 to account for the additional power used by the TV monitors at each desk and the electronic voting system.

Heat Gain from Occupants and Hot Water Use

The cooling loads generated by the building occupants are based on information in the ASHRAE *Handbook of Fundamentals* (1). In addition, the Texas Building Energy Conservation Design Standard (4) provides guidelines for hot water use. The number of people used for these calculations is based on a seat count in the Senate and House chambers and their galleries, and on an allowance of 15 ft^2/person in hearing and conference rooms, 100 ft^2/person in office areas, and 200 ft^2/person in circulation areas.

Infiltration

A major source of infiltration is the four sets of entrance doors on the first floor, which are large, tend to open and close slowly, and have no inner vestibule doors to reduce airflow. Based on discussions with operating personnel, the infiltration rate for each set of doors is estimated at 2,000 CFM in winter and 1,000 CFM in summer. Infiltration is estimated at 0.1 air change per hour (ACH) in the exterior zones, even with the building pressurized.

Special Areas

The model for the first-floor kitchen assumes high use for lunch and dinner every weekday; equipment is commercial grade with relatively high power demands and modest latent loads. Included are appliances such as refrigerators, freezers, ranges, and dishwashers. Diversity factors, schedule, and base equipment load for the Speaker's apartment were chosen to reflect residential patterns.

HVAC Systems

Although many zones have a mix of HVAC equipment types, this cannot be modeled with DOE-2. Therefore, each zone is treated as having one system type, with either fan-coil, single-zone, or multizone units according to the predominant type of equipment used in the zone. The ground and first floor offices and the library are modeled as fan-coil systems, with outside air supplied by single-zone air-handling units (AHUs) through ductwork and ceiling diffusers; the first-floor corridors, the kitchen, and the tunnel to the Capitol Extension use single-zone systems; and the second through fourth floors, the central core, and the south wing use multizone systems. The fourth- and fifth-floor attics have unit heaters to prevent freezing temperatures, while the upper part of the rotunda is treated as an unconditioned zone.

To control humidity, the fan-coil and multizone areas have associated systems that precondition outside air and deliver it to the occupied spaces at neutral conditions of temperature and humidity. Because DOE-2 does not allow more than one system to serve a zone, the preconditioning systems are modeled separately, and connected to dummy zones, one set for all fan-coil systems and one set for all multizone systems. Thus, the preconditioning systems meet the outside air loads, while the main systems meet only internal and infiltration loads. As designed, the preconditioning systems use mixing of conditioned outside air with return air to achieve effective reheat, with a coil bypass and damper system controlling the temperature of the outside air. These systems are modeled as reheat fan systems, which is the only DOE-2 system type that can deliver air at the desired conditions. The reheat system uses a variable-temperature (55°F to 75°F) cooling coil, which is disabled at outdoor temperatures below 60°F, when dehumidification is not needed.

Total supply, outside air, and exhaust airflows for each zone are taken from the diffuser specifications shown on the mechanical floor plans; outside airflows range from 13% to 20% of supply airflows. The fan power and airflow rates for the air handlers are taken from the mechanical equipment schedules, with the values for the multizone AHUs divided proportionally among the zones served. The electrical power used by the fans for each zone is specified on a kW/CFM basis, averaged over all units serving the zone.

Plant Specifications

Based on discussions with the State Purchasing and General Services Commission (SPGSC), a chiller efficiency of 0.65 kW/ton and a steam boiler efficiency of 75% were assumed for the central plant.

CAPITOL RESTORATION ENERGY EFFICIENCY DESIGN ALTERNATIVES

The set of design alternatives that was analyzed is described below.

1. Additional Window Shutters. Add interior wood shutters to 21,245 ft^2 of window that are not included in the prerestored condition. These are modeled by changing the shading coefficient from 0.82 to 0.65 and the U-value from 0.98 to 0.59 Btu/h-ft^2-°F. These values assume that 75% of these shutters are closed at any given time. U-values and shading coefficients are obtained from ASHRAE (1) and Pletzer et al. (7) for louvered wood shutters behind 1/4-in. glass in wood frames.

2. Cupola Ventilation Fans. Four 2,800 CFM exhaust fans are placed in each of the fourth floor attics. These fans operate to cool the attics by drawing in outside air when the temperature in the attic rises above 80°F and the ambient temperature is at least 4°F cooler.

3. Diaphragm at Oculus. Add a circular glass diaphragm at the oculus at the top of the interior dome to control venting through the dome. This is modeled by eliminating general infiltration in the perimeter zones on all floors; local infiltration at the four exterior doors on the first floor is maintained.

4. Skylight Interior Shade. Add a reflective-coated fabric shade beneath the skylights in the fourth and fifth floor attics to inhibit summer solar heat gain. The shading coefficient of the skylights is reduced from 0.86 to 0.30, and the U-value is reduced from 1.23 to 1.00 Btu/h-ft^2-°F. These values were taken from ASHRAE (1) for a high-reflectance, medium weave fabric behind 1/4-in. clear glass in a metal frame with no thermal break. This alternative was run with the shade in place all year, and with the shade used only during the summer months.

