
Energy Consumption of Personal Computer Workstations

R. F. Szydlowski
W. D. Chvála, Jr.

February 1994

Prepared for the U.S. Department of Energy
In-House Energy Management Program
Hanford Energy Management Committee
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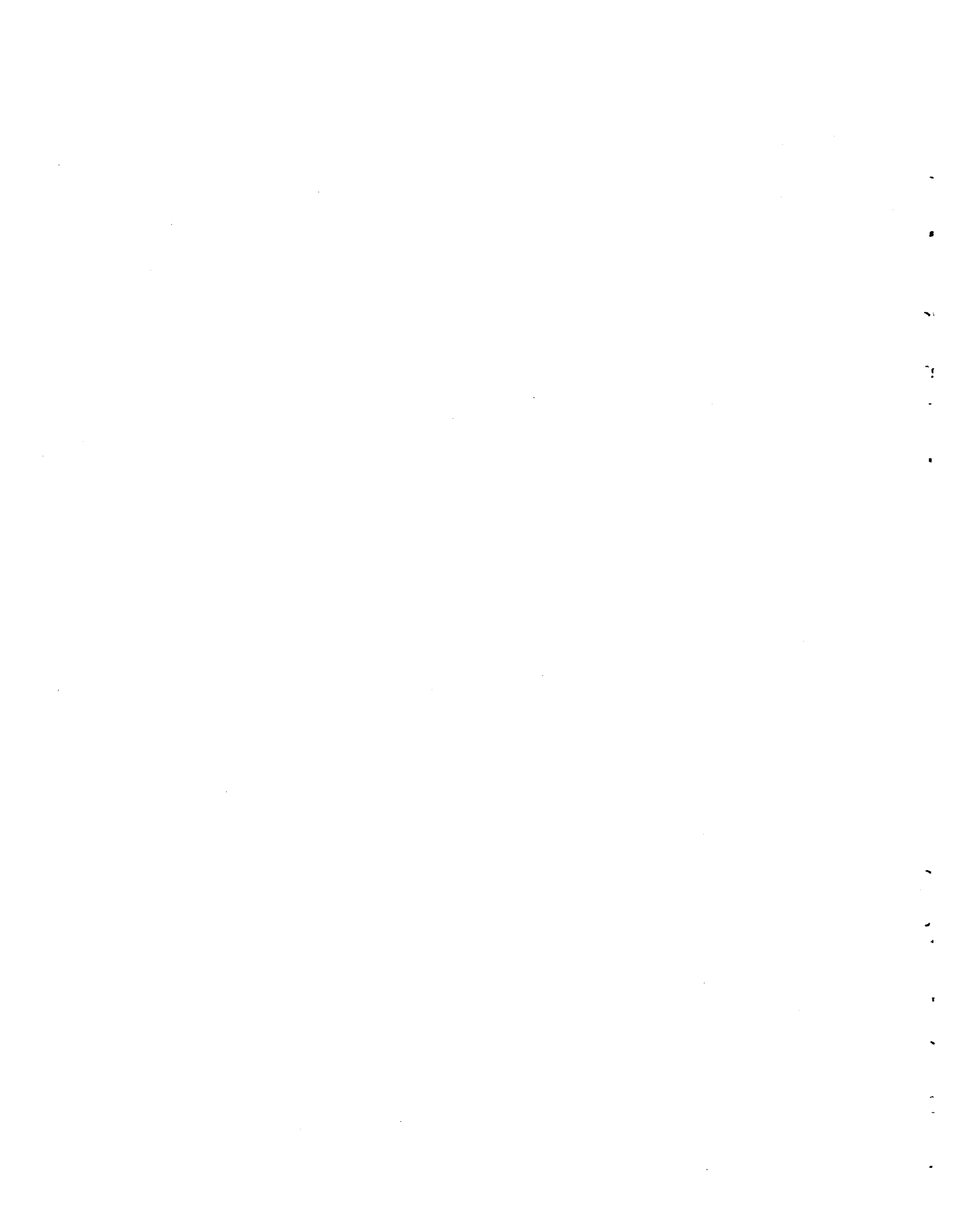
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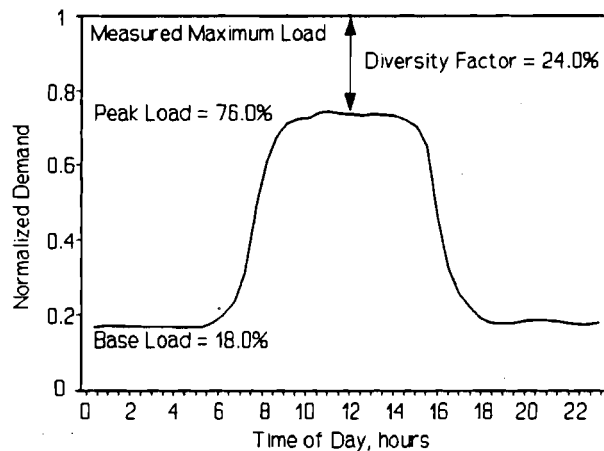


Summary

This field monitoring study metered 222 personal computer (PC) workstations, network printers, facsimile machines, and photocopiers in six buildings at the Hanford Site in Richland, Washington. A survey of 1,231 workstations provided additional information about the number and type of installed equipment in each building. The monitoring included PC equipment such as the central processing unit (CPU), monitor, printers, scanners, external disk drives, external modems, and other peripherals, in addition to other office equipment such as facsimile machines, photocopiers, coffee pots, clocks, and other office automation equipment.

A 24-h time-of-day demand profile was constructed from the week's worth of data collected at each workstation. By combining the demand profiles for all the workstations in a building, a building demand profile (BDP) can be constructed. By combining the BDPs from the test buildings, we were able to obtain a workstation demand profile for a *standard* building, called the *standard* demand profile (SDP). The SDP is a hat-shaped profile normalized to the maximum possible energy consumption. The baseload value is 18.0%, and the peak load value is 76.0%.

We found that the *standard* PC consumed 144 W (CPU = 85 W, monitor = 60 W) and the power consumption of the standard workstation (PC plus peripherals) was 173 W. Ninety-three percent of all PC workstations fall into a load class of 75 to 173 W.



Standard Demand Profile for Workdays

The power density for workstation equipment in the buildings we tested was, on average, 0.62 W/ft² (with a standard deviation of 0.16 W/ft²). The energy use intensity was, on average, 2.49 kWh/ft² (with a standard deviation of 0.53 kWh/ft²).

By comparing the surveyed data to monitored data, it was possible to determine how much the manufacturers' nameplate ratings overestimate the power consumption of individual devices. We found that the actual power consumption can be obtained by multiplying the nameplate power rating (amperes x 120 V) by 0.231.

The BDP of any building can be approximated using the SDP and shifting the base and peak values to reflect the characteristics of a specific building. The base and peak values can be approximated by performing a walk-through audit, noting what percentage of the PCs are on during the daytime and at night. We found that because monitors operate independently of CPUs, the best results were obtained by treating monitors and CPUs as separate devices and recording the on/off status independently. To test this methodology, the BDPs for our test buildings were approximated with an average error of 0.5% (standard deviation = 2.3%).

A device that senses keyboard/mouse inactivity and powers off the monitor was tested on 11 different workstations. A 21% reduction in demand and a 34% consumption savings were realized from a conservative sample consisting of PCs that are normally turned off during nonwork-hours. For the general population that has a nonwork-hours baseload of 18%, the monitor shutoff devices would produce a 57% reduction in power consumption.

The 13 photocopiers monitored in this study had an average electric demand of 154 W during nonwork-hours and 225 W during work-hours, and an average energy consumption of 4.7 kWh/day. Although energy savings modes are built into most new photocopiers, the power-saving modes were enabled on only 4 of the 13 photocopiers. A photocopier running at normal power consumes 1,546 kWh/yr on average, while a photocopier with an enabled energy savings mode consumes 736 kWh/yr, or a savings of 52.4%.

Three energy conservation measures (ECMs) were investigated as possible ways to save energy at the Hanford Site. The first method, an energy awareness campaign to encourage users to turn off their PCs when not in use, showed a maximum potential savings of 554,340 kWh/yr or \$18,814/yr for the entire Hanford Site. The second method, installing retrofit power controllers on existing PCs to shut them off when inactive, showed a potential savings of 1.74 million kWh/yr or \$62,610/yr. The final method addressed was replacing the existing stock of computers (through natural attrition of old units) with energy-efficient models such as those in the U.S. Environmental Protection Agency (EPA) new Energy Star program. This method showed a savings potential of at least 1.39 million kWh/yr or \$50,126/yr.

Although the savings potential appeared encouraging, the life-cycle cost (LCC) analysis produced negative net present value for each of the three alternatives when compared to the installation costs at Hanford. By selecting a smaller subset of the PC population (PCs normally left on at night but shut off over the weekend, or PCs that are normally left on all the time), the ECMs are recommended only in buildings that fall under the Westinghouse Hanford Company (WHC) electric rate

PC Energy Conservation Measure Recommendations

Energy Conservation Measure	Standard PCs (341 kWh/yr, 100% of PCs)			High Energy-Use PCs (692 kWh/yr, 12% of PCs)			High Energy-Use PCs (942 kWh/yr, 12% of PCs)		
	Richland Rates	WHC Rates	Typical U.S. Rates	Richland Rates	WHC Rates	Typical U.S. Rates	Richland Rates	WHC Rates	Typical U.S. Rates
Energy Awareness						★		★	★
Power Controller						★		★	★
Energy Star PCs						★		★	★

★ Star indicates recommended action.

(\$0.055/kWh, no demand charge). The maximum net present value for an ECM is \$43/PC for an energy awareness program for computers that are left on all the time in buildings serviced by WHC.

Because of the low electric rates at Hanford, most of the ECMs explored are not recommended. However, in areas with electric rates at or above the national average, the ECMs we examined become economically feasible.

Acknowledgments

The authors gratefully acknowledge the assistance of John Schmelzer (PNL) for developing the multiple-outlet monitors and keeping the field data acquisition equipment operating; Dianna Richards and Brett Barnes (students with the Northwest Organization of Colleges and Universities for Science [NORCUS] program) for field data collection, survey, and data processing activities; Patrick O'Neill and Michele Friedrich (PNL) for assistance in project development and data analysis; Guy Newsham (Institute for Research in Construction, National Research Council, Canada), Mary Ann Piette (Lawrence Berkeley Laboratory), Jeff Harris (Lawrence Berkeley Laboratory), and Steve Schliesing (PNL) for review and comments on this report.

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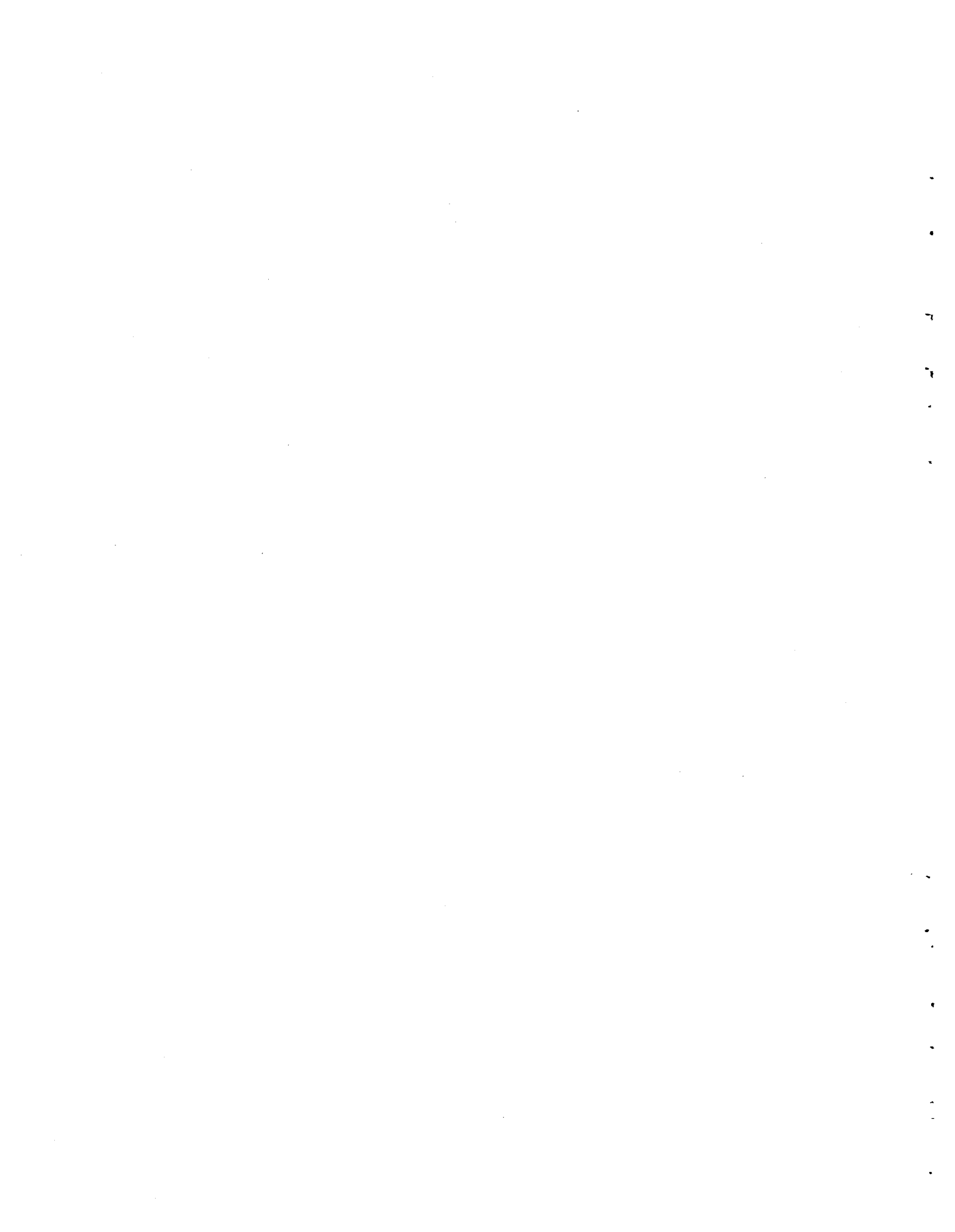
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Abbreviations and Acronyms

ASTM	American Society for Testing and Materials
BDP	building demand profile, normalized to maximum demand
CPU	central processing unit, the heart of a computer
CSA	Canadian Standards Association
DOE	U.S. Department of Energy
dPF	displacement power factor, phase shift
ECM	energy conservation measure
ELCAP	End-Use Load and Consumer Assessment Program (Bonneville Power Administration)
EPA	U.S. Environmental Protection Agency
EUI	energy use intensity, W/ft ²
FOT	fraction on-time
FOT _{CPU}	fraction on-time, based on computer (CPU only)
FOT _{NRC}	fraction on-time, based on NRC study
FOT _{PC}	fraction on-time, based on PC (CPU and monitor)
HEMC	Hanford Energy Management Committee
HVAC	heating, ventilation, and air conditioning
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IHEM	In-House Energy Management (DOE)
LAN	local area network
LCC	life-cycle cost
MOM	multiple-outlet monitor
NIST	National Institute of Standards and Technology
NPV	net present value
NRC	National Research Council, Canada

PC	personal computer (CPU and monitor only)
PF	power factor, (true power)/(apparent power)
PNL	Pacific Northwest Laboratory
RAM	random access memory
RMS	root-mean-square
SDP	standard demand profile, normalized to maximum demand
SDP _{IBM/Apple}	standard demand profile for IBM and Apple PC workstations
SDP _{SUN/DEC}	standard demand profile for DEC and SUN workstations
SDP'	standard demand profile, adjusted to new base and peak load fractions
SDP' _{CPU}	standard demand profile, adjusted to new base and peak values from FOT _{CPU} profile
SDP' _{Measured}	standard demand profile, adjusted to new base and peak values from measured building demand profile
SDP' _{PC}	standard demand profile, adjusted to new base and peak values from FOT _{PC} profile
SDP-2 _{IBM/Apple}	demand profile similar to SDP _{IBM/Apple} except that workday baseload is equal to peak load (i.e., PCs are normally left on at night during workdays but turned off on nonworkdays)
SDP-3 _{IBM/Apple}	demand profile similar to SDP _{IBM/Apple} except that baseload is equal to peak load for all nonwork hours (i.e., PCs are normally left on continuously during workdays and nonworkdays)
THD	total harmonic distortion
TSR	time-series record, recorded by C180 data logger at 30-min intervals
UL	Underwriters' Laboratory
V ac	voltage, alternating current
WHC	Westinghouse Hanford Company

1.0 Introduction

The explosive growth of the information age has had a profound effect on the appearance of today's office. Although the telephone still remains an important part of the information exchange and processing system within an office, other electronic devices are now considered *required equipment* within this environment. This office automation equipment includes facsimile machines, photocopiers, personal computers, printers, modems, and other peripherals. A recent estimate of the installed base indicated that 42 million personal computers and 7.3 million printers are in place, consuming 18.2 billion kWh/yr--and this installed base is growing (Luhn 1992).

From a productivity standpoint, it can be argued that this equipment greatly improves the efficiency of those working in the office. But of primary concern to energy system designers, building managers, and electric utilities is the fact that this equipment requires electric energy. Although the impact of each incremental piece of equipment is small, installation of thousands of devices per building has resulted in office automation equipment becoming the major contributor to electric consumption and demand growth in commercial buildings. Personal computers and associated equipment are the dominant part of office automation equipment. In some cases, this electric demand growth has caused office buildings' electric and cooling systems to overload.

Significant effort has been expended on engineering calculation, modeling, and indirect measurements based on whole-building "plug" loads, computer on-time (Tiller and Newsham 1993), and one-time electric measurements of personal computer workstation equipment during idle operation (Tiller and Newsham 1993; Norford et al. 1988). However, no direct field measurements of personal computer workstation load profiles had ever been taken. Load profiles are time-series data that show the actual electric demand and consumption throughout a test period of one or more days. Previous projects have not included taking such measurements because of the high cost of conducting field experiments, along with fear that technological changes and their rapid adoption would render the data obsolete as soon as it was published. However, this information is necessary for the identification of cost-effective energy conservation strategies, for both retrofit to existing equipment and purchase specifications for new equipment. Plus, the information helps in accurate design load calculations for new building design.

In this report, an extensive field study of computer workstation electric demand is described. The study was conducted by Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy (DOE) In-House Energy Management (IHEM) program and the Hanford Energy Management Committee (HEMC). The electric demand profiles of 222 personal computer workstations, network printers, and copiers were directly measured, and connected equipment at 1,231 personal computer

workstations in six buildings at the Hanford Site, Richland, Washington, was surveyed during August 1990 through August 1992. Each of the separate personal computer workstation components (e.g., computer, monitor, printer, modem, and other peripherals) was individually monitored to obtain detailed electric demand data for approximately 1-week periods.