5. High-Efficiency Lamps and Ballasts. Substitute high-efficiency lamps and electronic ballasts in all fluorescent and metal halide fixtures. This change is modeled by a reduction in lighting wattage for five fixture types: 2.5% in the metal halide fixtures, 22% in the 1- and 2-tube fluorescent fixtures, 20% in the 3-tube/ 2-ft fluorescents, and 16% in the 3-tube/8-ft fluorescents (luminous ceiling). This results in a reduction in installed lighting wattage of approximately 15% in ground floor and attic zones and 2% elsewhere (See Reference 3 for more detail).

6. Lighting Control Package. This includes the addition of 4-step dimmers on the lights above the luminous ceiling in the House chamber, and the installation of occupancy sensors in the ground floor offices, and all hearing, conference, and restrooms. The occupancy sensors are assumed to save 25% of the occupied period lighting energy use in the offices, and 40% of the occupied period lighting energy use in the hearing and conference rooms and in the restrooms (2).

7. Unconditioned Corridors. Delete the systems supplying air to the east- and west-wing corridors on the first floor, excluding areas adjacent to the exterior doors. This approach will rely on infiltration and return leakage from adjacent zones, as well as conduction through the walls of adjacent offices, for ventilation and temperature control.

8. Direct Digital Controls. These permit reset of the hot and cold deck temperatures in the multizone systems to accommodate the zones with the greatest heating and cooling loads at a given hour. The base case reset from 105°F to 85°F is deleted, but the summer shutdown of the heating coils is retained; the fixed cold deck temperature of 55°F used in the base case is deleted.

9. Thermostat Offsets. In this strategy the heating thermostat is set back from 72°F to 67°F and the cooling thermostat is set up from 75°F to 85°F during unoccupied hours for all conditioned zones. The multizone system heating/cooling coils are disabled, as necessary, to prevent forced temperature offsets.

10. Two-Speed Fan Operation with Outside Air Shutdown. Speed controls are added to the fan motors of the single- and multizone AHUs to reduce airflow during unoccupied hours (10 PM to 7 AM). During this time the fan-coil units are on night-cycle controls and the outside-air dampers are closed, except as necessary to balance exhaust airflows. During the day, the fans supply full design airflow, while at night they operate at either 50% or 75% of design flow. This control scheme is also used for the outside-air preconditioning systems, as is detailed in Reference 3.

11. Variable Air Volume Fans. Speed controls on the fan motors of the single- and multizone AHUs are set to provide continuously variable supply airflow, at an average energy use of approximately 0.6 W/CFM. The thermostats set the volume to match the heating or cooling demand in the zones. As with two-speed operation, this alternative was run with both 50% and 75% minimum airflows, with the ratio of outside air to supply air maintained constant.

Variable-volume operation is also applied to the outside-air preconditioning system for the multizone systems.

12. High-Efficiency Motors. High-efficiency motors are substituted for all supply and exhaust fans and for the elevator drives. The standard motors are assumed to meet minimally the Texas Energy Conservation Design Standard (Table 5-1 in Reference 4); the high-efficiency motors are as detailed in the specifications for the Capitol Extension (2), differentiated by motor size.

13. Increased ΔT Cooling Coil Design. In all HVAC systems substitute cooling coils designed for 16°F rather than the normal 10°F chilled water temperature difference in the AHUs, and 12°F rather than 10°F in the fan-coil units. This permits reduced chilled-water flow rates through the coils and results in lower pumping power. In addition, chilled water is supplied to

the cooling coils at 44°F, but returns at 58°F rather than 54°F, improving the central chiller efficiency from 0.65 to 0.61 kW/ton.

Combination Alternatives

Alternatives 14-17 represent various combinations of HVAC system control options, as identified in Table 1. The final composite of all alternatives selected for implementation includes the following:

- Additional window shutters (Alternative 1)
- High-efficiency lamps and ballasts (Alternative 5)
- Lighting control package (Alternative 6)
- Direct digital controls (Alternative 8)
- Thermostat offsets (Alternative 9)
- Night-cycle operation with outside air shutdown (part of Alternative 10)
- Variable-volume fans (Alternative 11)
- High-efficiency motors (Alternative 12)
- Increased ΔT cooling coil design (Alternative 13)

TABLE 1
Energy Use and Cost Summary

Texas Capitol Restoration Design Alternatives

	MBTU ELECTRIC	PEAK KW	MBTU GAS	YEARLY EXPENSE [$] ELECTRIC	GAS	TOTAL	YEARLY SAVINGS (COST) [$] ELECTRIC	GAS	TOTAL
BASE CASE	38,852	2,182	44,168	512,300	157,200	669,500	---	---	---
ALTERNATIVE 1 SHUTTERS	38,840	2,175	43,920	512,200	156,400	668,500	200	800	1,000
ALTERNATIVE 3 OCULUS DIAPHRAGM	38,742	2,173	43,873	510,800	156,200	667,000	1500	1,000	2,500
ALTERNATIVE 4 SKYLIGHT SHADE	38,715	2,161	44,416	510,500	158,100	668,600	1,800	(900)	900
ALTERNATIVE 4A SKYLIGHT SHADE, SUMMER ONLY	38,746	2,172	44,189	510,900	157,300	668,200	1,400	(100)	1,300
ALTERNATIVE 5 HI-EFF LAMPS & BALLASTS	38,289	2,141	44,241	504,800	157,500	662,300	7,500	(300)	7,200
ALTERNATIVE 6 LIGHTING CONTROLS	38,323	2,127	44,258	505,300	157,600	662,900	7,000	(400)	6,600
ALTERNATIVE 7 CORRIDORS UNCONDITIONED	38,757	2,178	44,140	511,000	157,100	668,100	1,300	100	1,400
ALTERNATIVE 8 DDC HOT/COLD DECKS	35,442	2,170	20,382	467,300	72,600	539,900	45,000	84,600	129,600
ALTERNATIVE 9 THERMOSTAT OFFSET	38,025	2,224	31,921	501,400	113,400	614,800	10,900	43,800	54,700
ALTERNATIVE 10 2-SPEED OPERATION									
50% MINIMUM AIRFLOW	35,695	2,185	35,433	470,600	126,100	596,700	41,700	31,100	72,800
75% MINIMUM AIRFLOW	36,438	2,185	37,413	480,400	133,200	613,600	31,900	24,000	55,900
ALTERNATIVE 11 VARIABLE VOLUME									
50% MINIMUM AIRFLOW	30,302	1,881	28,830	399,500	102,600	502,100	112,800	54,600	167,400
75% MINIMUM AIRFLOW	34,051	1,995	37,090	449,000	132,000	581,000	66,300	25,200	88,500
ALTERNATIVE 12 HIGH-EFF MOTORS	37,960	2,146	44,168	500,500	157,200	657,700	11,800	-----	11,800
ALTERNATIVE 13 HIGH ΔT COILS	37,853	2,123	44,168	499,100	157,200	656,300	13,200	-----	13,200

Texas Capitol Restoration Design Alternative Combinations

	MBTU ELECTRIC	PEAK KW	MBTU GAS	YEARLY EXPENSE [$] ELECTRIC	GAS	TOTAL	YEARLY SAVINGS (COST) [$] ELECTRIC	GAS	TOTAL	PERCENT SAVINGS
ALTERNATIVE 14 DDC, THERMOSTAT OFFSET, 2-SPEED OPERATION, NIGHT-CYCLE CONTROL										
50% MINIMUM AIRFLOW	31,466	2,205	13,310	414,900	47,400	462,300	97,400	109,800	207,200	30.9
75% MINIMUM AIRFLOW	32,306	2,205	13,056	426,000	46,500	472,500	86,300	110,700	197,000	29.4
ALTERNATIVE 15 DDC, THERMOSTAT OFFSET, VARIABLE VOLUME										
50% MINIMUM AIRFLOW	28,802	1,950	14,912	379,800	53,100	432,900	132,500	104,100	236,600	35.3
75% MINIMUM AIRFLOW	31,539	2,044	16,751	415,800	59,600	475,400	96,500	97,600	194,100	29.0
ALTERNATIVE 16 DDC, THERMOSTAT OFFSET, VARIABLE VOLUME, NIGHT-CYCLE CONTROL										
50% MINIMUM AIRFLOW	27,377	1,962	11,655	361,000	41,500	402,500	151,300	115,700	267,000	39.9
75% MINIMUM AIRFLOW	29,854	2,054	12,308	393,600	43,800	437,400	118,700	113,400	232,100	34.7
ALTERNATIVE 17 DDC, THERMOSTAT OFFSET	35,383	2,199	18,315	466,500	65,200	531,700	45,800	92,000	137,800	20.6
FINAL COMPOSITE NEW SHUTTERS, HIGH-EFFICIENCY LAMPS & BALLASTS, LIGHTING CONTROLS, DDC, THERMOSTAT OFFSET/ SETUP, VARIABLE VOLUME, NIGHT CYCLE WITH OA SHUTDOWN, HIGH-EFFICIENCY MOTORS, HIGH ΔT COILS										
75% MINIMUM AIRFLOW	27,529	1,881	12,052	363,000	42,900	405,900	149,300	114,300	263,600	39.3

ENERGY ANALYSIS OF BASE CASE AND ALTERNATIVES

A summary of annual energy use and projected energy cost savings for the DOE-2 simulations, using long-term (TMY) weather data for Austin, are presented in Table 1. Results for the base case and for each alternative and combination of alternatives are given. However, Alternative 2 (Attic Ventilation Fans) is omitted because, as is discussed below, it results in zero energy savings.

Summary statistics for the base case are given in Table 2. The peak electric demand is seen to be 2,182 kW (6.86 W/ft^2), and the annual energy intensity is 261 kBtu/ft^2-yr. Assuming utility rates of \$0.045/kWh and \$3.56/MBtu as applicable to the Capitol Complex for 1991, this gives an annual energy cost of \$669,500 or \$2.10/ft^2-yr. Because this electrical rate does not explicitly include demand charges, the reduction in peak load will give additional savings.