The report details the methodology and equipment used in collecting field measurements and survey data. It also describes the resulting analysis of personal computer workstation electric demand and energy consumption. Limited results for two other major pieces of office automation equipment--facsimile machines and photocopiers--are also included in this report. In addition, the energy savings potential and cost-effectiveness of an electric power controller that automatically turns off a computer's monitor during keyboard/mouse inactivity was evaluated as one energy conservation retrofit technology strategy. Of particular interest are Section 8, which demonstrates practical application of these results to other buildings, and Section 9, in which the impact of applying three different energy conservation strategies is calculated for the Hanford Site.

The purpose of the study described here was to evaluate how personal computer workstations and other office automation equipment influence building "plug" loads and to estimate the energy conservation potential of various techniques/technologies that can be applied to better match equipment power consumption to user needs. An important feature of the work is the development of a *standard* workstation demand profile and a technique for estimating a whole-building demand profile that provides a method for transferring this information to utility energy analysts, design engineers, building energy modelers, and others.

To the best of our knowledge, this study is the first in which standard time-of-day electric demand profiles are developed from extensive direct field measurements of load profiles.

2.0 Background

In estimating the energy consumption characteristics of various pieces of electronic office automation equipment, the only information that is usually available is the manufacturer's nameplate electric rating. The nameplates typically provide values of maximum amperage rating, often supplemented with voltage and wattage ratings, which can be used to calculate power consumption. However, our research and that of others (Webb and Caruana 1991; Wilkins et al. 1991; Pratt et al. 1990a, 1990b; Nguyen et al. 1988; Norford et al. 1988; Tiller and Newsham 1993) have shown that nameplate ratings do not accurately represent the true magnitude of the energy consumption of a piece of equipment. This is not surprising because nameplate ratings indicate maximum equipment loading for safety purposes, not expected nominal energy consumption. Even if the nameplates were accurate indicators of energy consumption, they do not provide valuable time-of-day demand information.

Electric energy use in buildings is often disaggregated into groups by end-use types. One method employed by PNL and Bonneville Power Administration's End-Use Load and Consumer Assessment Program (ELCAP) (Pratt et al. 1990b) breaks electric end uses into six groups: interior lighting, exterior lighting, hot water, HVAC systems, auxiliary and emergency circuits, and other end uses. "Other end uses" commonly refers to building plug loads, elevators, refrigeration, cooking, and miscellaneous other loads. Although personal computers and office automation equipment are not the only plug loads, they are commonly considered to be a significant load in that category.

According to 1986 estimates, computers and other miscellaneous office equipment consumed 15% to 17% of the total energy in commercial buildings in the Pacific Northwest (DeLaHunt 1990). Estimates of total energy use by office equipment in office buildings range between 1.0 and 3.5 kWh/ft²-yr for 1983, with projections of 4.2 to 10.8 kWh/ft²-yr by the year 2011 (Piette et al. 1991). The energy impacts are even more substantial when the additional air conditioning requirements attributable to equipment heat generation are considered (COMSUL 1990; Integral Design/Engineering 1991; Wilkins et al. 1991; Tiller and Newsham 1993). Although cooling costs can be significant, they are extremely difficult to quantify.

Peak demand growth is at least as important as the increased energy consumption. A New England load growth analysis in the mid-1980s estimated that of a total 13.6% increase in peak summer demand, 9% was attributable to computers and miscellaneous electronics (Michaels et al. 1990). Based on a 1990 survey, many new U.S. office building designs already specify a wiring capacity for plug loads at 5 to 10 W/ft² (Whiddon & Associates, Inc. 1990), compared to a 0.5-W/ft² allowance before the widespread use of microcomputers in the office. Although surveys of office equipment nameplate ratings may indicate an electric demand of 5 to 10 W/ft², the actual demand is

probably 2 to 3 W/ft² or less (Shepard et al. 1990). Manufacturers' nameplate ratings overestimate demand, typically by two to five times actual (Shepard et al. 1990; Integral Design/Engineering 1991; Tiller and Newsham 1993). Therefore, the high cost associated with these high-capacity specifications for both new buildings and retrofit of existing buildings may not be justified. It is hard to predict if demand will continue to increase at the current rate: more electronic office equipment is being installed, but it is also starting to become more energy-efficient through improved design.

Energy efficiency of personal computer workstation equipment has become a hot topic. After all, many of the sophisticated power conservation techniques built into the latest battery-operated laptop computers (e.g., low-power chips, automatic power management) could be applied to desktop computers. Most computer manufacturers agree that the technology is available and can be incorporated into the standard desktop computers, as soon as buyers are willing to pay a slightly higher cost for the energy savings features. The Environmental Protection Agency (EPA) Energy Star program is a positive step in creating a market for more energy-efficient computer equipment by encouraging buyers to purchase equipment that meets energy conservation standards set by the EPA. The standards dictate that Energy Star computers and video display monitors have a power-saving mode that operates either at 80% of normal power or less than 30 W each. To date, 22 manufacturers have Energy Star computers and monitors in production; 70 others have pledged to comply.

However, even the most efficient equipment will waste energy if left on when not in use. In addition, the existing stock of computer equipment cannot take advantage of new built-in energy conservation technologies but must rely on user action or retrofit products. The simple act of turning off (manually or automatically) a workstation that is not being used will result in significant reductions in energy consumption and peak demand for both the workstation and the building's cooling system. For this reason, some of the add-on power management products need to be given careful consideration. A preliminary evaluation of one such retrofit technology is included in this report.

3.0 Scope

In this report, a *personal computer workstation* is defined as a system assembled from a number of individual devices, including the computer, monitor (video display terminal), printer, external disk drive, external modem, plotter, and other peripheral equipment, as illustrated in Figure 3.1.

Throughout the remainder of this report, *computer* will refer to only the central processing unit (CPU), which does not include the monitor. A *personal computer (PC)* is defined as the computer plus monitor—without any other external peripheral equipment. One exception is a computer that has a built-in monitor, such as the original Apple Macintosh, or workstations whose monitors are not powered separately and thus cannot be monitored separately. For example, some SUN and DEC workstations power the monitor directly from the CPU box. These definitions are necessary to uniquely identify the energy characteristics of a computer, monitor, PC (i.e., combined computer and monitor), and PC workstation (i.e., computer, monitor, and all peripheral equipment). Central mainframe and minicomputer systems are not included.

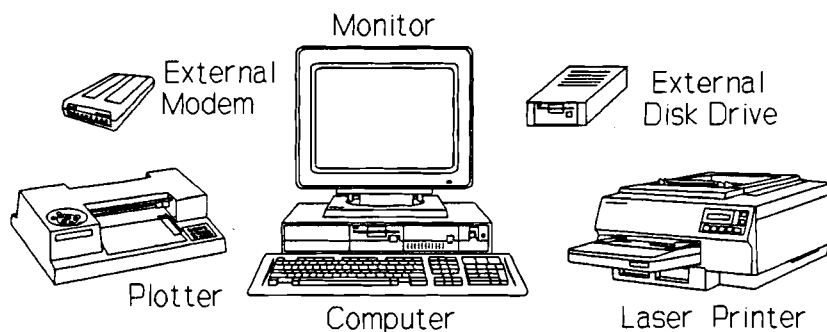


Figure 3.1. The Major Components of a Personal Computer Workstation

This study was conducted at the Hanford Site, a 560-mi² research installation near Richland, Washington, operated by four contractors for the U.S. Department of Energy. More than 15,000 employees conduct over 1,000 programs in environmental restoration and energy research at the Site. Six office buildings at the Site were chosen for investigation. Table 3.1 lists basic characteristics of these buildings, which varied in size, operating company, number of occupants, and use. All of the PC workstations in four of the buildings were surveyed to identify the types and number of installed PC workstation equipment. Because of its very large size, the Federal Building's equipment list had to be extrapolated from a survey that covered approximately one-third of the building. The Stevens

Table 3.1. Basic Characteristics of the Six Test Buildings

Building Name (primary use)	Total Area, Square Feet	Office Area, Square Feet	Number of Staff	Number of Workstations Installed	Number of Workstations Monitored
Federal (administrative)	203,375	146,525	1,187	916 ^(a)	68
TCPC (administrative & engineering design)	105,291	91,790	515	310	49
Stevens (scientific research)	59,834	19,000	150	210 ^(b)	47
OSB (administrative)	27,737	17,936	164	160	24
Sigma I (scientific research & computer science)	20,440	12,029	95	121	34
Sigma IV (administrative & scientific research)	20,440	12,029	119	129	1 ^(c)
Total	437,117	299,309	2,230	1,846	222
Average	72,853	49,885	372	308	36

^(a) Because of this building's large size, the installed workstation list was extrapolated from a survey that covered approximately one-third of the building (305 workstations).

^(b) Because of this building's large size, the installed workstation list was extrapolated from a survey that covered approximately one-half of the building (97 workstations).

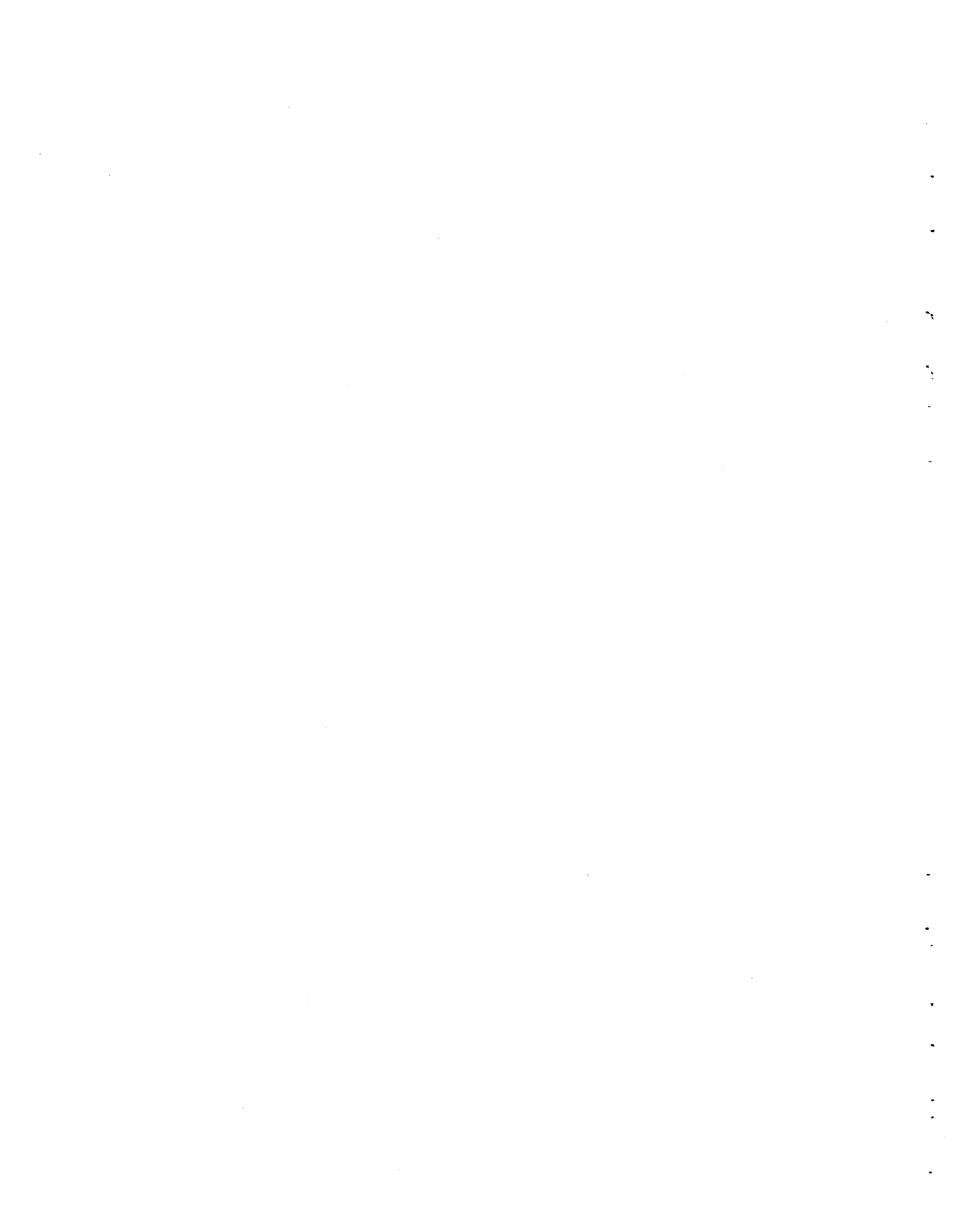
^(c) The single site monitored was a photocopier.

building equipment list was also extrapolated from a survey that covered approximately one-half of the building. A total of 1,846 workstations were identified in the six buildings.

A representative sample of 189 PC workstations that contained 3,472 individual devices was selected for field measurements. Although nine network printers were monitored, most network equipment (e.g., all file servers, local area network equipment switches and drivers, and most network printers) was not included. This equipment could not be turned off to connect the monitoring equipment without adversely affecting users connected to the network. Also excluded were some other major office equipment, such as central copy center equipment, due to difficulties associated with turning off their power. Although the demand associated with this equipment may be significant, this equipment was necessarily outside the scope of work for this survey. However, it should be investigated in the future.

In addition to PC workstations, a very limited set of medium-sized office photocopiers (13 devices) and facsimile machines (7 devices) was monitored. Electric demand and consumption savings resulting from the installation of automatic power controllers was evaluated through field measurements (11 locations). Software-controlled switches (e.g., terminate and stay resident programs that control hardware switches) and behavioral-based techniques (e.g., energy conservation awareness and incentive programs) were not investigated.

The data analysis goal was to document the impact of existing PC workstation equipment on the demand and energy consumption of a building's plug loads. This documentation included a comparison of manufacturers' nameplate ratings to measured demand, as well as development of electric demand profiles for the computer, monitor, personal computer, PC workstation, and other office equipment. The analysis did not include the impact of a PC workstation's heat generation on the heating and cooling system of the building in which it was operated.



4.0 Methods and Procedures

Documented in this section are the methods and procedures used to collect the field data and process it into a useful form. Figure 4.1 illustrates the field data acquisition and data processing required to collect and process the field measurements data.

A 1-week monitoring period, with a time-series record (TSR) integration period of 30 min, provided the required detail for both workday and nonworkday demand profiles. At the end of the week, data was downloaded to a portable computer in the field, and the loggers were moved to the next workstations. Installation and removal of the monitoring equipment required a short shutdown of the workstation equipment. The monitoring equipment was typically installed during work-hours in less than 5 min. During the week-long monitoring period, the equipment was typically located under the computer desk or table and was transparent to the user's operation of the workstation. All of the data process was conducted on desktop personal computer workstations, some of which were monitored for this study.

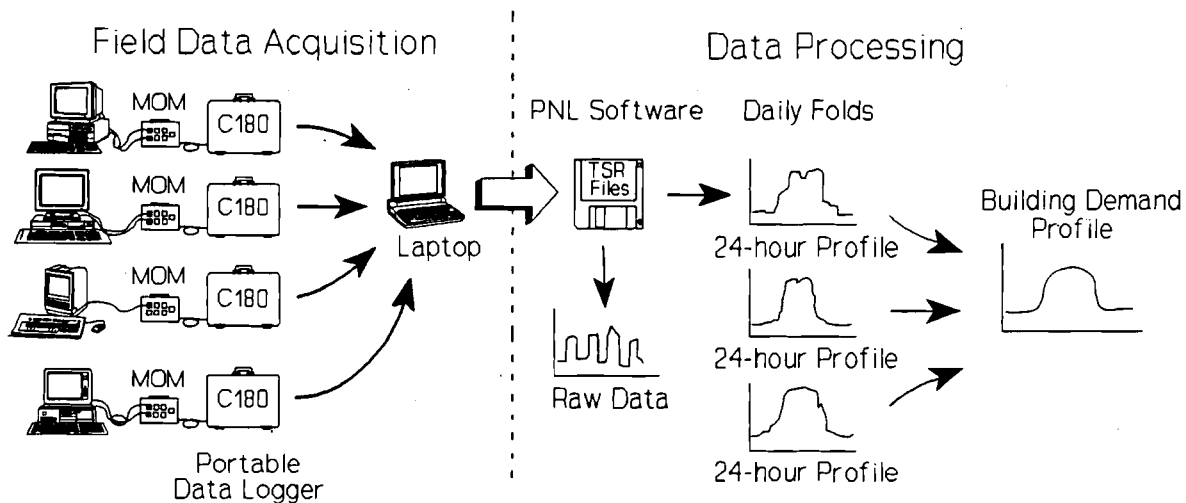


Figure 4.1. Field Data Collection and Data Processing Flow Schematic

4.1 Automatic Data Acquisition System

Four data acquisition systems, composed of a PNL-developed multiple-outlet monitor (MOM) and a Synergistic Control Systems C180™ data logger, were used to conduct all the field

measurements. The MOM, shown in Figure 4.2, was developed as a substitute multiple-outlet electric power strip that can separately monitor up to seven workstation devices. The C180 data loggers used electric current transformers and potential transformers built into the MOM to sample the amperage and voltage and to conduct real-time calculation of true electric power and apparent power for each of the seven outlets and the total workstation.

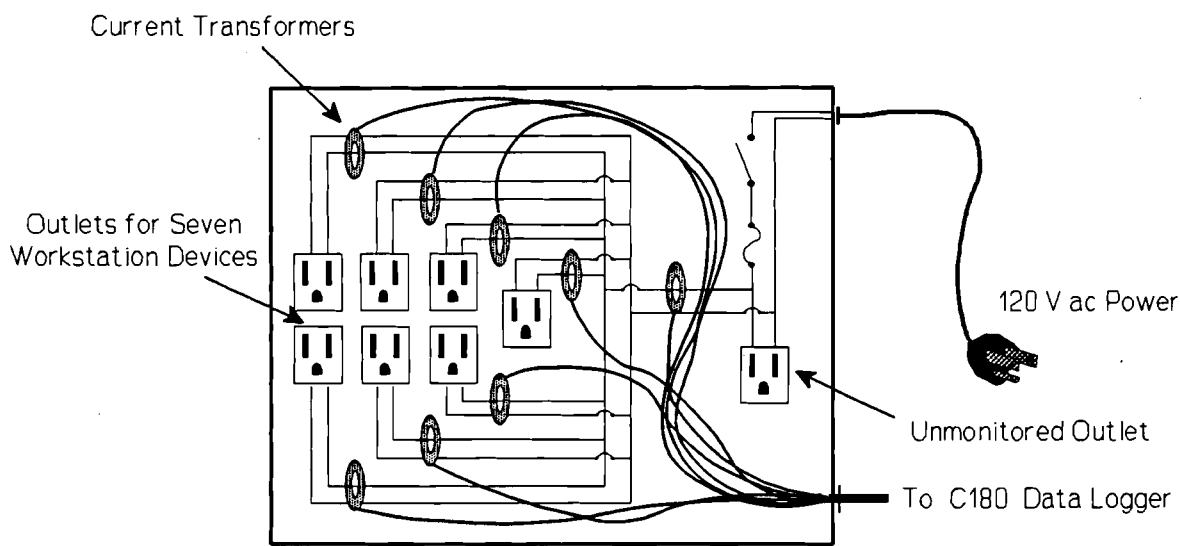


Figure 4.2. Multiple-Outlet Monitor (MOM)

Each workstation device was connected to a separate outlet on the MOM. The monitor and CPU were connected to the first two outlets, while other PC equipment and auxiliary devices were connected to the remaining outlets. Other PC equipment includes external disk drives, external modems, scanners, and plotters. Other auxiliary equipment includes photocopiers, facsimile machines, calculators—even coffee pots and fans. Great care was taken to include the auxiliary loads at each workstation, as their contribution to the total demand and consumption is not well understood.