Evaluation of Design Alternatives

Building Envelope Alternatives

Additional Window Shutters. The overall effect of the additional window shutters is minimal, with savings of about 0.1% (\$1,000/yr) of base-case energy expenses. Because of the dark color of the shutters and placement inside the glass, there is little reduction in solar gain. Although the shutters provide additional insulation, this effect is minimal.

Attic Ventilation Fans. Because of the strong thermal coupling between the attics and the chambers below, the condition of attic temperatures above 80°F with the outdoor temperature at least 4°F lower never occurs, so energy savings are zero. When attic temperatures are high, the outside temperature is even higher.

Dome Oculus Diaphragm. The diaphragm at the dome oculus reduces infiltration, but shows minimal effect and cost savings. However, these simulation results are uncertain because information about infiltration in the building is at best an estimate.

Skylight Shades. The shades on the attic skylights also produce little savings (up to \$1,300/yr). With full-year deployment, almost half of the savings in summer cooling load are offset by the loss of beneficial passive solar heating of the attics in winter. Savings are greater with the shade deployed in the summer only, but this will be offset by the additional costs of seasonal deployment and removal.

Internal Loads Alternatives

High-Efficiency Lamps and Ballasts. This measure does not greatly reduce the overall energy use because only fluorescents, found in ground-floor offices, restrooms, mechanical rooms, and attic luminous ceiling backlights, are affected. However, there is a 40 kW reduction in peak electrical demand.

Lighting Control Package. The lighting control package similarly has a small effect overall because it is applied to only a small fraction of the lights, but has a significant effect in the zones where it affects a majority of the lighting. Again, the reduction in peak demand of approximately 55 kW is significant.

Systems Control Alternatives

Changes in the operation of the HVAC systems provide the greatest opportunity for energy efficiency and cost savings.

Unconditioned Corridors. Although this alternative provides little energy savings, the elimination of the corridor HVAC systems will save on construction costs. Because the corridors are buffered by surrounding zones, DOE-2 indicates that the temperature will be maintained in the 75-79°F range throughout the year. Actual temperatures will match the surrounding zones more closely because of conditioned return-air leakage from offices and infiltration from the entrance lobbies.

Direct Digital Controls. The use of DDC in the multizone systems is highly effective, indicating energy savings of nearly \$130,000/yr. Multizone systems with fixed deck temperatures are inherently inefficient, especially under low load conditions, because both the heating and cooling coils operate at all times. However, with DDC the cold deck temperature is set to meet the cooling needs of the warmest zone, and the hot deck is set to meet the heating needs of the coolest zone. This alternative results in a projected reduction of 9% in electrical energy and more than 50% in natural gas energy.

Thermostat Offsets. Thermostat offsets reduce energy use when the building is essentially unoccupied. The reduction is mostly in heating energy, with approximately 27% less gas used than in the base case. Electrical energy reduction is only 2%, with a 40 kW increase in peak electric demand; energy cost savings of nearly \$55,000/yr are about half of those obtained for the DDC option. The peak electric demand increase results from zone temperature pulldown requirements.

Two-Speed Fan Operation with Outside-Air Shutdown. This measure, which includes night-cycle operation of the fan-coil units, substantially reduces energy use during unoccupied hours through the reduction in supply and outside airflows. It

TABLE 2

Simulated Annual Energy Use and Energy Cost for Prerestored and Restored Capitol [c]

	Peak Electric Demand (kW)	Peak Demand Intensity (W/ft^2)	Electricity Use (kWh)	Gas Use (MBtu)	Energy Use (MBtu)	Energy Intensity (kBtu/ft^2-yr)	Electricity Cost[b] (\$)	Gas Cost (\$)	Total Energy Cost[b] (\$)	Energy Cost Intensity (\$/ft^2-yr)
Restoration Base Case	2182	6.86[a]	11,383,545	44,168	83,020	261[a]	512,300	157,200	669,500	2.10[a]
Restoration with composite of energy efficiency alternatives	1881	5.91[a]	8,065,924	12,052	39,581	124[a]	363,000	42,900	405,900	1.28[a]
Prerestored[c]	1652	5.26[d]	11,058,790	61,591	99,335	316[d]	497,600	219,200	716,800	2.28[d]

[a] Based on gross usable area of 318,095 ft^2 (tunnel to Capitol Extension included here but not in prerestored case)
[b] Utility costs: \$0.045/kWh, \$3.56/MBtu
[c] Based on calibrated model using long-term (TMY) weather data
[d] Based on gross usable area of 314,095 ft^2

gives up to an 8% reduction in electrical energy, up to a 20% reduction in gas use, and up to nearly $73,000/yr in energy cost savings.

Variable Air Volume AHUs. Using motor speed controls to provide continuously variable supply airflow gives the greatest projected energy savings of all the individual alternatives. The reduction is up to 20% in electrical use, up to 35% in gas use, and up to $167,000/yr in energy cost savings. In addition, there is up to a 100 kW reduction in peak electric demand. This control strategy allows the HVAC systems to respond to heating and cooling demands, rather than constantly operating to meet peak loads.

System Equipment Alternatives

The high-efficiency motors result in 10% less electricity used by the fans, and 7% less energy used for elevators. Overall, the motors provide a 2% reduction in electrical consumption, while the coils give 3% savings. There is also a 35 kW reduction in peak electric demand with high-efficiency motors, and a 60 kW reduction with high ΔT coils. Energy cost savings are in the $12,000-13,000/yr range.

Combination Alternatives

The combination alternatives show the coupled effects of combined measures. Savings are similar to the individual alternatives, although in most cases they are not directly additive. The final composite of all selected energy efficiency options gives reductions of 29% in electrical energy use, more than 70% in natural gas use, 100 kW lower peak demand, and an overall cost saving of more than $263,000, or 39%.

Comparison of Base Case and Final Composite

Figures 2a and 2b compare the annual whole-building energy use and cost for the base case and final composite, broken down by energy end use category. For the base case, annual average plant heating energy use is 15.8 Btu/h-ft^2 and cooling energy use is 4.3 Btu/h-ft^2. These graphs show that the combined design alternatives have a major effect on space heating, a significant effect on space cooling and HVAC auxiliaries, but only a minor effect on lighting and elevator energy use and cost. Monthly patterns of electricity and natural gas use (not presented here) show less seasonal variation in natural gas use in the final composite than in the base case (3). Comparative summary statistics are given in Table 2; note that the final composite reduces peak demand to 1,881 kW (5.91 W/ft^2), energy intensity to 124 kBtu/ft^2-yr, and energy cost to $405,900 or $1.28/ft^2-yr.

MODELING OF THE CAPITOL IN ITS PRERESTORED CONDITION

To calibrate our DOE-2 model of the Capitol, we modeled it in its prerestored condition, as it was operated during the January-September 1991 period, before the beginning of restoration construction. We modeled the building using the best available input data for the DOE-2 simulation. These data were taken from drawings and specifications, supplemented by extensive surveys of the building, coupled with maintenance personnel interviews. The results of this simulation were compared with the measured whole-building electric data, the only reliable data available. Because of the considerable uncertainty in some of the input data, mainly the installed equipment loads and the lighting and equipment diversities and operating schedules, adjustments to these values were then made to calibrate the model to the measurements.

The Prerestored Capitol Model

The prerestored Capitol differs from the restored condition primarily in the ground floor office arrangement and in the

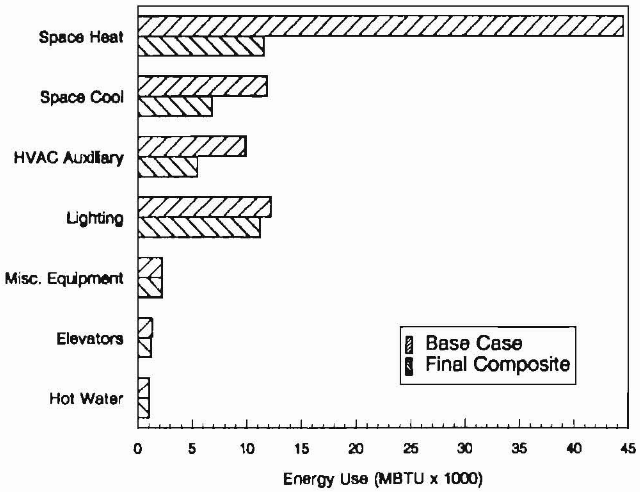

Figure 2a
Annual Energy Use Component for Capitol Restoration

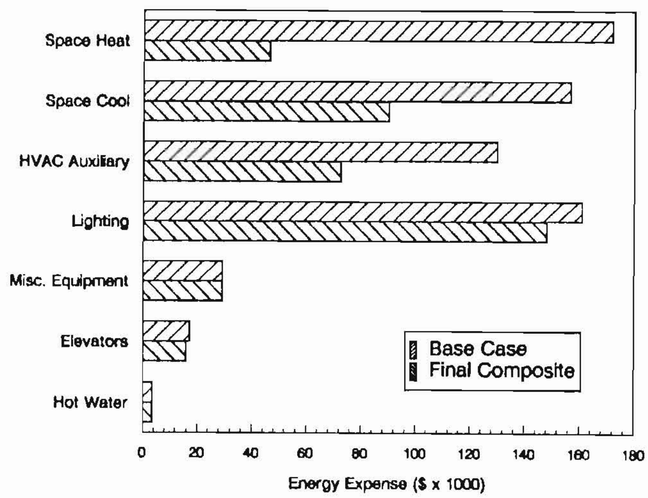

Figure 2b
Annual Energy Expense Components for Capitol Restoration

occupancy and equipment densities throughout all office areas. In addition, the prerestored Capitol does not include the tunnel to the Capitol Extension, and so has a gross floor area of 314,095 ft^2, of which 254,560 ft^2 are conditioned. We relied on "as built" drawings, supplemented by extensive surveys of the building and interviews with building operating personnel, to define the DOE-2 model input. Described below are the changes made to the DOE-2 model of the restored Capitol; items not discussed here were treated identically in both the restored and prerestored models.