The C180 data loggers are capable of recording more than 1 week of 30-min TSRs in internal battery-backed random access memory (RAM), so the data acquisition equipment did not need attention during the monitoring period. IBM-compatible portable computers were used to communicate with the data loggers via the SYNERNET[®] software program (Synergistic Control Systems, Inc.). SYNERNET was used to control both configuration of the C180s and automatic data transfer to the portable computer.

4.2 True Electric Power Measurements

All the electric power measurements recorded using the C180 data logger are true power for both sinusoidal and nonsinusoidal voltage and current wave forms. This is important because the switching power supplies in most workstation equipment are nonlinear and dramatically distort the current waveform. The result is degraded electric power quality, with typical total harmonic distortion (THD) in the current waveform of greater than 100%. Many low-cost, commonly available ammeters calculate the root-mean-square (RMS) value of alternating current by measuring the peak or average value and assuming that the waveform is sinusoidal. This assumption can result in errors of 50% to 100% (McEachern 1987) for the waveforms produced by the nonlinear switching power supplies found in personal computers and other office equipment.

To verify the accuracy of our monitoring equipment, the waveform profile obtained from a C180 data logger was compared to the profile captured using a BMI 3030A PowerProfiler® for a Compaq LTE 386s/20 personal computer and a Texas Instruments microLaser printer. Figure 4.3 shows that the waveforms and calculated parameters obtained from the C180 data logger compare very well with the more accurate, sophisticated, and expensive BMI PowerProfiler®. Appendix A contains more detailed information about the measurement comparison.

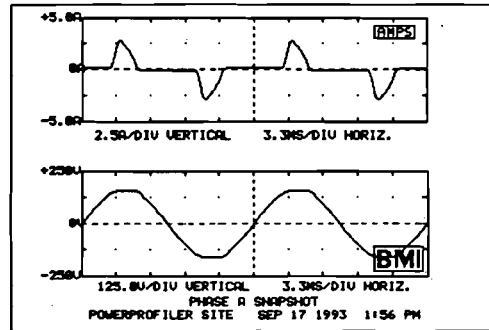
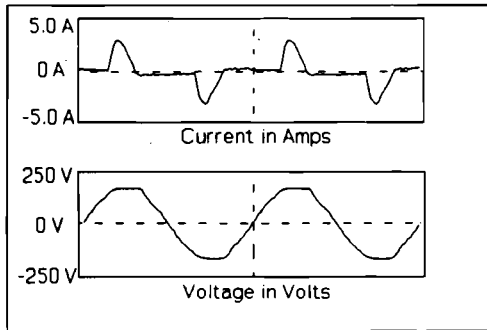
Figure 4.3 also dramatically illustrates the effect of harmonic distortion on line voltage and current. The voltage waveform is nearly sinusoidal, with minor peak clipping. The voltage waveform had a THD of 2.6%, due mainly to heavy loading of the transformer with other electric loads in the building. This is within the 5% THD of line voltage that utilities are required to provide customers, as specified by the Institute of Electrical and Electronics Engineers (IEEE) Standard 519 (IEEE 1981). The current waveform had THDs of 107.1% and 129.3%, attributable primarily to the device being measured. This current waveform is typical of nonlinear power supplies, where current is drawn only during a short time when the voltage is greater than a design threshold level.

Power quality problems can be also be characterized by *power factor*, the ratio between true and apparent power. Where waveforms are sinusoidal, the true power factor (PF) and displacement power factor (dPF) are equal and represent the degree of phase shift between voltage and current. However, the power supplies found in office equipment distort the waveform, causing power factors ranging from 0.5 to 0.9 with minimal waveform displacement. For example, the Compaq personal computer in Figure 4.3 has a power factor of 0.67 and a current displacement of only 8 degrees. Interpretation of the 0.67 as dPF would result in an incorrect calculation of 48 degrees of waveform displacement instead of the actual 8 degrees.

Compaq LTE 386s/20

Synergistics C180E Data Logger

BMI 3030A PowerProfiler

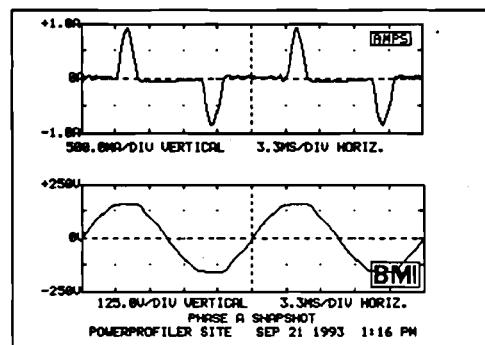
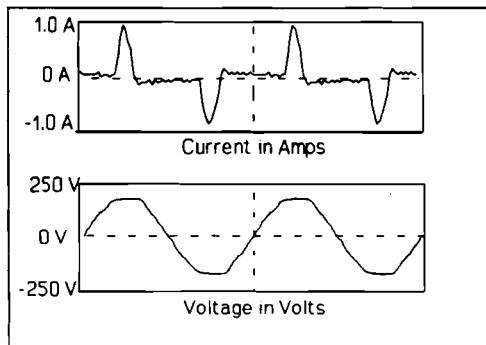


122.1 V rms	-	Voltage, Volts _{rms}	-	121.6 V rms
807 mA rms	-	Current, Amperes _{rms}	-	811 mA rms
61 W	-	Power, watts	-	65.15 W
98.53 VA	-	Apparent Power, VA	-	99.47 VA
0.62 PF	-	Power Factor	-	0.66 PF
N/A dPF	-	Displacement Power Factor	-	0.99 dPF
112 % THD	-	Total Harmonic Distortion	-	107.1% THD

Texas Instruments Laser Printer

Synergistics C180E Data Logger

BMI 3030A PowerProfiler



120.6 V rms	-	Voltage, Volts _{rms}	-	120.1 V rms
300 mA rms	-	Current, Amperes _{rms}	-	305 mA rms
21 W	-	Power, watts	-	21.65 W
36.18 VA	-	Apparent Power, VA	-	36.24 VA
0.59 PF	-	Power Factor	-	0.60 PF
N/A dPF	-	Displacement Power Factor	-	1.00 dPF
134 % THD	-	Total Harmonic Distortion	-	129.3% THD

Figure 4.3. Example of Workstation Equipment Electrical Characteristics

Harmonic distortion causes difficulty in many different ways. During monitoring in the Federal Building, voltage drops below 110 V caused our C180 data loggers to fail. Subsequent investigation revealed that the PCs being monitored had also experienced numerous, previously unexplained, faults during the preceding year. The original C180 data logger power supplies were replaced with more robust versions to handle the lower voltage. Harmonic currents also cause increased heat dissipation in transformers that were designed to operate at the fundamental frequency of 60 Hz. Harmonic distortion, low power factors, and shifted current waveforms ($dPF < 1.0$) are electric systems problems encountered daily in U.S. office buildings.

4.3 Office Automation Equipment Survey

In addition to the field measurements, a short informal office automation equipment survey was used to collect information about every workstation installed in each building. The following information was recorded for 1,231 PC workstations, network printers, and copiers:

- types of electronic equipment present
- manufacturer and model of each
- nameplate ratings
- occupation of primary user
- nominal work-hours.

Users were not queried about the operation of their workstations, for fear they would alter their normal operating pattern during the monitoring period. All of the measured and surveyed data were summarized in electronic databases, allowing detailed analysis of all available equipment characteristics. A copy of the survey form used to collect workstation information is included in Appendix B. A detailed list of all the workstation equipment identified through the surveys, with a breakout of the measured equipment, is also presented in Appendix B.

The survey did not distinguish between black-and-white and color monitors because presurvey observations revealed that there were very few black-and-white monitors. Further, many of those black-and-white monitors were large (e.g., 19- to 21-in.), high-resolution monitors on SUN or DEC workstations.

The survey did not try to identify the age of the equipment because most of the users did not have accurate information. Such vintage data could be used to examine how energy use of office equipment are changing over time. An age range could be inferred for the computer based on the

processor type, such as IBM PC compatibles (8088 and 8086 processors) being the oldest and computers with 486 processor being the newest. In some cases, the product name and model may also allow inference of age.

4.4 Data Processing

Approximately 100,000 time-series records comprise the 4.3 Mb of data collected, all of which had to be verified and converted to a useful form. All of the raw TSR data was plotted immediately following download from the data acquisition system to verify that the data was reasonable for the workstation and user. Questions about unusual workstation operation, such as major time periods with zero on-time, were resolved by talking to the user before they forgot their activity during the test week. In some cases, data collection problems, such as the user accidentally unplugging the data acquisition system, required that the workstation be monitored an additional week.

A PNL-developed data reduction/aggregation software package called ACCESS was used to automatically combine and reduce the raw TSR data into several useful forms for both individual devices and workstation totals. The most useful data analysis forms are average 24-h demand profiles developed for workdays and nonworkdays. The calculation procedure is shown in Equation (4.1). Workdays are normally Monday through Friday weekdays. Nonworkdays are weekends and holidays. These average-day demand profiles are useful summaries of the raw TSR data, which otherwise varies dramatically from hour to hour and day to day as workers' office hours vary due to meetings, business travel, and vacations.

$$\text{Average Demand Profile}_i = \frac{\sum_{j=1}^n \text{TSR}_i(j)}{n} \quad (4.1)$$

where i = time of day
 j = day during monitoring period (separated by workdays and nonworkdays)
 n = total number of days monitored
 TSR = time-series record of electric demand, recorded by data logger.

An example of raw TSR data for a particular monitored device is shown in Figure 4.4. By itself, this data is not particularly useful for determining whole-building plug load impacts. The raw TSR data was processed into the 24-h demand profile shown in Figure 4.5, which provides a better

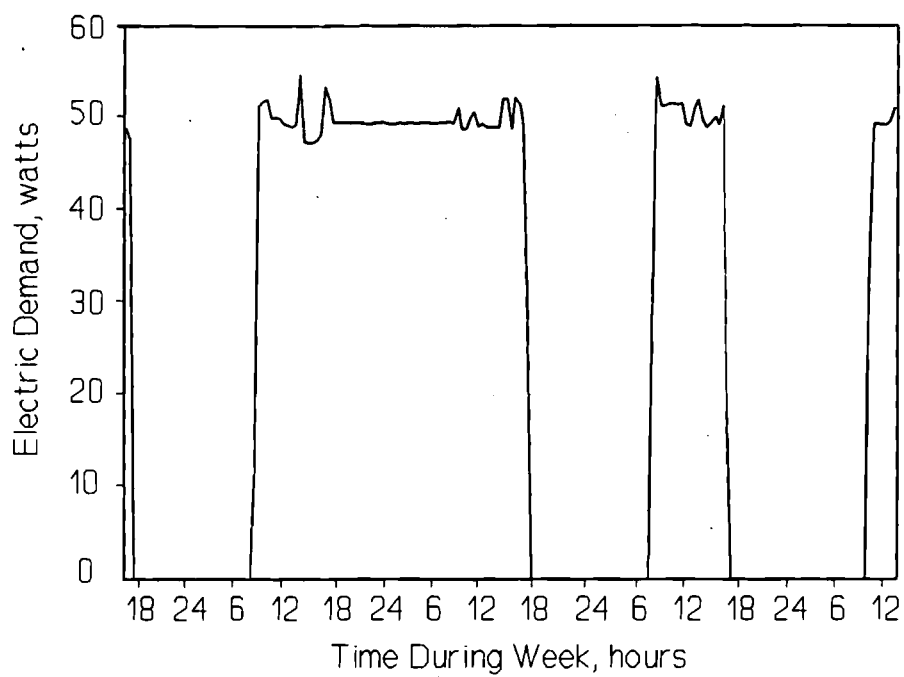


Figure 4.4. Raw Time-Series Data

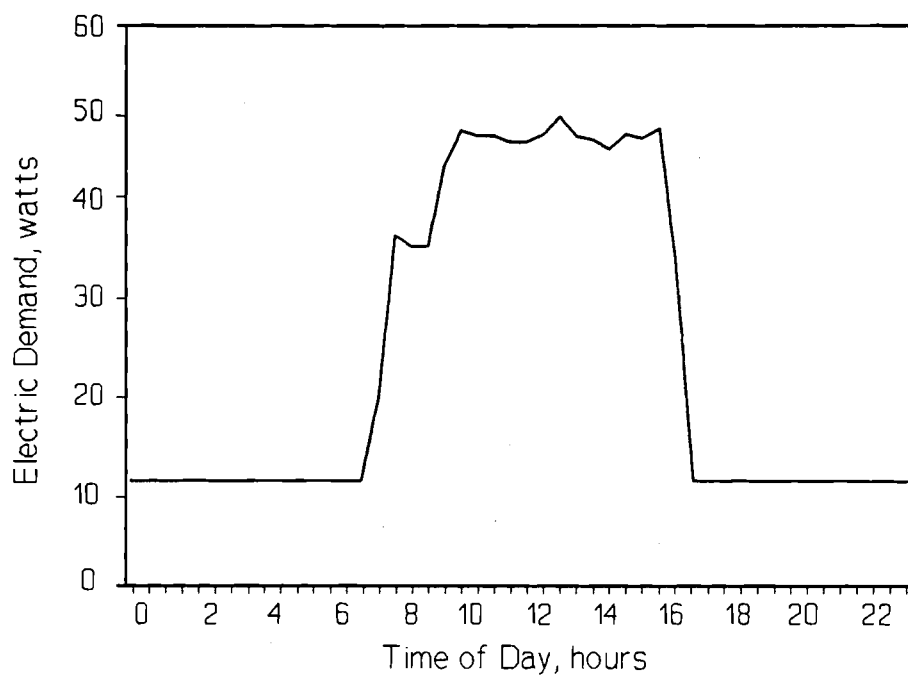


Figure 4.5. 24-Hour Fold, Demand Profile

representation of the typical operating characteristics of a workstation. The demand profile is calculated by averaging all of the TSRs for each time of day. For example, the 1:00 p.m. workday demand value is an average of all the 1:00 p.m. TSRs for all the workdays monitored.

To interpret the results, note that at 4:00 a.m. the 24-h demand profile shown in Figure 4.5 has a power demand of approximately 12 W, when the raw data shown in Figure 4.4 shows a workstation that uses either 0 W when off or approximately 50 W when on. At no time does the workstation actually demand 12 W; instead, the 12 W indicates that the workstation was on one out of four nights during the monitoring period.

The individual workstation demand profiles were summed to develop a measured building demand profile. Although the form of this measured profile was representative of the entire building's demand profile, the magnitude of the demand was incorrect because it was based on the sample of monitored workstations instead of on the total installed workstations. The field monitoring was limited to a subset of all the installed workstations because of the high cost of conducting field monitoring activities. However, whole-building demand profiles were constructed using measured building demand profiles that were scaled based on the number and type of installed workstations, as determined by the surveys. These whole-building demand profiles are thus accurate both in form and in magnitude of demand.

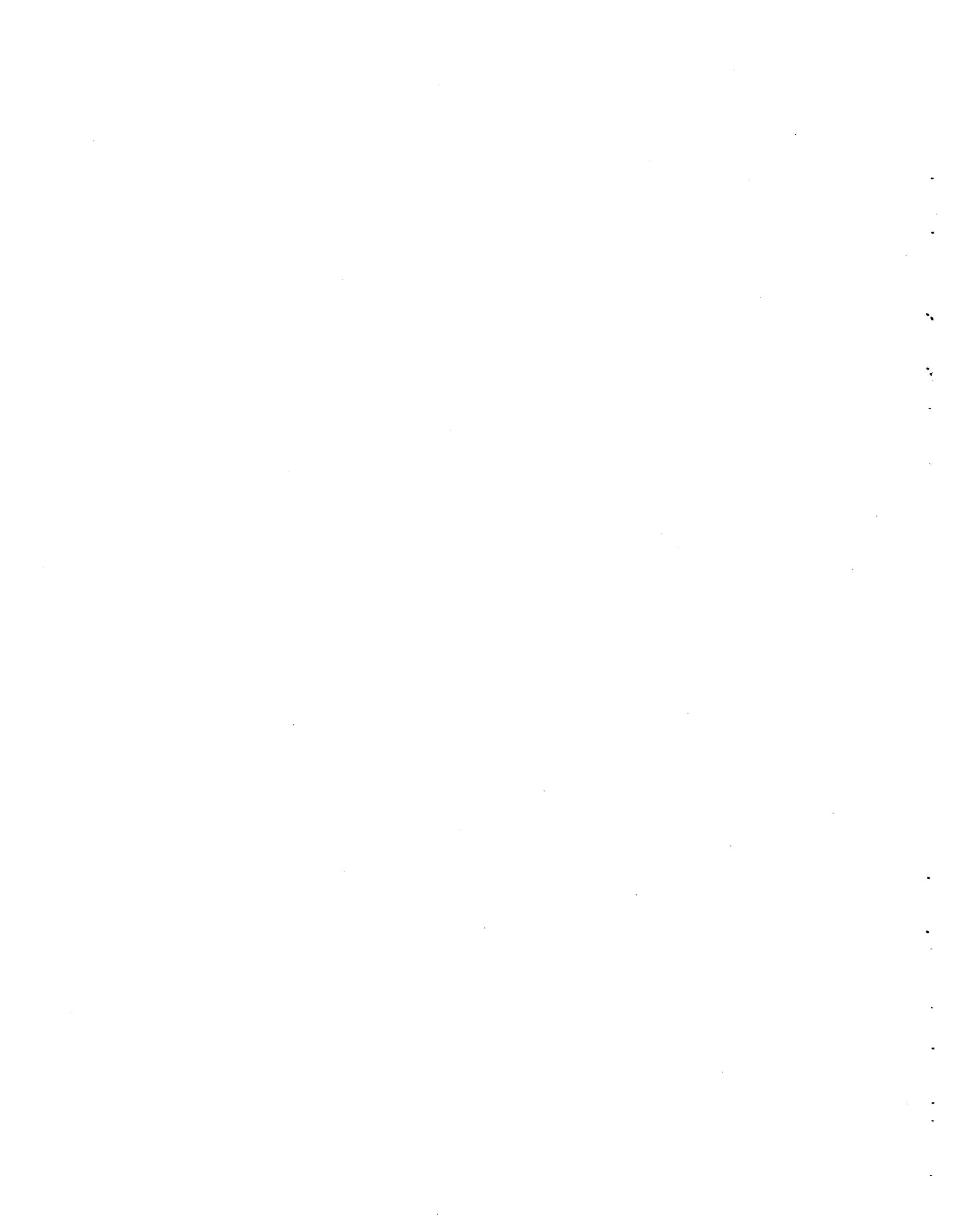
Because the field monitoring equipment was limited to four data acquisition systems, every workstation in a building could not be monitored simultaneously. Whole-building profiles were calculated from individual demand profiles that were measured on different weeks during the monitoring period. Except for a building in which a major reorganization (staff inflow, egress) or an infusion of significant new/upgraded workstations, the sum of these measurements is very close to the value that would have been obtained if all the measurements were made simultaneously. With the exception of vacations, office equipment experiences little seasonal variation.

For less than 5% of the workstations, a specific model of computer was identified in the survey but was not included in the measured sample because it was a very small portion of the total installed workstations. The peak demand of these unmonitored workstations was estimated to be equal to the average peak demand for the same computer model monitored in other buildings or, if not monitored elsewhere, to be the average of the peak demand for all the monitored workstations in the building being analyzed. This peak demand magnitude was applied to the measured demand profile of the building being analyzed. The shape of the demand profile was not borrowed from the building in which the demand measurement was actually made. This ensured that the shape of the demand

profile from the workstations that were monitored in other buildings would not distort the demand profile of the building being analyzed.

Note that the individual demand profiles are averages of multiple days, which typically include equipment that is on on some days and off on others. Because each device can be only on or off, the maximum demand of the equipment will usually be higher than any of the demand profile values. (Exceptions are for equipment that was always on for a particular time and the very few devices that have an automatic standby mode.) However, because most of the equipment was on for at least one TSR (30-min integration time) during the field monitoring, each device's maximum load was determined by finding the maximum TSR during the test period. For most nonprinting devices, the maximum TSR was less than 5% higher than the typical full-operation mode TSRs, indicating that electric demand is independent of idle or full-operation modes.

The metering results from the measured workstations were combined with the surveyed data to extrapolate whole-building demand and consumption impact for each building in our sample group. In addition, the profiles from the five buildings can be combined to produce a *standard* electric demand profile, as discussed in Section 5.



5.0 Results

The results presented in this section are based on at least one week of monitoring at each of 222 locations conducted between August 1990 and August 1992. A total of 592 individual devices were monitored. Of the 222 locations, only 189 were workstations with a personal computer. The other locations--those that had photocopiers or network printers, or that were monitored for a second time as part of the PC monitor controller evaluation (Section 6)--are itemized in Table 5.1.

Only 182 of the 189 locations with personal computers were included in the analysis presented in this section. The remaining 7 locations had incomplete data sets resulting from occupant interventions such as unplugging the data logger power during part of the monitoring period or unplugging part of the workstation equipment power from the MOM during an unknown part of the monitoring period.

Table 5.1. Summary of Monitored Sites

	Monitored	Used in Analysis
Workstations	189	182
Photocopiers	13	13
Network Printers	9	9
Facsimile Machines	7 ^(a)	6 ^(a)
Monitor Controllers	11	11
Total Monitored Sites	222	215

^(a) The facsimile machines were monitored as part of the workstation or network printer sites.

5.1 Computer Classification

Table 5.2 shows a breakdown of the average operating load for the personal computer (i.e., CPU and monitor) configurations tested. The personal computers were categorized into one of four load classes. These load classes are somewhat arbitrary because the load of a specific personal computer model can vary widely, depending on its configuration. For example, the average electric demand of IBM PC-AT workstations ranged from 61 to 200 W, depending on the installed internal cards (e.g., network, video, disk drive controller) and monitor size. Because of this variation, a

Table 5.2. Personal Computer Classification for Monitored Workstations

	<i>Standard Personal Computer</i>	Class I, ^(a) 0 to 75 W	Class II, 75 to 175 W	Class III, 175 to 250 W	Class IV, 250 to 350 W
Number of PCs Monitored	182	4	158	17	3
Measured Power, W					
Average	144.0	33.6	138.7	201.1	289.2
Standard Deviation	43.1	3.9	26.7	28.2	44.9

^(a) All Class I computers have built-in monitors (Apple Macintosh), which were assumed to use 10 W.

personal computer was included in a specific load class if the average electric demand of all personal computers with that CPU type fell within the load class.

Included in Table 5.2 is the demand information for a *standard* personal computer. These values were obtained by averaging all 182 individual personal computer systems monitored. This *standard* personal computer, and the *standard* workstation and *standard* demand profile to follow, provide a mechanism for applying the results from this limited test sample to estimating the impact of PC workstations on any whole building.

Table 5.3 provides a breakdown of each personal computer load class by computer model. Class I consisted entirely of small Macintosh computers. No laptop computers used as desktop computer substitutes were monitored in the Class I list because less than 1% was identified in the survey. Laptop computers that were part of a docking station ended up in Class II, just like typical desktop computers. Although laptop computers clearly use less energy than typical desktop computers, only the very newest models have displays that are of sufficient readability to allow sustained long-term use. Even then, the small keyboards and lack of expandability for network access limits their acceptance as a desktop computer substitute. Class II was the most common, identified 93% of the time in the survey. Classes III and IV were limited to a few of the largest systems.

Figure 5.1 shows the relative quantity of installed (based on the surveys) and monitored personal computers in each load class. This shows that although the selection of monitored workstations could not be designed as a completely random statistical sample, it is a fair representation of each load class. The largest class, Class II, represented 93% of the total surveyed PCs and 87% of the total monitored PCs. Because of the dominance of the Class II PC, the *standard* personal computer is approximately a Class II personal computer. The *standard* value of 144 W is therefore the best estimate of personal computer load in situations where the computer model is unknown (e.g., manufacturer, model, configuration).

Table 5.3. Workstation Models Monitored in Each Personal Computer Class

Class I, 0 to 75 W	Class II, 75 to 175 W		Class III, 175 to 250 W	Class IV, 250 to 350 W
MAC Plus MAC SE	CLUB Compaq 386/20e Compaq 386/25 Compaq LTE 386a/20 DECstation 3100 Gateway 2000 386/25 Genesis 286 HP Vectra IBM PC IBM PC AT IBM PC XT IBM PS/2 50 IBM PS/2 55sx IBM PS/2 60 IBM PS/2 70	MAC II MAC Iici MAC Iix MAC Iix MAC SE/30 Northgate 425i SUN Sparc I SUN Sparc II SUN Sparc I/PC Texas Micro Win 386 WIN 386ax WIN Turbo AT	AST 386/33 Compaq 386/33L HP 9836C IBM PS/2 80 SUN 386i	Compaq 386/20 VAXstation II

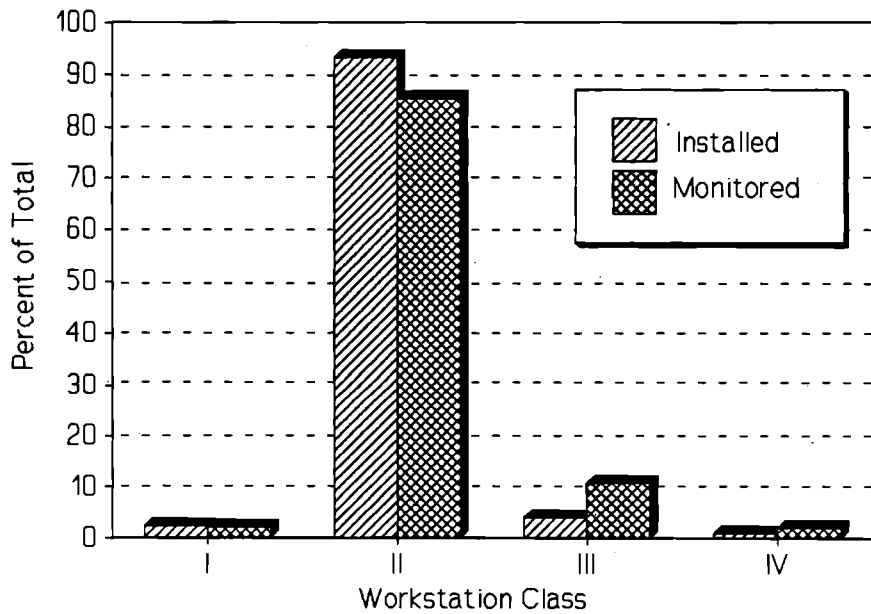


Figure 5.1. Distribution of Monitored Sites

Table 5.4 is a component-based breakdown of the whole workstation in each load class. It shows the individual contributions to average electric demand of the personal computer (i.e., CPU and monitor) and a variety of peripheral equipment commonly found as a part of a workstation. As noted above, the determinant of load class into which a computer system fell was the electric demand of the CPU and monitor. This is because peripherals generally contributed less than 20% to the total electric demand of a workstation—with the exception of those in Class I.

The penetration for each piece of peripheral equipment was determined by surveying the composition of all of the workstations in the six buildings surveyed. Thus, the penetration of 18% for impact printers for Class II workstations means that 18 out of 100 of these systems (as surveyed) had impact printers. The value of the average electric demand was calculated by averaging the metered data for all of a particular type of peripheral. For example, the 80-W average electric demand of a laser printer was determined by averaging the metered data from 10 different types of laser printer. The contribution to the total workstation electric demand of a particular peripheral is calculated by multiplying the peripheral's electric demand by the penetration.

Table 5.4. Personal Computer Workstation Load by Class

	<i>Standard Workstation, W</i>	Class I, W	Class II, W	Class III, W	Class IV, W	
Personal Computer:						
CPU	85 ^(a)	34	79	131	209	
Monitor	60	0	61	70	80	
Total CPU and Monitor	145	34	139	201	289	
Peripherals:	Average Demand, W	Peripheral Equipment Penetration, % of Workstations with Device				
Impact Printer	13	17%	10%	18%	5%	0%
Laser Printer	80	25%	30%	24%	39%	40%
External Drive	22	13%	40%	12%	32%	0%
Modem	8	1%	0%	1%	3%	0%
Plotter	13	3%	0%	3%	8%	0%
Scanner	19	1%	7%	1%	0%	0%
Autocad	6	9%	0%	8%	24%	40%
Other PC Equip	26	7%	10%	7%	3%	0%
Total Peripherals, W	28	38	27	42	34	
Total Workstation, W	173	72	166	243	323	

^(a) Electric demand given in watts except percentage figures as noted.

The penetration of printers may seem high, considering that most of the surveyed workstations were connected to a local area network (LAN) with printing resources. For example, a total of 42% of the Class II workstations had a local printer—either impact (18%) or laser (24%). A few of the local printers operated off the LAN instead of being directly connected to the computer, but they were typically used by that workstation exclusively or provided printing services for a very few nearby workstations. Whether connected directly to the local computer or through the LAN is not important if the printer provides mainly local support. The survey did not distinguish between directly connected and LAN-operated printers that were located in individual offices. Dedicated network printers were not included in the development of Table 5.4.

Less than 1% of the printers identified were color printers, so no attempt was made to distinguish electric demand variations based on black-and-white versus color printing capability. There was also no attempt to identify printer usage based on pages printed per day because this information was typically unavailable.

5.2 Nameplate Ratings

When estimating power consumption of personal computers, usually the only information available is the manufacturers' nameplate ratings. The nameplates usually provide values of voltage and amperage or power rating in watts, which can be used to calculate nominal power consumption. This rating value is rarely reached because it is improbable that any device in a building will actually demand the rated value and that every device would be operating simultaneously. For consistency, nameplate power ratings for all the equipment were calculated from rated amperage multiplied by 120 V ac, with no assumed power factor [see Equation (5.1)]. This procedure was used because nameplates list the voltage and amperage more commonly than they do the wattage, and there is no nameplate information regarding power factor.

$$Power_{Nameplate\ Rating} = Amperes_{Nameplate\ Rating} * 120.0\ V\ ac \quad (5.1)$$

Manufacturers provide nameplate ratings as part of the requirements for testing laboratories such as Underwriters' Laboratory (UL) in the United States or Canadian Standards Association (CSA) in Canada. The labeling requirement specifies that the equipment's actual electric demand must never exceed 80% of the rated (nameplate) value. However, because most computer systems are designed to support the addition of internal cards or expansion chassis, the labeling must account for the maximum electric demand configuration. Because most of these computer systems will typically have

only a small number of expansion devices installed, the actual electric demand will be much lower than even the 80% of rated value.

Computer equipment that does not support internal expansion is also subject to severe overrating. In some cases, manufacturers use the maximum current ratings associated with each component that is used in their equipment instead of conducting a comprehensive test on the new product. The testing agencies will accept this development of an overall product rating if the assembled product consumes less than 80% of the lowest rated component. For example, several products that have various electric demand all use a common power supply, resulting in an identical rated value for each of the products.

The question remains: What fraction of the equipment's nameplate rating should be used when planning for a building's plug load? The answer is presented in the list of power de-rate values in Table 5.5. The power de-rate is defined as the fraction of nameplate power rating that was actually measured, as defined in Equation (5.2). Because valid nameplate ratings were not available for all the PCs, the de-rating values are based on a subset of the PCs listed in Table 5.2.

$$De-rate = \frac{Power_{Measured}}{Power_{Nameplate\ Rating}} \quad (5.2)$$

Table 5.5. Power De-Rate Values for Personal Computers by Class

	Standard Personal Computer	Class I, ^(a) 0 to 75 W	Class II, 75 to 175 W	Class III, 175 to 250 W	Class IV, 250 to 350 W
Number of PCs with Valid Nameplate Rating Information	118	5	97	13	3
Measured Power, W					
Average	147.2	33.6	141.8	198.3	289.2
Standard Deviation	46.4	3.9	27.3	27.3	44.9
Average Nameplate Rating, ^(b) W	681.1	120.0	688.9	793.4	880.0
Power De-Rate					
Average	0.231	0.280	0.222	0.254	0.327
Standard Deviation	0.069	0.032	0.070	0.045	0.042

^(a) All Class I computers have built-in monitors (Apple Macintosh), which were assumed to use 10 W.

^(b) Nameplate Power Rating = rated amperage multiplied by 120 V.

Although all of the power de-rate values are based on data for personal computers (i.e., computer and monitor), nonlinear power supplies are very similar for all electronic office equipment, and the power de-rates can be applied to the entire range of PC workstation equipment. The exception is electronic equipment that has a significant electric heater or motor load, such as a laser printer or copier during warmup or operation. Table 5.5 also includes the supporting data for calculation of the power de-rate values and the values for a *standard* personal computer.

The de-rate values indicate that the calculated nameplate wattages were three to five times greater than actual. Nevertheless, this is useful information. By multiplying the nameplate rating by a power de-rate value, we can obtain an estimated power demand, as shown in Equation (5.3).

$$Power_{Estimated} = Power_{Nameplate\ Rating} * De-rate \quad (5.3)$$

For example, a building planner is expecting 100 workstations with various types of equipment. A quick, but excessively high, estimate of plug load would be to add the nameplate ratings of all the workstation equipment. A more accurate workstation load can be obtained by adding all the nameplate values and multiplying by the *standard* power de-rate value of 0.231.

A National Research Council, Canada (NRC) study (Tiller and Newsham 1993) calculated power densities of 1.3 and 1.4 W/ft² at two sites based on nameplate ratings. The NRC's calculation method used either nameplate wattage (if available) or the product of nameplate amperage, 120 V ac, and an assumed 0.8 power factor. The actual power densities, based on one-time measurements in the idle state, with a BMI 3060 Power Profiler, were 0.3 W/ft² for both of NRC's sites. The NRC's power de-rate value is approximately 0.22 when calculated as measured power divided by rated power. Or, the power de-rate is 0.28 if the NRC's assumed 0.8 power factor is removed. The NRC's power de-rate values of 0.22 to 0.28 closely bracket our average power de-rate of 0.23.

5.3 Workstation Densities

It is often difficult to estimate how many workstations a building will contain. Reasonable estimates can be obtained using general building characteristics, such as workstations per total square feet, workstations per square feet of office space, and workstations per number of staff. In Table 5.5, the values obtained for our sample of six buildings are shown along with a *standard* building that was constructed by combining the sample buildings. Note that the *standard* value is not an average of the

six individual building values, but rather is based on the six-building total for number of workstations, areas, and number of staff members.

The workstation density ranges between 0.63 and 1.40 workstations per staff member. The administration buildings had workstation densities of 0.63 to 0.98 workstations per staff member. The highest workstation densities, 1.27 to 1.4 workstations per staff member, were found in buildings with substantial scientific research activities (Stevens and Sigma I).

Table 5.6. Workstation Equipment Densities

Building ^(a)	Total Area, ft ² /Workstation	Office Space, ft ² /Workstation	No. Workstations/ Staff Member
Federal	222.03	160.00	0.77
TCPC	339.65	296.10	0.63
Stevens	284.92	90.48	1.40
OSB	173.36	112.10	0.98
Sigma I	168.93	99.41	1.27
Sigma IV	158.45	93.25	1.08
Average	224.55	141.88	1.02
Standard Deviation	67.06	72.81	0.27
<i>Standard Office Building</i>	236.79	162.14	0.83

^(a) Refer to Table 3.1 for building area, office space area, number of staff, and number of workstations for each building.

5.4 Workstation Demand Profiles

Application of the results specific to the five monitored buildings to other buildings requires the development of a normalized building demand profile for PC workstations. The first step was to develop measured workstation demand profiles for each building, as discussed in Section 4.4, "Data Processing." These are average profiles of all the monitored data, with some minor corrections for missing data. The survey data was used to extrapolate from these measured workstation demand profiles to estimated whole-building workstation demand profiles (see Appendix C).