Zoning Configuration. In the prerestored condition the core zone, which is unconditioned, extends down to the first floor instead of the ground floor. The snack bar area and electrical transformer vault form an additional zone on the ground floor. In addition, the tunnel to the Capitol Extension is deleted, the first floor corridors are unconditioned, and the first floor kitchen is incorporated into the west wing as office space. Mezzanine offices are added on the first through fourth floors.

Schedules. The schedules for occupancy, lighting, and equipment use, and for HVAC system operation, are essentially the same as for the restored Capitol. An addition is a schedule for the snack bar, and one for the external and dome flood lighting, which is based on the sunrise and sunset hours.

Electrical Loads. Because no accurate as-built drawings were available, lighting and equipment loads were established by identifying a set of representative spaces (based on occupancy density and use type), counting the number of fixtures and equipment items, and recording the wattage specified on each (3). Based on these surveys, power densities were calculated for each representative space. Then, with observations made during the sample surveys, in combination with available floor plans, the zones were subdivided into representative spaces. Zonal composite lighting and equipment power densities were determined as floor-area-weighted averages of these spaces.

Lighting: Specifications for all corridor lighting, lighting in the central core and dome, the external lighting and dome flood lights, and the night/emergency lighting were obtained through consultations with the Capitol maintenance staff. A lighting diversity factor of 90%, based on observation during surveys, was included in the design values. Based on these procedures, installed lighting levels are 2.08 W/ft^2 for offices and adjacent circulation space, and 2.12 W/ft^2 for all conditioned spaces.

Equipment: Specifications for equipment with high power draws (for example, large copiers and printing equipment), were obtained from vendor information. Approximate equipment diversity factors, estimated from discussions with the building occupants and maintenance staff, were incorporated into the design values. Based on these procedures, and an estimated diversity of 80%, design equipment levels are 2.5 W/ft^2 in the office spaces, resulting from high densities of computers, printers, FAX machines, and other office equipment; a detailed zonal breakdown of lighting and equipment loads is given in Reference 3. Equipment loads for the snack bar were based on the assumption that the two 12 kW supply mains were fully loaded during hours of peak operation. The electrical vault specifications assumed that transformer and switch gear losses were 5% of rated power.

Heat Gain from Occupants. We used the same procedures as were used for the restored Capitol to calculate heat gain from occupants in the prerestored case, except that in the office spaces the people densities were obtained from seat counts, rather than from people per square foot values.

HVAC Systems. Each zone was treated as having only one system type: fan-coil, constant-volume reheat, or dual-duct, according to the predominant type of equipment used in the zone. The ground floor, first floor north wing and first floor west wing south offices are modeled as fan-coil units, with outside air supplied by single-zone air handling units through duct work and ceiling diffusers; the Senate chamber and second and third floor east wing offices are modeled as dual-duct, variable-air-volume systems with outside air preconditioning; and the remaining areas, including the library and House chamber, are modeled as constant-volume reheat systems. The first floor corridors, the attics, and the lower and upper core zones are unconditioned.

The primary information sources for the air distribution systems were the incomplete "as built" drawings and records of revisions made to the mechanical systems, supplemented by discussions with the Capitol maintenance staff and combined with engineering judgement. Supply, outside air, and exhaust flows were taken from the diffuser specifications. Outside airflows ranged from 7 to 20% of supply airflows, with an average of 16%. Fan power, design air flow rates, and reheat coil temperatures were taken from the mechanical equipment schedules, with the values for multizone AHUs divided proportionally among the zones served.

Plant Specifications. On the basis of consultations with the SPGSC, the chiller efficiency was set at 0.71 kW/ton and the boiler efficiency at 65% for the period June - September 1991. The chilled water supply temperature was set at 42°F.

Simulation Results for the Prerestored Capitol Model

DOE-2 was run using weather data measured at the Capitol Complex by the LoanSTAR monitoring program for the period June-September 1991. The results are presented in Figure 3, which shows the hourly whole-building electricity use, in kilowatts, plus the fan and outdoor lighting energy use components, for the third week of July, during which time the Legislature was in session. Note that this plot, which is based on appropriate hourly reports from DOE-2 to be comparable with the measured data, does not include heating or cooling plant energy; however, local fan and pump use is included. Thus, these results represent the behavior of an existing building as predicted by a carefully constructed model, but without the enlightenment of a comparison to measured data.

Note that peak weekday electricity use is 1460 kW, while at night the use drops to 470 kW. The effect of turning on and off the exterior lights, a 90 kW load, can be seen clearly. Although the weekday and weekend periods are clearly distinguished, Saturdays and Sundays were modeled identically.