These measured demand profiles were then normalized to the measured maximum load. The measured maximum load is calculated by summing the maximum load measured during the monitoring period for each device. This is equivalent to having all the equipment turned on simultaneously. The result is called the normalized building demand profile, or BDP for short. Figures 5.2 and 5.3 show the BDPs for workdays and nonworkdays. Additional details regarding the

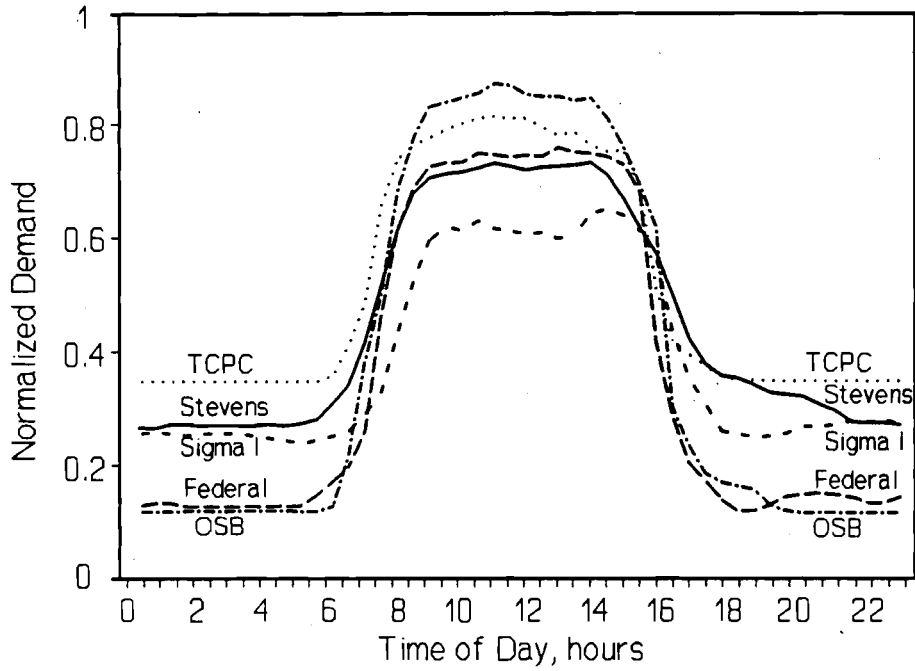


Figure 5.2. Workday Workstation Building Demand Profiles

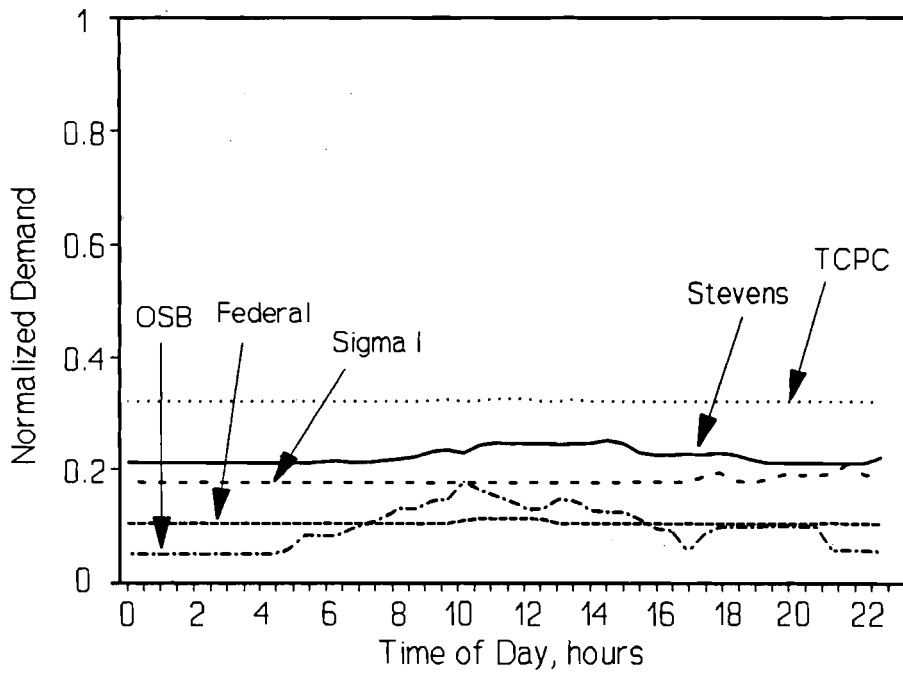


Figure 5.3. Nonworkday Workstation Building Demand Profiles

personal computer (CPU and monitor) and peripheral equipment portions of the workstation demand profile are presented in Appendix D.

Each workday and nonworkday BDP sets consists of 48 data points (e.g., 24 h of 30-min data) that define the demand profile for workstations during an average day. The demand values are the fraction of maximum demand. The maximum demand will occur only if all the workstation equipment is powered on at the same time. However, with a large number of users and workstations, diversity of operation results in 12% to 35% of the equipment demand being off, even during the middle of a workday.

Although all BDPs for office buildings that are occupied approximately from 8 a.m. to 5 p.m. are similarly shaped, each building has a unique BDP reflecting its distinctive characteristics. The test buildings selected intentionally represent a variety of building use types, so the significant variation in BDPs is not unexpected. Some buildings have a greater percentage of workstations left on at night, as is evidenced by a higher nighttime value. The morning start time is very similar for all the buildings. However, the Stevens Building had more staff that work as late as 10:00 p.m., and the Federal and Sigma I buildings had some second-shift activity that increases the demand between 10:00 p.m. and midnight.

A *standard* demand profile (SDP) for an office building was developed by using a weighted average of the BDPs from all five monitored buildings (see Figures 5.4 and 5.5). The weighting accounted for the number of workstations in each building. The workday *standard* demand profile has a baseload of 18.0% and peak load of 76.0% of the maximum load, with a very predictable demand increase and decrease during the start and end of a typical workday. Table 5.7 lists the base, peak, and diversity characteristics for load fractions for the SDP and each of the individual buildings.

The SDP reflects building occupant impact on the demand and power consumption of office workstations. The baseload is attributable to equipment that is left on over night. There is potential for energy savings by turning off some of this equipment. The peak load is less than 100% because of the diversity in equipment usage. Diversity examples include equipment that is rarely used or is not on because the staff are out of the office (vacation, sick leave, or travel) and staff who actually turn off equipment when it is not being used.

The workday *standard* demand profile's nearly constant demand during regular office hours and nighttime allows for the workday *standard* demand profile to be accurately approximated as a simple "hat profile." The hat profile assumes a 18.0% nighttime baseload and a 76.0% daytime peak load. As shown in Figure 5.6, the hat profile has a fixed baseload from midnight to 7:00 a.m. and from

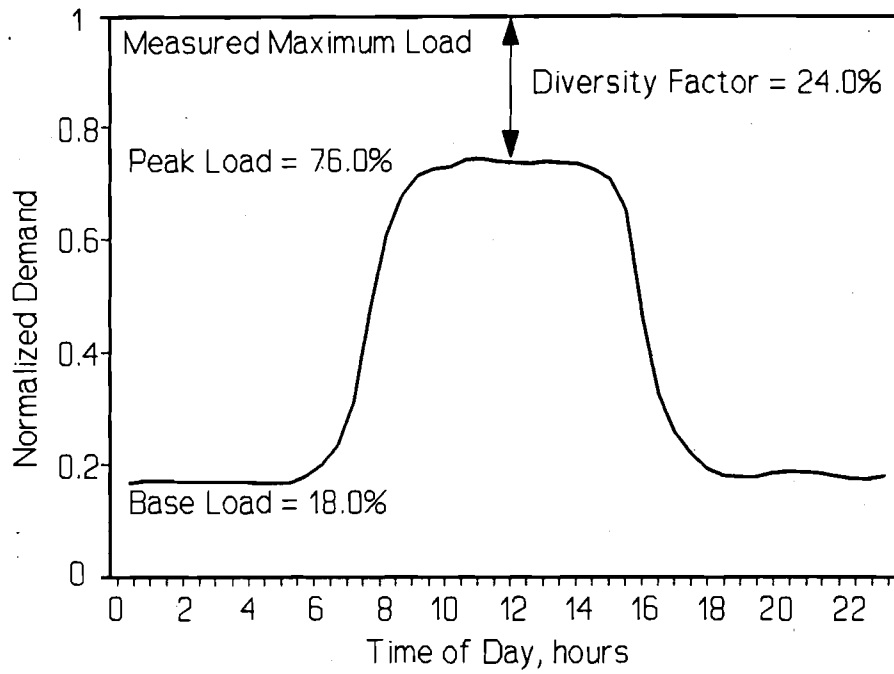


Figure 5.4. Workday Workstation *Standard* Demand Profile

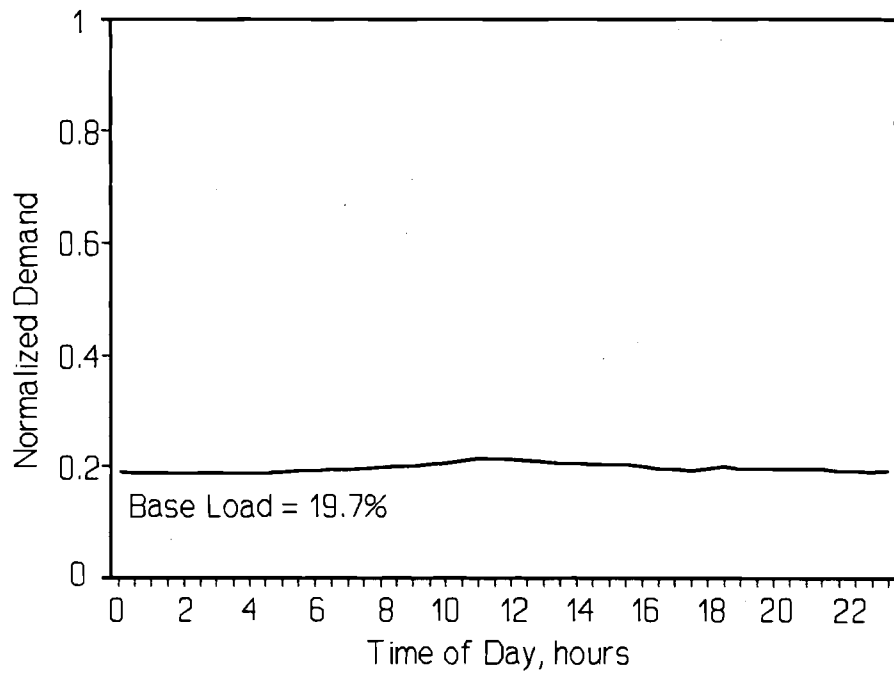


Figure 5.5. Nonworkday Workstation *Standard* Demand Profile

Table 5.7. Workstation Building Demand Profile Characteristics

Normalized Building Demand Profiles (BDPs)	Base Load	Peak Load	Diversity
Federal	0.118	0.744	0.256
TCPC	0.400	0.804	0.196
Stevens	0.229	0.751	0.249
OSB	0.101	0.832	0.168
Sigma I	0.291	0.701	0.299
<i>Standard Demand Profile (SDP)</i>	0.180	0.760	0.240

5:30 p.m. to midnight. The baseload linearly increases to a fixed peak load that lasts from 8:00 a.m. to 4:30 p.m. and then linearly decreases back to the original baseload. The daily energy consumption of this simple hat profile is within 1.4% of the more complicated 48-data-point SDP. In cases where ease of use is important or for input into building energy computer modeling programs, using the hat-shaped profile may be perfectly acceptable. The nonworkday SDP can be simplified to a constant 21.0% value. The numeric values for each point of the workday and nonworkday SDPs and hat profile are found in Table 5.8.

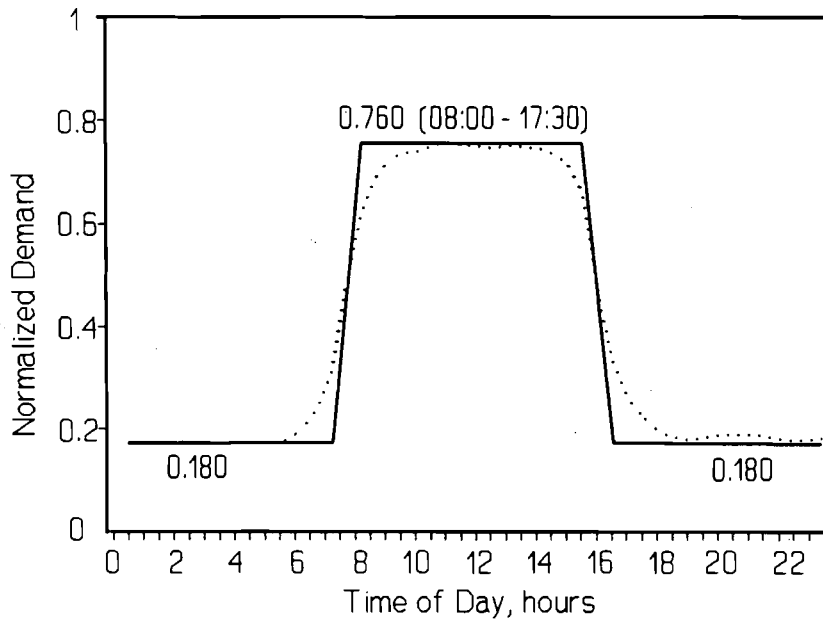


Figure 5.6. Standard and "Hat" Workday Workstation Demand Profiles

Table 5.8. Standard and "Hat" Demand Profile Values

Hour of Day	Workday		Nonwork-Day ^(a)	Hour of Day	Workday		Nonwork-Day ^(a)
	SDP	"Hat"	SDP		SDP	"Hat"	SDP
0	0.182	0.180	0.198	12	0.750	0.760	0.226
	0.182	0.180	0.197		0.751	0.760	0.223
1	0.182	0.180	0.197	13	0.760	0.760	0.222
	0.179	0.180	0.197		0.756	0.760	0.224
2	0.179	0.180	0.197	14	0.749	0.760	0.224
	0.180	0.180	0.197		0.737	0.760	0.220
3	0.179	0.180	0.197	15	0.720	0.760	0.221
	0.179	0.180	0.197		0.670	0.760	0.219
4	0.181	0.180	0.197	16	0.469	0.470	0.213
	0.182	0.180	0.197		0.330	0.180	0.210
5	0.182	0.180	0.198	17	0.261	0.180	0.209
	0.195	0.180	0.204		0.231	0.180	0.202
6	0.227	0.180	0.204	18	0.202	0.180	0.210
	0.269	0.180	0.204		0.191	0.180	0.214
7	0.340	0.180	0.206	19	0.188	0.180	0.210
	0.500	0.470	0.208		0.188	0.180	0.208
8	0.624	0.760	0.211	20	0.194	0.180	0.208
	0.690	0.760	0.214		0.196	0.180	0.210
9	0.728	0.760	0.216	21	0.196	0.180	0.209
	0.738	0.760	0.220		0.192	0.180	0.209
10	0.733	0.760	0.222	22	0.189	0.180	0.201
	0.744	0.760	0.228		0.185	0.180	0.205
11	0.752	0.760	0.230	23	0.185	0.180	0.201
	0.746	0.760	0.229		0.184	0.180	0.203

^(a) The nonworkday "Hat" demand profile is a constant value of 0.210.

5.5 Personal Computer Demand Profiles

The workstation demand profiles shown in Section 5.4 included all PC workstation equipment--computer, monitor, printer, external disk drives, and so on. A similar demand profile was developed for the PC (CPU and monitor) only. A comparison of workstation and PC SDPs in Figure 5.7 shows that the PC SDP baseload decreases from 0.180 to 0.175 and the peak load increases from 0.760 to 0.792. These two SDPs are similar because the PC represents approximately 80% of the total PC workstation demand.

Similarly, workstations can be divided into two classes: single-user PCs (IBM/Apple) and distributed resource machines (SUN/DEC). These two workstation classes have different use patterns. Figure 5.8 shows the IBM/Apple and SUN/DEC SDPs and includes the PC SDP for comparison. The SUN and DEC workstations are a special case because they are typically network

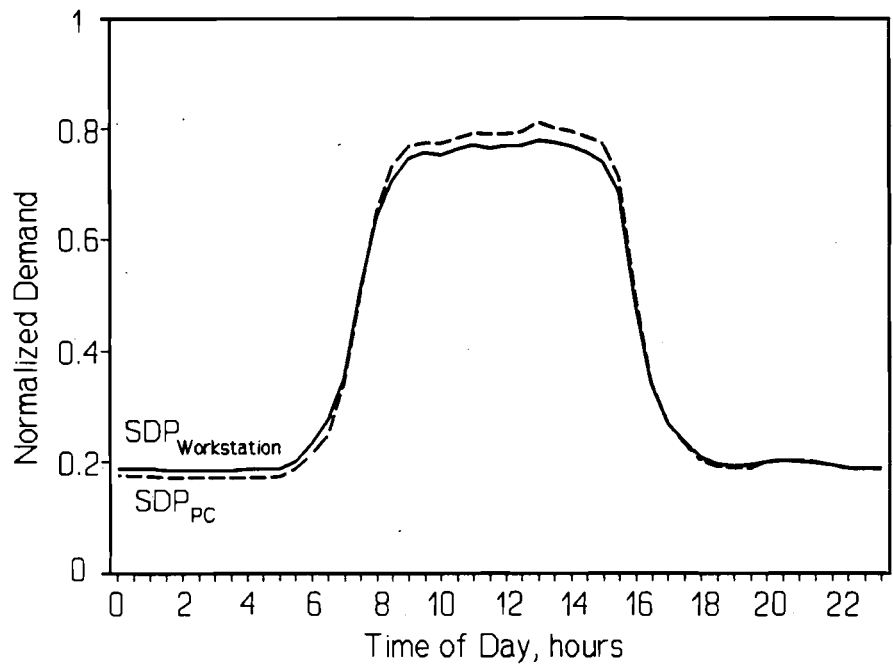


Figure 5.7. Workstation and PC Standard Demand Profiles

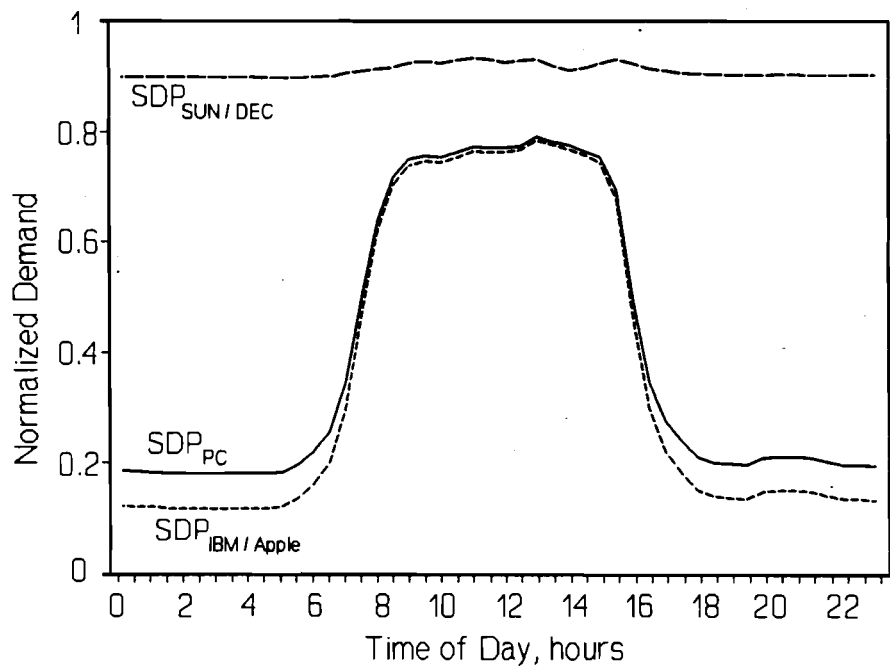


Figure 5.8. IBM/Apple and SUN/DEC Standard Demand Profiles

resources (with distributed computing and data storage) and cannot be easily turned off during non-work-hours. The SUN and DEC workstations represent only 11% of the total workstations, but most are on continuously. The resulting SDP for IBM and Apple computers has a baseload that decreased from 0.175 to 0.117. This means that most of the IBM/Apple computer category is being turned off during nonwork-hours. The IBM/Apple SDP is very important because most energy conservation measures are targeted toward this category of computers and monitors, and the demand during nonwork-hours may be the majority of potential energy savings measures. We used this profile in to calculate energy savings from three energy conservation scenarios (described in Section 9).

5.6 Methods for Estimating Workstation Demand Profiles

The *standard* demand profile (SDP) or the simplified hat profile are the best estimators of a BDP in the absence of any specific information about the building's PC workstation operation. However, the SDP is a less accurate estimator of individual BDPs than it is for the average of a group of buildings. The error in energy consumption between the SDP and individual BDPs for the five buildings ranged between -20.0% and 14.3% ($\mu = -3.4\%$, $\sigma = 12.5\%$). Errors for the hat profile were similar. All the error results are listed in Table 5.9. Graphic comparisons of the individual BDPs and SDP for each of the five monitored buildings are presented in Appendix D.

Table 5.9. Errors for Workday Workstation Demand Profile Estimation Techniques

	SDP	"Hat"	SDP' _{Measured}	SDP' _{CPU}	SDP' _{PC}
Stevens	-10.3	-11.4	-3.9	13.2	1.8
Federal	14.3	12.9	1.1	-1.3	-5.6
TCPC	-20.0	-21.0	1.6	-10.2	-7.7
Sigma I	-8.8	-10.0	2.6	8.4	-1.3
OSB	7.6	6.3	1.0	-9.5	-1.8
Average	-3.4	-4.7	0.5	0.1	-2.4
Standard Deviation	12.5	12.4	2.3	9.4	3.8

The accuracy of the SDP for individual buildings can be improved by adjusting the SDP to reflect base and peak load fractions unique to each building. The adjusted SDP (called SDP') is calculated as

$$SDP'_i = \left(\frac{SDP_i}{SDP_{Peak}} + \left(\frac{BDP_{Base} - SDP_{Base}}{BDP_{Peak} - SDP_{Peak}} \right) \left(\frac{1 - \frac{SDP_i}{SDP_{Peak}}}{1 - \frac{SDP_{Base}}{SDP_{Peak}}} \right) \right) BDP_{Peak} \quad (5.4)$$

or, after inserting the workday SDP's base (0.180) and peak (0.760) load fraction values,

$$SDP'_i = \left(\frac{SDP_i}{0.760} + \left(\frac{BDP_{Base} - 0.237}{BDP_{Peak} - 0.763} \right) \left(\frac{1 - \frac{SDP_i}{0.760}}{0.763} \right) \right) BDP_{Peak} \quad (5.5)$$

where

- SDP'_i = adjusted building demand profile value at time i
- BDP_{base} = building demand profile baseload fraction
- BDP_{peak} = building demand profile peak load fraction
- SDP_i = standard demand profile value at time i
- SDP_{base} = standard demand profile baseload fraction
- SDP_{peak} = standard demand profile peak load fraction.

Three methods of estimating the unique base and peak load fractions were evaluated. The most accurate uses measured values determined through a field monitoring process similar to that used in this study. The error in energy consumption between the $SDP'_{Measured}$ (adjusted SDP based on measured BDP profiles) and the SDP ranged between -3.9% and 2.6% ($\mu = 0.5\%$, $\sigma = 2.3\%$). The $SDP'_{Measured}$ values are very good BDP estimates. However, most users of the SDP would find such field studies prohibitively expensive and time-consuming.

The second and third methods of estimating the unique base and peak load fractions are relatively simple alternatives based on equipment fraction on-time (FOT). The first of these is based on the computer (CPU only), called FOT_{CPU} . The inherent assumptions are that 1) the equipment's electric demand is either full on or zero, with no standby operation that has a reduced power demand (except for printers with usage-dependent electric demand), and 2) the monitor and peripheral equipment are on whenever the computer is on (except printers connected to a network and left on 24 h/day, and monitors routinely turned off by the user).

The FOT_{CPU} is an inexpensive estimator of base and peak load fractions because it can be calculated from walk-through audits that simply count the on/off status of computers at various hours during the day. This could be limited to two walk-through audits: one at midday, to determine peak FOT_{CPU} , and another very early in the morning (before the staff normally starts work), to determine base FOT_{CPU} . This survey can also be used to determine the maximum load, which is necessary to estimate the actual building demand, by recording workstation nameplate ratings, models, and/or quantity installed, as discussed in Sections 5.1 and 5.2.

The FOT_{CPU} values were calculated using the existing electric demand profile data instead of conducting walk-through audits. The FOT_{CPU} was calculated as the computer's 30-min TSR divided by the maximum TSR for that computer during the monitoring period, as shown in Equation (5.6):

$$FOT_{CPU}^i = \frac{TSR_{CPU}^i}{TSR_{CPU, Max}} \quad (5.6)$$

The maximum TSR represents the average electric demand when the computer was on 100% of the time, which has an associated FOT_{CPU} of 1.0. This calculation procedure produces a 24-h FOT_{CPU} profile equivalent to conducting walk-through audits every 30 min for one week. Figure 5.9 shows the FOT_{CPU} profiles for the five monitored buildings.

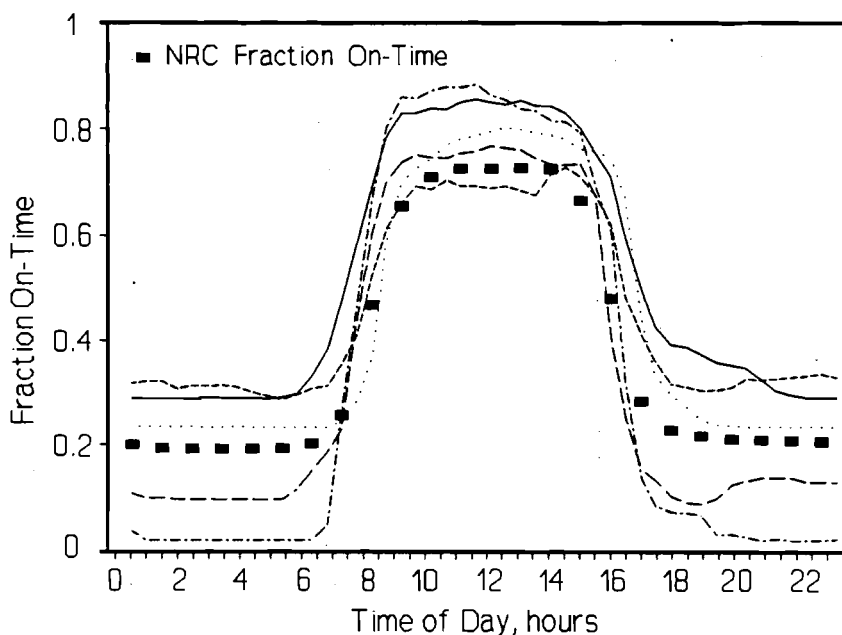


Figure 5.9. Workday Computer Fraction On-Time Profile for Test Buildings

The NRC study used a similar approach by recording minutes of on-time for IBM and Macintosh computers using a terminate-and-stay-resident software program. Because individual components of a workstation were not monitored, the monitor and peripheral equipment were assumed to be on whenever the computer was on. Other PC workstations, such as SUN or DEC systems, and network printers were not included in the NRC study. For comparison, the FOT_{NRC} profile is included in Figure 5.9. The energy consumption for the FOT_{NRC} profile is 1.9% lower than for the SDP.

A comparison of the SDP'_{CPU} (adjusted SDP based on FOT_{CPU} profiles) and individual BDPs revealed an unexpected result. The error in energy consumption between the SDP'_{CPU} and the individual BDPs ranged between -10.2% and 13.2% ($\mu = 0.1\%$, $\sigma = 9.4\%$). The small average error, but large standard deviation, indicate that SDP'_{CPU} is a less accurate estimator of individual building BDPs than it is for the average of a group of buildings. Figure 5.10 shows a comparison of the SDP'_{CPU} , SDP, and FOT_{NRC} , along with a shaded area that represents a 95% confidence interval ($\pm 2\sigma$) for SDP'_{CPU} . The reason for the errors seems to be that a large number of the workstation equipment devices, such as the computer monitors, were operated independent of the computer on/off status. Even with the new generation of computer equipment, many users are comfortable with frequent on/off cycles of their computer monitors but are unwilling to cycle the computer as frequently, fearing possible equipment failure and data loss.

The FOT_{CPU} can therefore be improved by using the personal computer (i.e., CPU and monitor) as two separate devices instead of the computer only. The FOT_{PC} is calculated as a simple average (equal weighting) of the fraction on-times calculated separately for the computer (CPU) and the monitor. The FOT_{PC} is expected to be a good estimator of base and peak load fraction because 1) it automatically accounts for monitors that are operated independent of the computer and 2) the PC demand dominates the total workstation demand, as shown in Appendix D. Determining the FOT_{PC} using a walk-through audit is similar to determining the FOT_{CPU} , except that the monitor on/off status must also be recorded.

The error in energy consumption between the SDP'_{PC} (adjusted SDP based on FOT_{PC} profiles) and individual BDPs ranged between -7.7% and 1.8% ($\mu = -2.4\%$, $\sigma = 3.8\%$). This is a significant improvement over SDP'_{CPU} . The SDP'_{PC} has an average that shows a small increase in underestimation bias and a standard deviation that is two-thirds smaller. In fact, the accuracy of the SDP'_{PC} approaches that of the much more difficult to calculate $SDP'_{Measured}$. Figure 5.11 shows a comparison of the SDP'_{PC} and SDP, along with a shaded area that represents a 95% confidence interval ($\pm 2\sigma$) for SDP'_{PC} . Graphic comparisons of the individual BDPs and SDP'_{PC} for each of the monitored buildings is presented in Appendix E.

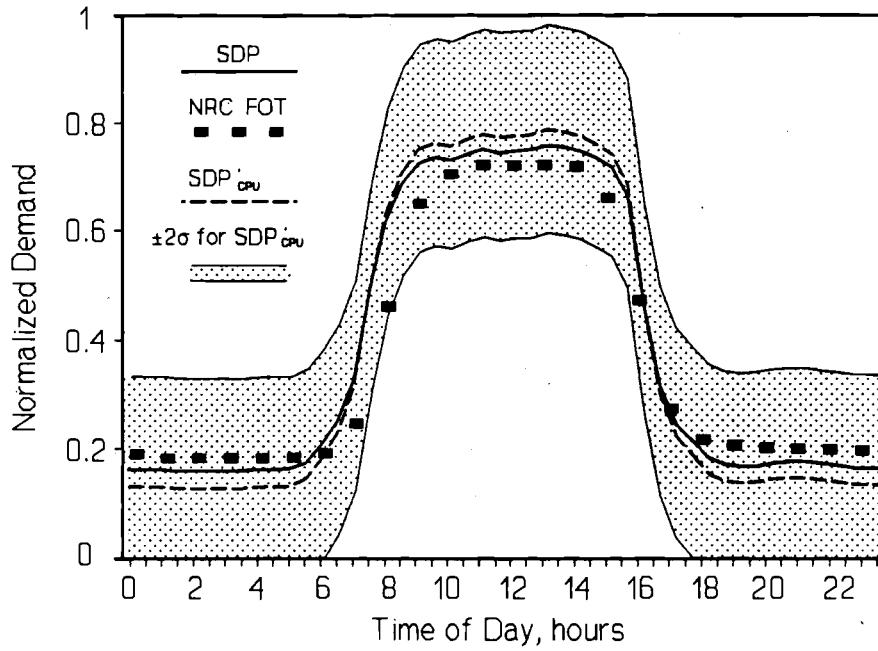


Figure 5.10. Workday Computer Fraction On-Time Profile for a *Standard Building*

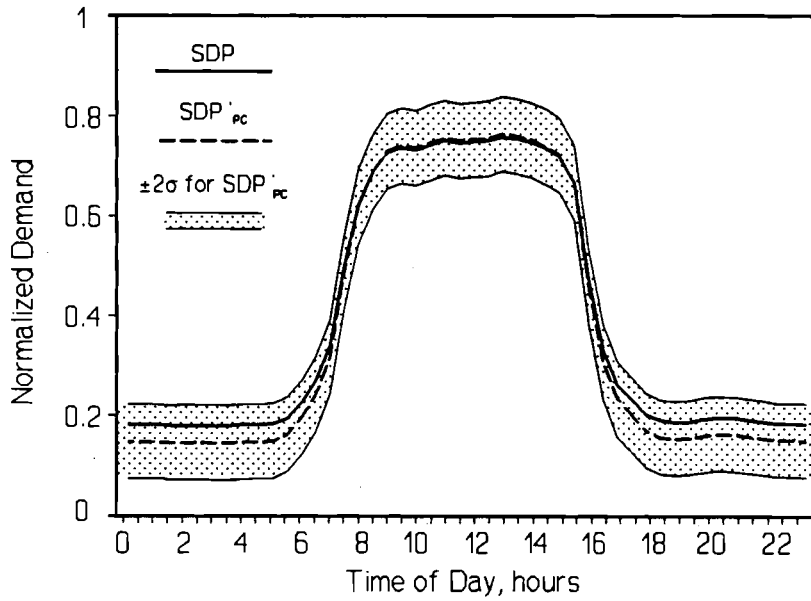


Figure 5.11. Workday PC Fraction On-Time Profile for *Standard Building*

The SDP'_{PC} continues to be a less accurate estimator of individual building BDPs than it is for the average of a group of buildings. The reasons for the errors are twofold. First, the equal weighting of the computer and monitor in calculating the FOT_{PC} does not reflect the different electric demand for the two devices. Second, it is clear that a significant fraction of the workstation equipment was operated independent of the PC on/off status.

5.7 Summary Demand Profile for All Office Automation Equipment

The maximum measured demand and energy use intensity (EUI) were calculated for each of the five metered buildings. These demand and EUI values are the measured demand profiles (discussed in the next section) extrapolated to the total number and type of workstations installed in the building (based on the survey information). The demand and EUI values are listed in Table 5.10. At 0.86 W/ft², the highest workstation demand is almost three times larger than the 0.3 W/ft² measured by the NRC (Tiller and Newsham 1993) but much lower than the 5- to 10-W/ft² plug load that has been calculated based on nameplate rating values (Whiddon & Associates, Inc. 1990). Considering that the total plug loads will include both workstations and some additional equipment, and that the plug load should be capable of handling all workstation equipment being turned on at the same time, the plug load values of 2 to 3 W/ft² suggested by Shepard et al. (1990) are reasonable. The *standard* maximum demand calculated from our data was 0.58 W/ft².

Table 5.10. Workstation Power Density and Energy Use Intensity

Building	Power Density, W/ft ²	EUI, kWh/ft ²
Federal	0.59	1.94
TCPC	0.41	2.02
Stevens	0.50	2.42
OSB	0.86	2.65
Sigma I	0.74	3.41
Sigma IV	(a)	(a)
Average	0.62	2.49
Standard Deviation	0.16	0.53
<i>Standard Office Building</i>	0.58	2.18

(a) No metered data for Sigma IV building. Surveyed information only.

The workstation EUIs for our sample of buildings range from 1.94 to 3.41 kWh/ft²-yr. The EUIs are based on the building's total area instead of just office space. This is very close to previous estimates of total energy use by office equipment in office buildings that ranged between 1.0 and 3.5 kWh/ft²-yr for 1983 (Piette et al. 1991). Piette's EUI estimate included mainframe and minicomputer energy use—computers that we excluded from this study. The *standard* EUI calculated from our data was 2.18 kWh/ft²-yr.

All the measured data for all the monitored equipment was combined into a demand profile composed of six equipment types—CPUs, monitors, PC printers, copiers, facsimile machines, and other plug loads (e.g., peripheral workstation equipment, task lights, coffee pots, radios). Two time periods of interest were examined: the peak load hours of 8 a.m. to 4 p.m. during workdays and baseload hours of 8 p.m. to 5 a.m. on workdays and nonworkdays. Figure 5.12 shows the baseload and peak load demand by equipment type.

The baseload and peak load demand is divided into segments as shown by the stacked bar graph. Each segment represents the proportion of the total electric demand caused by each equipment type. Second, the three largest segments are subdivided using pie charts to provide additional detail within each equipment type.

The detail provided in Figure 5.12 allows calculation of the demand reduction attributable to a proposed energy efficiency measure that is applied to a specific equipment type. For example, what would be the overall impact of a 40% reduction in IBM compatible computer demand due to purchase of Energy Star computers? The work-hours stacked bar graph shows that 45% of the demand is attributable to computers. The pie chart to the right shows that IBM compatibles comprise 76% of the personal computer demand. Therefore, IBM-compatible computers account for 34.5% of the total work-hours demand (calculated as $76\% * 45\% = 34.5\%$). As a result, the demand reduction potential with Energy Star computers would be 40% of 34.5%, or 13.8% of overall work-hours demand.

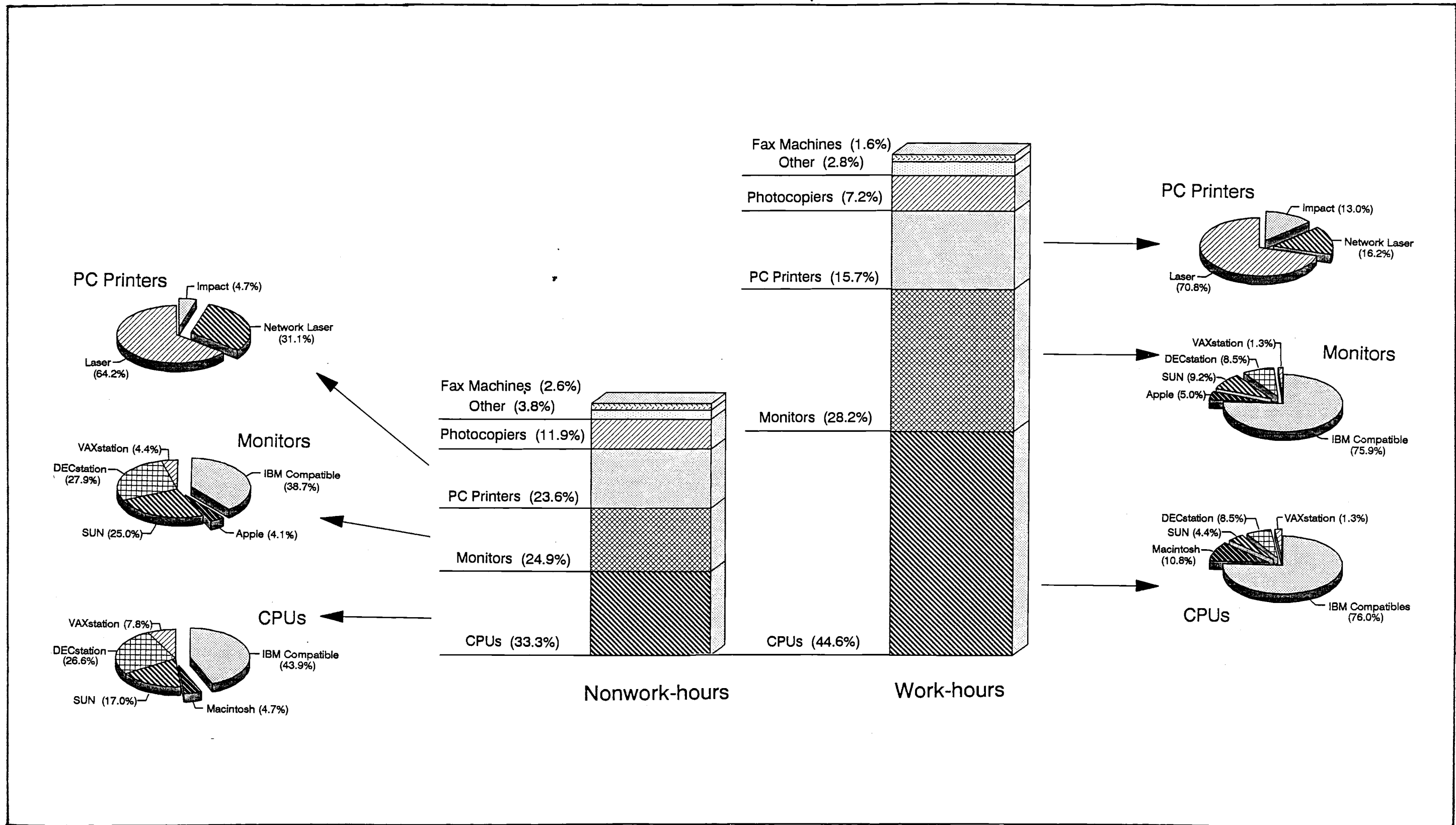


Figure 5.12. Work-Hours and Nonwork-Hours Demand by Equipment Type

6.0 PC Monitor Power Controller Evaluation

The best way to conserve energy is to turn off devices that are not being used. While screen savers blank the screen to save the triphosphors, they leave the monitor's internal elements warm and consuming the same amount of power as when lit. Automatic power controllers operate differently, sensing keyboard activity and turning off the power to the monitor when no activity has been detected after a set period of time. Pressing any key will re-power the monitor, returning the display to exactly where the user left off. Open software applications are not affected by the monitor power cycle.