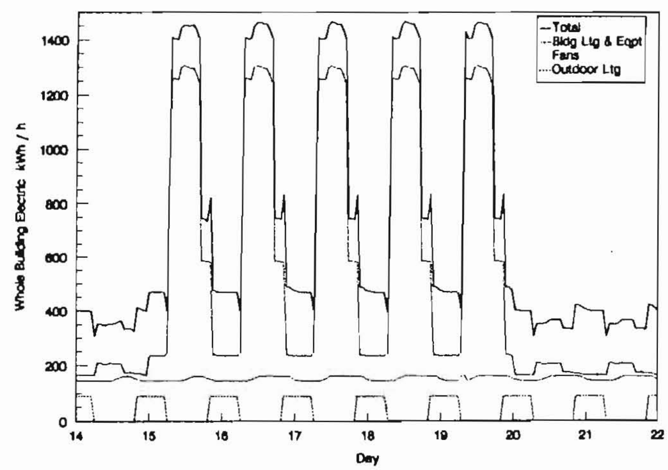

Figure 3 Simulated whole-building electricity use (excluding heating and cooling plant energy) for prerestored Capitol - third week of July 1991

Calibration of Simulation Model with Measured Electricity Data

Monitored hourly data for the Capitol were collected only for short periods during 1991. Because of construction on the Capitol Extension and instrumentation contractor problems, steam condensate pump run time data are available only for portions of January and February, chilled water energy data are available for about two weeks in April, and whole-building electric data are available for July-September. The whole-building electric measurements are the only reliable ones of the three sets.

Examination of the measured electricity use shows consistent daily and weekly patterns (Figure 4). Furthermore, Saturday patterns are distinct from Sunday patterns when legislators and their staff are preparing for the coming work week. The morning buildup in electricity use (7 AM to 11 AM), and the evening decline (5 PM to midnight), are nearly linear, with a superimposed pulse representing the exterior lighting. Usage is flat from 11 AM to 5 PM. Note that the buildup and decline transitions are not nearly as abrupt as was assumed in the precalibration simulation. Another interesting observation is that the September measured electricity use declines slightly from that of July and August, coinciding with the end of the legislative session (August 25) for that year.

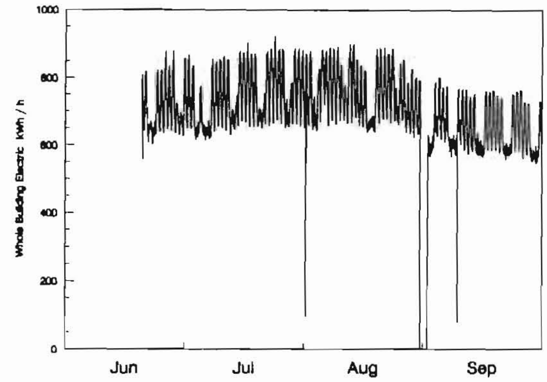

Figure 4a
Seasonal Pattern for July through September 1991

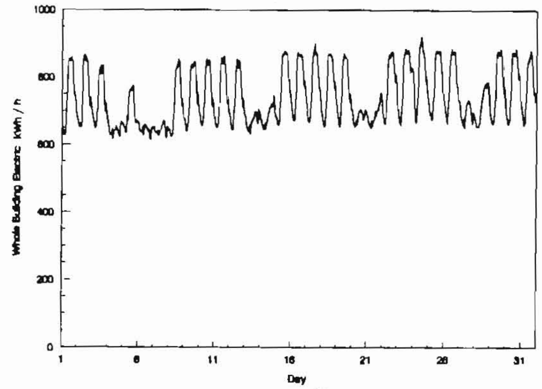

Figure 4b
Monthly Pattern for July 1991

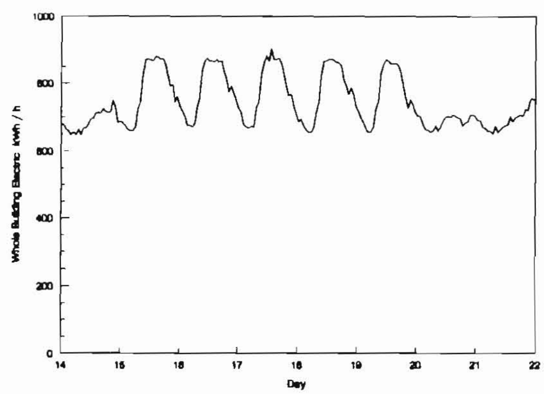

Figure 4c
Weekly Pattern for 3rd week in July 1991

Measured Whole-Building Electricity Use (Heating and Cooling Plant Energy Excluded) for Prerestored Capitol

A remarkable feature of the measured data is that the reduction in building electricity use from the daytime peak to the nighttime and weekend valleys is only some 25%, rather than the approximately 75% shown in Figure 3 for the precalibrated model; the peaks are lower, and the valleys are considerably higher than predicted. This indicates that the schedules for lighting and equipment (especially equipment) are lower than expected during the peak occupied period. Furthermore, lights and equipment are not being turned off at night and on weekends nearly as much as expected. Based on these results, a set of typical day types (weekday, Saturday/ holiday, and Sunday) was developed to represent the diurnally varying schedule for lights and equipment (Figure 5). These schedules were calculated by taking the ratio of hourly to peak electricity use at each hour for the four plus weeks of July.