The PC users in this limited evaluation found the 10- to 20-s warmup time necessary to re-power the monitor acceptable, so long as the time-out period was long enough to prevent frequent interference during normal operation. Time-out periods of 20 to 30 min seemed appropriate. Issues about controller set points, user acceptance, and potential penetration of such monitor controller devices were not investigated.

PNL obtained two Swedish devices with which to evaluate the monitor power controller concept. The Monitoff™ monitored keyboard activity only and had a time-out period adjustable from 30 s to 1 h. The SDK-1000 model sensed both keyboard and mouse activity and was factory set for a 20-min time-out period. Application of the Monitoff was limited to PC workstations that did not use a mouse. Because both monitor power controllers were used, the Monitoff was set to match the SDK-1000 preset 20-min time-out.

Monitor power controllers were installed and measured on 11 workstations for at least one week each. The energy savings were calculated by estimating a demand profile for the same monitor during the same time with no power controller. This was accomplished by using computer (CPU) on-time as an indicator of when the monitor would have been on without the power controller. The difference between the two demand profiles indicated the consumption and demand savings.

Figure 6.1 shows that the monitor power consumption was reduced 25% to 51%. Figure 6.2 shows the average normalized demand profile for the 11 monitors with power controllers. The average energy consumption reduction was 34%. The average peak demand reduction was 21%. Depending on demand charges in the electric utility rate structure, a cost savings associated with the demand reduction may be comparable to the reduced consumption.

Note that the results are dependent on the specific sample of PCs selected. Larger energy savings will result from selection of low-usage but high on-time PCs. This includes PCs that are left

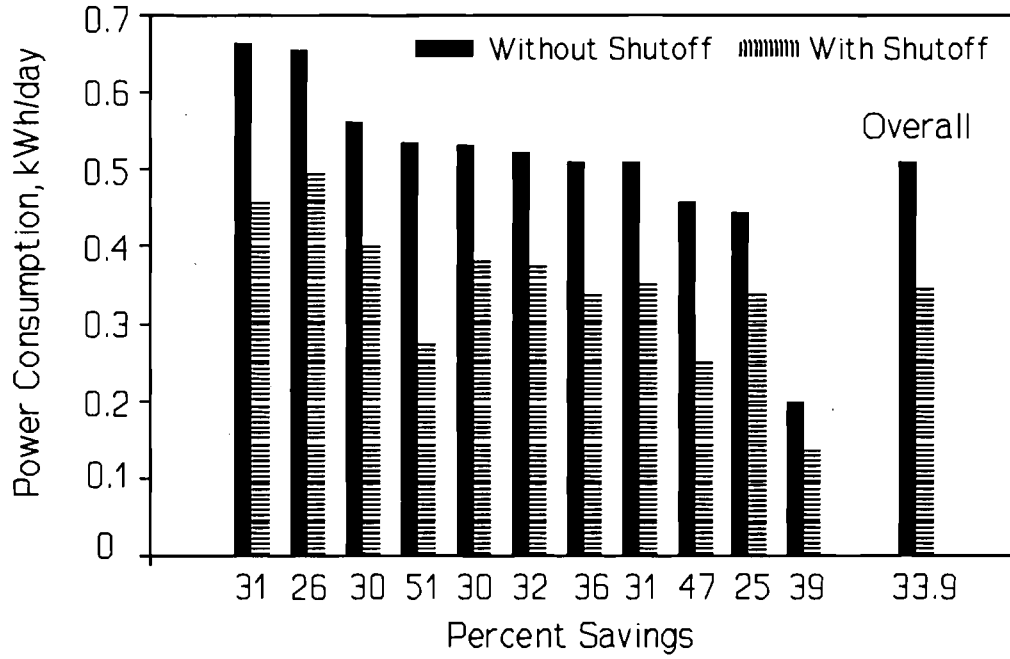


Figure 6.1. Energy Savings with Monitor Controller

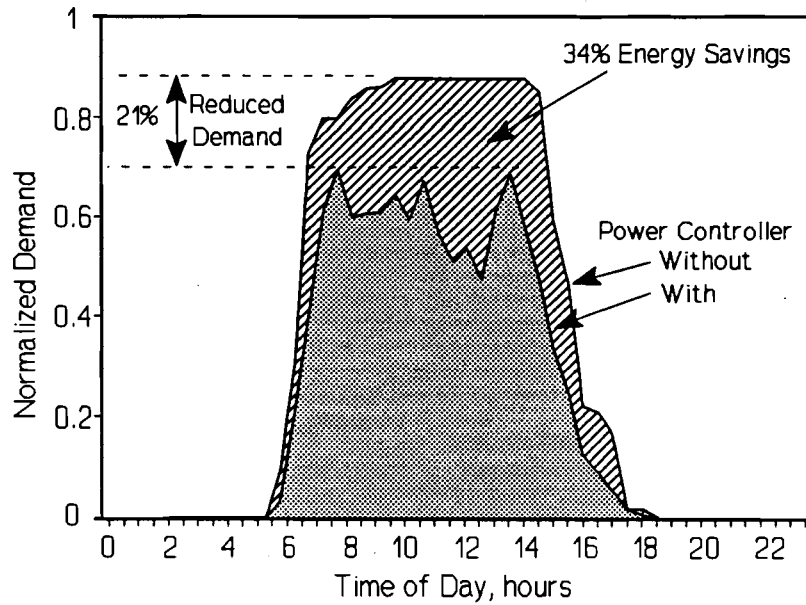


Figure 6.2. Workday Energy and Demand Savings with Monitor Controller

on overnight on workdays and continuously on nonworkdays. The sample selected was expected to demonstrate a very conservative energy savings because it did not include computers that were normally left on at night on workdays and continuously on nonworkdays. All the energy savings was therefore limited to inactivity periods during work-hours.

Extrapolation of this power controller test to the PC population is shown in Figure 6.3. The "without power controller" demand profile from Figure 6.2 was modified to include an 18% baseload. The 18% baseload represents the average number of PCs left on during nonwork-hours, as defined by the SDP. The workdays energy savings increased from 34% to 48%, and the addition of nonworkday energy savings results in an annual energy savings of 57%. This represents the power controller energy savings potential for the PC population. Although some of the computers that are left on overnight and on nonworkdays are operating and may not be turned off, almost all of the monitors are candidates for automatic power controllers. An application of power controllers, estimates of demand and consumption savings, and an economic analysis are described in Section 9.

In the short time since our data was collected, these devices have advanced significantly. The most sophisticated device, known as SmartBar™, is controlled by software configured by the user. This provides greater potential for energy savings because not only the monitor but other PC workstation equipment, including the computer itself, can be controlled by the SmartBar. Automatic power control of computers is acceptable to users only if the power controller includes software that

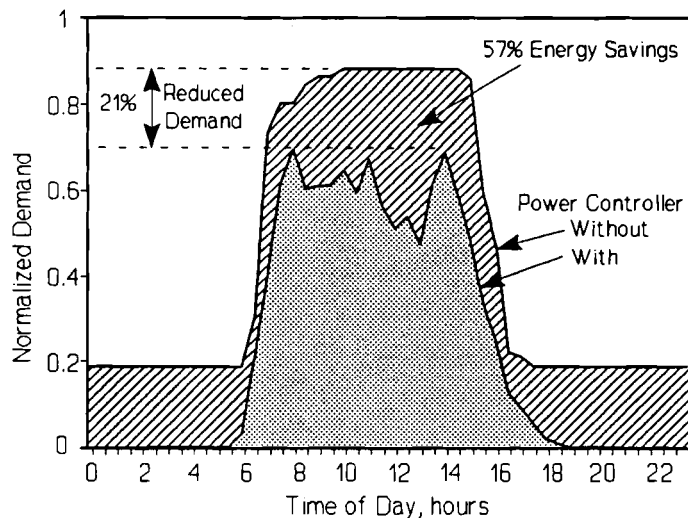


Figure 6.3. Monitor Controller Savings Extrapolated to the General Population of PCs

allows the automatic saving and retrieval of all open applications. The manufacturer claims to have such software for both IBM compatible computers, while running either MS-DOS® or Windows™ applications, and Apple computers.

In the NRC study, Tiller and Newsham (1993) used an NRC-developed SmartBar to control power to both the computer (16 sites) and monitor (9 sites). The SmartBar was programmed to turn off the monitor after 15 min of keyboard/mouse inactivity, and the computer after 60 min of keyboard/mouse inactivity. The NRC results showed an 82% reduction in monitor on-time. This high savings value was dominated by three PCs in the sample of nine that were on almost continuously, but were used very little. This may not be representative of the PC population. The NRC study methodology was not capable of determining demand reduction for the monitor. The NRC results for installation of a power controller on the computer showed a 63% decrease in consumption and 35% reduction in demand. A larger sample size (16) may make this a more representative result. The NRC results for computer energy savings compare very well with this study's projected 57% and 21% savings in consumption and demand.

7.0 Photocopiers

By combining data from all 13 of the monitored photocopiers from our buildings sample, we constructed a workday 24-h demand profile for photocopiers. Although most newer copiers boast nighttime energy savings modes, the monitored copiers showed very little night savings. The average electric demand for the 13 copiers was 154 W during nonwork-hours and 225 W during work-hours (see Figure 7.1).

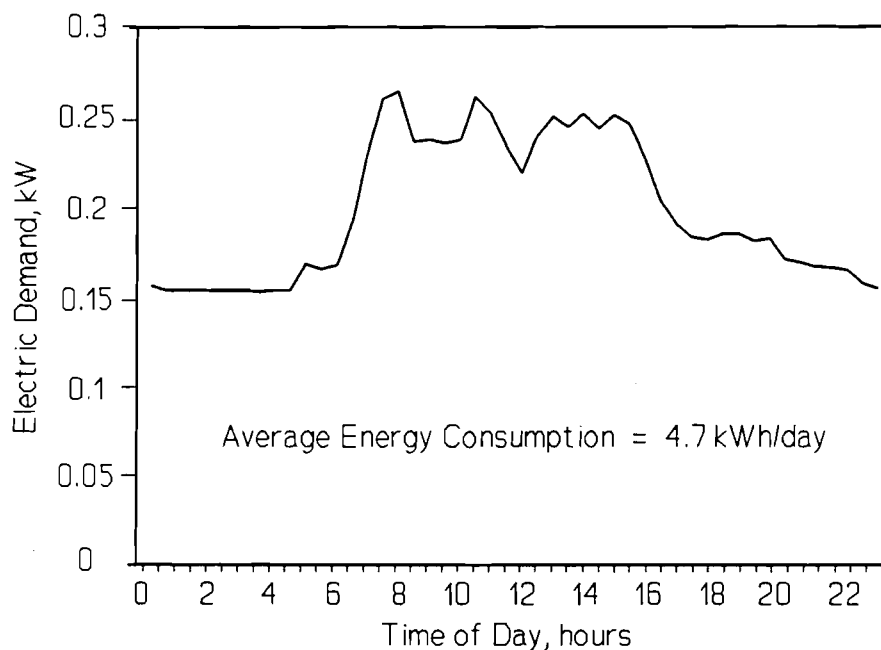


Figure 7.1. Workday Demand Profile for Photocopiers

The 13 monitored copiers were of three types: high power (2 copiers), normal power (7 copiers), and power-saver (4 copiers). The average power consumption for each group is 9.4 kWh/day, 4.1 kWh/day, and 3.4 kWh/day, respectively (see Figure 7.2).

Although there is an American Society for Testing and Materials (ASTM) standard method for measuring the energy use of copiers with several modes (e.g., warmup, standby, copying)(ASTM 1982), the measurements we made were simply the actual operating demand. These measurements are meant to illustrate actual operating conditions in the field instead of ideal conditions typical of a

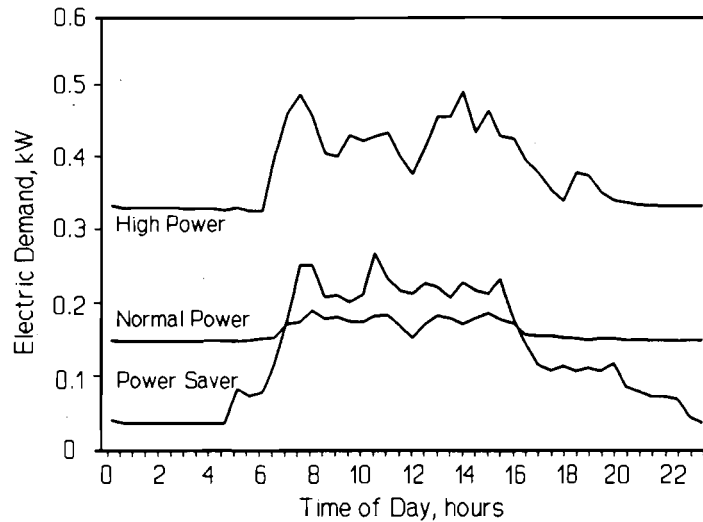


Figure 7.2. Workday Demand Profile for Three Groups of Photocopiers

laboratory-based test. The scope of the photocopier monitoring did not allow investigations of energy demand as a function of usage (based on pages per day) or photocopier speed.

Figure 7.3 shows two identical Mita DC-328 copiers in two different buildings. The first copier uses a built-in power-saver mode that reduced the demand to 18 W for 40% of the time; the second copier runs at 178 W full power 24 h/day. While the second copier included a built-in power-saver feature, it was not being used, as was the case for most of the monitored copiers. Only 4 of the 11 photocopier profiles showed a power-saving mode. The daytime (7:00 a.m. to 5:00 p.m.) demand for the second copier averaged 177 W versus 220 W for the first copier, which indicates a high usage for the second copier. From 5:00 p.m. until 9:00 p.m., both copiers operated at full power at nearly identical demand, indicating low usage for both copiers. The fact that our average copier profile, as shown in Figure 7.1, shows very little nighttime energy savings indicates that copiers utilizing power-saver controls are a small subset of the total copier sample.

To demonstrate potential savings, we compared three copier operating scenarios. The first copier operated at full power 24 h/day, seven days a week (168 h/wk at 177 W). The second copier operated at full power from 8 a.m. to 6 p.m. but entered a power-saver mode (98 h/wk at 18 W) at other times. The power-saver mode was a warm standby that requires less than 5 min delay for full operation. The third copier used a power saver similar to that of the second copier (30 h/wk at 18 W), but with the addition of an intelligent timer that shut off the unit completely from 10 p.m. to 6 a.m. on workdays and all day on nonworkdays (68 h/wk at 0 W). Regular operation at full power

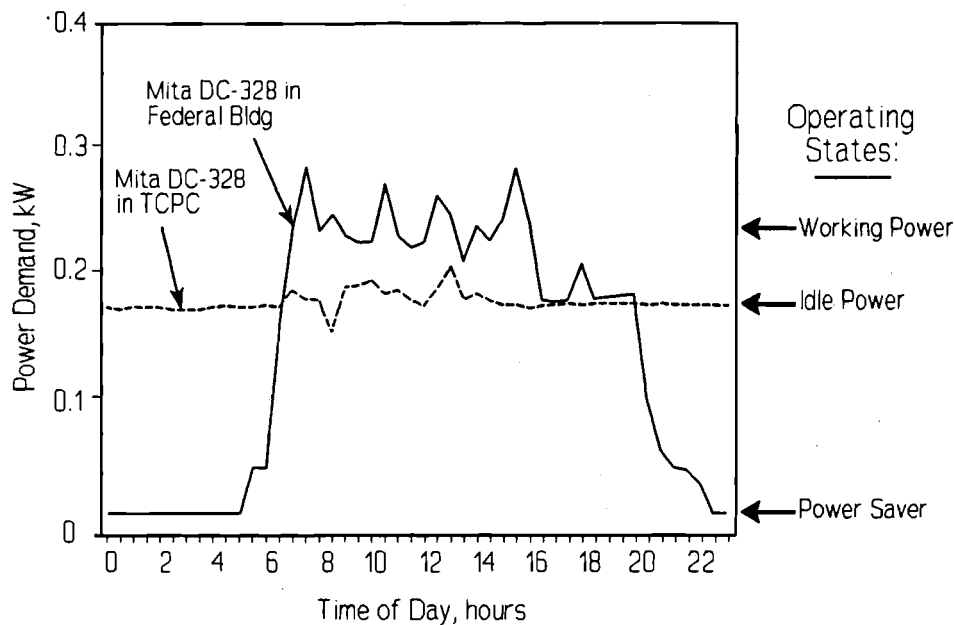


Figure 7.3. Comparison of Photocopier Demand Profiles for Different Operating Modes

consumes approximately 1,546 kWh/yr. Enabling the power saver reduces consumption to 736 kWh/yr, a savings of 52.4%. Enabling the power saver and turning the copier off during nonwork-hours consumes 672 kWh/yr, a savings of 56.5% over full-power operation (see Table 7.1).

Development of an adaptive power saver that learns from previous usage patterns and modifies the sleep mode times would potentially optimize energy savings while maximizing user acceptance. The proposed controller would respond to learned usage patterns instead of preset times. Such an adaptive controller could be used on a variety of other equipment, including PC workstation equipment and lights.