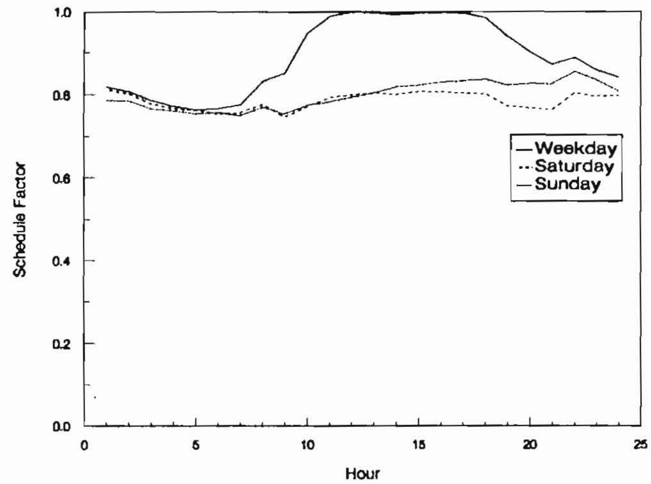

Figure 5 Normalized schedule factors for typical day types for prerestored Capitol - based on measured whole-building electric data

Using the typical day schedules, and adjusting them to match the electricity use observed in the measured data for July, a calibrated DOE-2 model was run for the same three-month period of 1991, with the results shown in Figure 6. As expected, the simulated and measured electricity use results compare closely.

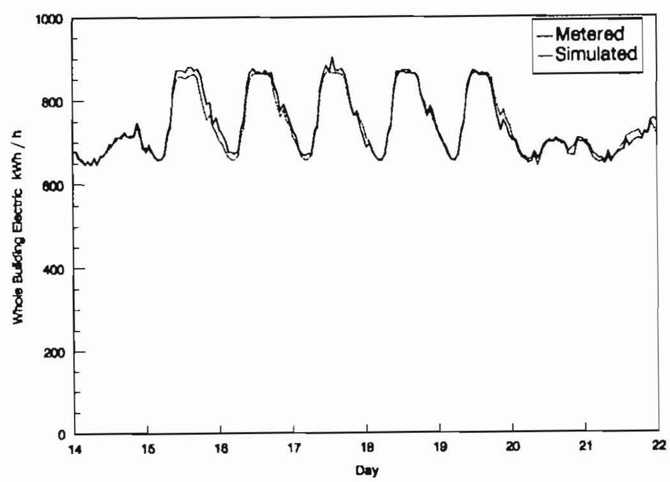

Figure 6 Comparison of calibrated model for prerestored Capitol with measured whole-building electric data - third week of July 1991

Finally, an annual simulation was run using the calibrated model for the prerestored Capitol with long-term (TMY) weather data for Austin. The results represent the expected annual energy use for the building, including all heating and cooling plant energy, with the assumption that the Legislature is in session throughout the year. Annual results are presented in Table 2, which shows that annual total energy intensity is 316 kBtu/ft^2-yr, and peak electric demand is 1,652 kW (5.26 W/ft^2). Using the 1991 utility rates used for the restored Capitol, this results in an annual energy cost of $716,800 or $2.28/ft^2-yr. Hopefully, this high energy use will be reduced by the inclusion of the package of energy efficiency alternatives in the restored Capitol.

CONCLUSIONS

Based on this analysis of the Capitol, the following conclusions can be drawn.

1. a. Building envelope measures (such as additional window shutters, a diaphragm at the dome oculus, and a skylight shade) save minimal energy and energy cost, on the order of only a few thousand dollars per year. Lighting measures (high-efficiency lights and lighting controls) result in modest energy cost savings of $6,000 to $7,000 per year, and peak demand reductions of about 50 kW. System equipment measures (high-efficiency motors and high temperature difference cooling coils) show annual energy savings of $12,000 to $13,000 and peak demand reductions of up to 60 kW.

b. The most effective energy cost reduction measures are HVAC system control measures, such as direct digital control of coil temperatures, thermostat offsets, and 2-speed or variable-air-volume fans with outside air control. These save up to $167,000 per year and reduce peak demand by up to 300 kW.

c. A composite of all selected energy efficiency measures is expected to save nearly $264,000 per year (a 39% savings), and result in a peak demand reduction of 300 kW (a 14% reduction).

2. When modeling a building that has highly unusual occupancy and use patterns, such as a state Capitol, uncertainties in lighting and equipment use can be considerable. Even when extensive survey data are available, the uncertainty in lighting and equipment operating schedules, is sufficient to cause peak electric power to be significantly over-predicted; similarly, nighttime electric power is likely to be substantially under-predicted if it is assumed that the vast majority of lights and equipment are turned off at night. It seems that occupants don't turn lights off, or cleaning crews turn them back on. Furthermore, office equipment such as computers, copiers, and FAX machines is likely left on overnight.

3. Measured whole-building electricity use for the Capitol during the summer legislative session of 1991 shows remarkably consistent daily and weekly energy use patterns. Thus, typical weekday, Saturday, and Sunday lighting and equipment schedules can be developed to calibrate successfully an hourly simulation model of the building.

4. Simulated annual energy use for the Capitol in its prerestored condition is 316 kBtu/ft^2-yr. It is hoped that this high energy intensity will be reduced by the inclusion of the package of energy efficiency alternatives in the restored Capitol. Furthermore, more energy conscious behavior of the occupants in turning off lights and equipment when not in use, will also be necessary to reduce this energy intensity.

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