Table 7.1. Photocopier Potential Power Savings

	Normal Power	Power Saver	Smart Timer
Operating Scenario:			
Full Power, 177 W	168 h/wk: 24 hours per day, 7 days a week	70 h/wk: (8 a.m. - 6 p.m.) 7 days a week	70 h/wk: (8 a.m. - 6 p.m.) during work days
Warm Standby, 18 W		98 h/wk: (6 p.m. - 8 a.m.) power-saver mode 7 days a week	30 h/wk: (6-8 a.m. & 6-10 p.m.) power-saver mode during work days
Power Off, 0 W			68 h/wk: (10 p.m. - 6 a.m.) during weekdays and all day during weekend and holidays
Power Consumption	1546 kWh/yr	736 kWh/yr	672 kWh/yr
Percent Savings	0% (Base Case)	52.4%	56.5%

8.0 Application of the *Standard Demands and Profiles*

Equally as important as understanding the workstation electric demand in our sample buildings is applying what was learned to other buildings. The *standard* demand profile can be used to approximate a building demand profile for most office buildings, and it can be customized based on the detail of information available. Because of the wide variation in our sample buildings, the SDP will typically apply to any building in the general population.

8.1 Estimating a Building Demand Profile

Surveys were conducted to determine the number and types of workstations found in six different office buildings. The size of the buildings varied from 20,440 to 203,375 ft². Table 8.1 shows the distribution of workstations for the smallest and largest office buildings. These two buildings will be used to illustrate how the results presented in Section 5 may be applied to other buildings. A listing of workstations identified in all the sample buildings is presented in Table B.1.

Table 8.1. Survey of Workstation Populations in Two Buildings

Type of Workstation	Average Electric Demand, W	Sigma I Building Workstations (20,440 ft ²)	Federal Building Workstations (203,375 ft ²)
Class I ^(a)	33.6 ^(b)	14	20
Class II	138.7	100	869
Class III	201.1	7	27
Class IV	289.2	0	0
<i>Standard Workstation</i>	144.0		
Total Number of Workstations		121	916

^(a) Refer to Table 5.2 for a definition of workstation classes.

^(b) Average Electric Demand taken from Table 5.4.

As an example, let us assume that the owner of the small office building wants to estimate the contribution of the workstations to the total peak electric demand of the building. If the owner has the survey information contained in Table 8.1, then it is a simple matter to combine this with the data presented in Table 5.4. The actual procedure is captured in Equation (8.1):

$$LOAD = \sum_{i=1}^IV N_i * P_i \quad (8.1)$$

where N_i = the number of workstations in load class i
 P_i = the average load of workstations in load class i .

Summing the predicted power consumption in each load class results in a total workstation consumption of 15.7 kW for the smaller Sigma I building. If the owner had not known the composition of workstations in the building (i.e., what classes of workstations would be present), but had information only on the total number, the demand value given for the *standard* workstation could have been used. By doing so, the total workstation demand is estimated to be 17.4 kW. The actual monitored workstation demand is 15.1 kW, which means our estimates are within 4.0% and 15.2%, respectively. Again, the closeness of these two estimates can be directly attributed to the fact that Class II workstations are the most prevalent in most buildings.

As a second example, let us assume that the building manager of the large office building wants to estimate the daily demand profile of the workstations in his building. This is possible using the standard demand profile (SDP) and several observed attributes of the building in question. Using Equation (8.1), the workstation demand would be estimated to be 126.6 kW. Because of a recent energy awareness campaign, the building manager believes that the occupants of this building do much better than average at shutting off their systems at night. Only about 15% of the workstations are not turned off--compared to the *standard* profile, which shows that 18% are left on at night (see Figure 5.4). The building manager verifies this by a walk-through audit of the building, to quantify the percentage of workstations left on at night. Likewise, a walk-through audit of the building during the day indicates that 80% of the workstations are on at any one time. As previously mentioned, fraction on-time is not precisely equal to electric demand but, for approximation purposes, can be assumed equal.

The procedure he would follow is similar to that in the first example, except that the building demand profile is approximated using the FOT_{pc} data to adjust the *standard* demand profile to reflect the peak load and baseload fractions unique to this building. This new profile is called the SDP'_{pc} . The new profile has $Bldg_{base} = 0.15$, $Bldg_{peak} = 0.80$, and estimated Peak Load = 126.6 kW [from Equation (8.1)] as shown in Figure 8.1. Each 30-min value in the SDP'_{pc} is determined using Equation (5.4) and the SDP values given in Table 5.8. In this case, the error between the SDP'_{pc} and

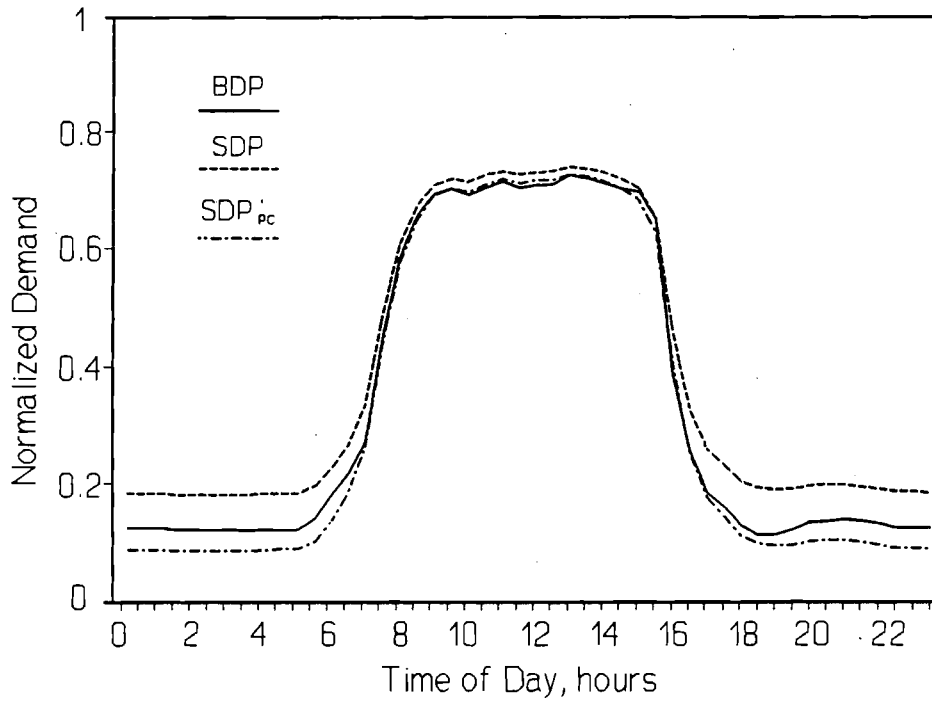


Figure 8.1. Workday Demand Profile for a Large Office Building

the actual monitored BDP is 3.5%. This is a better approximation than using the original *standard* demand profile. The error between the *standard* demand profile and the actual monitored profile is 11.5%.



9.0 Energy Savings Potential at the Hanford Site

Although the proliferation of personal computer workstations and other office automation equipment has increased the demand for energy in office buildings, it also represents an area of potential energy savings through increased conservation and energy efficiency measures. The energy savings and life-cycle costs economic analysis for 27 scenarios were evaluated. These scenarios included three energy conservation measures (ECMs), three electric utility rate structures, and three electric demand profiles.

The ECMs evaluated were

- Implement an energy awareness program to educate PC workstation users to turn off PCs when not in use.
- Retrofit existing monitors and computers with automatic power controllers.
- Purchase energy-efficient PCs as replacements on failure or obsolescence.

The electric utility rate structures used were

- the City of Richland Electric Utility, Richland, Washington
- Westinghouse Hanford Electric Utility, Richland, Washington
- a typical U.S. electric utility rate structure.

The PC electric demand profiles were

- the $SDP_{IBM/Apple}$ presented in Section 5.5
- the $SDP-2_{IBM/Apple}$, a high energy-consumption demand profile that has a workday baseload equal to the peak load for the $SDP_{IBM/Apple}$ (i.e., PCs normally on and not used during workday nonwork-hours [nighttime] and off during nonworkdays)
- the $SDP-3_{IBM/Apple}$, the highest energy-consumption demand profile that has both workday baseload and nonworkday demand equal to the peak load for the $SDP_{IBM/Apple}$ (i.e., PCs normally on and not used during both workday nonwork-hours [nighttime] and nonworkdays).

The implementation costs and assumptions for each of the three ECMs are detailed in Sections 9.1 through 9.3. The following basic assumptions were used for each ECM.

The energy savings estimates are for IBM- and Apple-compatible PCs only. Other computers (i.e., SUN and DEC workstations) were not included because they are typically distributed system resources and cannot be easily removed from their LAN. The energy savings estimates also exclude the potential savings for peripheral equipment. Laser printers, which are 12% of the total PC workstation demand and 71% of the peripheral equipment demand, should be considered in future energy awareness and retrofit power controller programs. Although the power for laser printers can be controlled by retrofit power controllers, many of the laser printers are connected through a LAN and cannot be easily removed.

The cost-effectiveness of these energy savings measures is dependent on the local cost of energy. Electric rates at the Hanford Site are based on two sources. The City of Richland electric utility rate structure has demand charges of \$4.64/kW on-peak (daytime) and \$1.04/kW off-peak (night and weekend), and a consumption charge of \$0.02/kWh. Westinghouse Hanford Company has a direct Bonneville Power Administration contract for \$0.055/kWh, with no direct demand charges. These electric rates are very low and not representative of most other areas of the United States. For comparison, the economic analysis includes a typical U.S. electric rate structure of \$10/kW on-peak demand and \$0.10/kWh consumption.

According to provisions of 10 CFR 436, federal agencies are required to analyze all potential energy investments using a life-cycle costing (LCC) methodology developed by the National Institute of Standards and Technology (NIST) (National Bureau of Standards 1987). The NIST LCC methodology proceeds by calculating all relevant costs of a project and discounting them to result in present dollars, then subtracting that sum from a similarly constructed LCC of a "no-action" baseline. This difference is called the net present value (NPV) of the action being considered. Actions are recommended for implementation if the NPV is positive and greater than the NPV of any competing actions. This methodology results in minimizing the LCC of energy services at a site. The NIST "Building Life-Cycle Cost" Program (Version 4.0) (Petersen 1993) was used to calculate all the LCC values.

The number of PC workstations for PNL (3,287), one of the contractors at the Hanford Site, was estimated based on a combination of an existing property control database that lists computers assigned to specific buildings and estimates based on PC workstations per staff. The number of PC workstations for the whole Hanford Site (9,239) was extrapolated from the PNL estimates by scaling the PNL staff to the non-craft services Hanford Site staff. The assumption was that craft services staff (e.g., carpenters, plumbers) do not typically have PCs.

9.1 Energy Awareness

Teaching energy conservation is the least expensive ECM, although possibly the most difficult in terms of effort required to produce the desired change over the long term. Studies have shown that while initial efforts at raising energy awareness are often successful, the modified behavior returns to its original patterns within a short time. The NRC study's energy awareness test (Tiller and Newsham 1993) experienced an average 14% energy savings over an 8-week period. The savings were higher at the start of the test period, but they had diminished to approximately zero at the end as users gradually returned to old PC usage habits. For an education program to work, the involved parties must work hard for an extended period to cause a permanent change in habits. To achieve and maintain a high participation rate (nearly 100%) at the Hanford Site (15,000 employees and 9,239 PCs), the energy awareness program was assumed to require a staff of two. The assumed program cost was \$15/PC/yr.

This ECM assumes that PC users will become actively involved in reducing the energy consumption of their PC workstations by turning off all computers and monitors when not in use. Based on the energy savings determined in our evaluation of PC monitor controllers (Section 6), the savings for monitors were assumed to be 21% demand and 57% consumption during workdays and 100% consumption and demand during nonworkdays. Users were not expected to turn off their computer (CPU) during work-hours because of the inconvenience of saving open software applications and rebooting the computer. There is 0% computer energy savings during work-hours. However, users were assumed to turn off computers during nonwork-hours.

9.2 Retrofit Power Controllers for Existing Equipment

The large inventory of existing PC workstation equipment can be made more energy-efficient through retrofit of power controllers. These power controllers sense keyboard/mouse activity and automatically turn off and on selected equipment. The latest power controllers will not only power off the monitor but also turn off the computer (CPU) and other workstation devices, all based on user-selectable parameters of inactivity time and device to be controlled. The power controller devices will realize a savings equal to the energy awareness campaign at 100% participation, plus the savings from turning off the computer during work-hours. Although other PC workstation devices could also be controlled by the power controller, this scenario assumes control of only IBM/Apple PC monitors and computers.

In large quantities, the retrofit power controllers can be purchased for \$50 to \$150 each. However, implementation of the retrofit power controllers must include purchase, distribution,

training, and repair services, which will add approximately \$25 per PC. The economic analysis assumed \$125 per PC, based on a device that can control both computer and monitor, large quantity purchase, and implementation at the Hanford Site. A \$5/yr operations and maintenance (O&M) cost was used to repair or replace a 5% power controller equipment failure rate.

The increased energy savings, compared to energy awareness program, results from computers that are turned off during work-hours when they were on but not in use. For this power control option to be accepted by users, the power controller must include software that allows automatic saving and retrieval of all open applications during computer shutdown and reboot. This is a critical component for successful implementation of this ECM.

9.3 Purchasing Energy-Efficient Equipment

Energy efficiency technologies, similar to those already available in laptop portable PCs, can be designed into new PC workstation equipment. The workstation equipment included in the EPA's new Energy Star program is required to have a low-power state that is at least an 80% reduction from normal idle power, or less than 30 W. The equipment will sense user inactivity and automatically initiate and recover from the low-power, or sleep, state. Built-in energy saving features should cost much less and should be seamlessly integrated into the personal computer operation, resulting in greater user participation than for the retrofit power controllers.

There are numerous new product announcements, but few actual Energy Star rated devices on the market, so firm data on the incremental cost of new energy-efficient PC equipment is unavailable. Because of pressure from large buyers (state and federal agencies) specifying energy-efficient PCs in new purchases and competing products, the incremental cost is expected to be small. The assumed incremental cost was \$100 per PC (computer and monitor). Until the energy-efficient PC technology becomes widespread, organizations that currently purchase low-cost clone PCs will have an incremental cost that includes switching to more expensive namebrand PCs. In this case, the incremental cost for energy-efficient PCs may be \$1000 or more.

Energy-efficient equipment continues to consume a reduced power demand during periods of inactivity. The energy and cost savings for energy-efficient equipment are less than for the retrofit power controllers because the power controllers turn power off to the equipment instead of just reducing demand. However, user acceptance of the energy-efficient equipment is expected to be much higher because the equipment will recover from the low-power state in 1 to 5 s instead of the 10 to 40 s needed to recover from a power-off state.

The replacement period for personal computer systems in an organization varies depending on purchasing patterns. In research facilities such as those at the Hanford Site, the entire stock of personal computer equipment becomes obsolete and is replaced in approximately 5 years. The implication is that if an organization commits to buying energy-efficient equipment, the maximum energy savings for the site will be realized in 5 years. However, the maximum savings for each new energy-efficient computer will be realized immediately.

9.4 Economic Analysis

The baseline or "no-action" demand and consumption is presented in Table 9.1. These baseline energy costs on the demand for a standard PC (see Figure 5.4), the three electric rate structures, and the three PC demand profiles. The implementation cost, energy and demand savings, cost savings, and NPV are summarized by electric rate structure in Tables 9.2 through 9.4. The LCC analysis is based on a 5-yr equipment life with no salvage value. Simple payback, which is not part of LCC analysis, is included for reference only. All the cost analysis results shown in Tables 9.1 through 9.4 are expressed in terms of cost per PC.

The LCC analysis recommends "no-action" for PCs that are operated according to the measured demand profile (SDP_{IBM/Apple}). The NPV is negative for all three ECMs and all three electric rates. At the assumed costs and measured demand profile for the Hanford Site, the lowest-cost energy conservation option is to do nothing. This is counter to popular opinion regarding the value of PC energy conservation.

In fact, the costs of the ECMs would have to be dramatically lower to be recommended. For Richland electric rates, the costs could not exceed \$3/PC/yr for the energy awareness program, \$20 capital and no annual O&M for the retrofit power controller, and \$15 incremental cost for the purchase of new energy-efficient PCs. Under Westinghouse electric rates, the costs could not exceed \$7, \$38, and \$31. And for the typical U.S. electric rates, the costs could not exceed \$13, \$80, and \$64. The low electric rates at the Hanford Site make ECMs for PCs unattractive at this time.

Selective application of the ECMs will optimize the investment. When high energy-consumption PCs are targeted (SDP-2_{IBM/Apple}), the energy awareness program for Westinghouse and all three ECMs for the typical U.S. electric rates are recommended actions. When targeting the highest energy-consumption PCs (SDP-3_{IBM/Apple}), all three ECMs for both Westinghouse and the typical U.S. electric rates are recommended actions. No ECMs are recommended for the low Richland electric rates under any PC demand profile.

Table 9.1. Baseline Energy Costs

Energy Savings Measure	Annual Energy Consumption (kWh)	Annual Electric Demand (W-mo)		Annual Energy Cost (1993 \$)	Annual Demand Charge (1993 \$)	Total Annual Energy Cost (1993 \$)
		Peak	Off-Peak			
Richland Electric Rates:						
	@ \$0.020/kWh	@ \$4.64/kW	@ \$1.04/kW			
SDP _{IBM/Apple} ^(a)	341	107	17	6.82	6.20	13.02
SDP-2 _{IBM/Apple} ^(b)	692	107	62	13.84	6.76	20.60
SDP-3 _{IBM/Apple} ^(c)	942	107	107	18.83	11.97	30.80
Westinghouse Electric Rates:						
	@ \$0.055/kWh	n/a	n/a			
SDP _{IBM/Apple}	341	n/a	n/a	18.76	n/a	18.76
SDP-2 _{IBM/Apple}	692	n/a	n/a	38.06	n/a	38.06
SDP-3 _{IBM/Apple}	942	n/a	n/a	51.81	n/a	51.81
Typical U.S. Electric Rates:						
	@ \$0.100/kWh	@ \$10/kW	n/a			
SDP _{IBM/Apple}	341	107	n/a	34.1	12.84	46.94
SDP-2 _{IBM/Apple}	692	107	n/a	69.2	12.84	82.04
SDP-3 _{IBM/Apple}	942	107	n/a	94.2	12.84	107.04

^(a) SDP_{IBM/Apple} is the standard demand profile for IBM/Apple PCs presented in Section 5.5.

^(b) SDP-2_{IBM/Apple} is a high energy-consumption demand profile that has a workday baseload equal to the peak load for the SDP_{IBM/Apple} (i.e., PCs normally on and not used during weekday nonwork-hours [nighttime] and nonworkdays [weekends and holidays]).

^(c) SDP-3_{IBM/Apple} is the highest energy-consumption demand profile. It has both workday baseload and nonworkday demand equal to the peak load for the SDP_{IBM/Apple} (i.e., PCs normally on and not used during both weekday nonwork-hours [nighttime] and nonworkdays [weekends and holidays]).

Table 9.2. Life-Cycle Cost Analysis for City of Richland Electric Rates

Energy Savings Measure	Installed Cost (1993 \$)	Annual O&M Cost (1993 \$)	Annual Energy Savings (kWh)	Annual Demand Savings (W-mo)		Annual Energy Savings (1993 \$)	Annual Demand Savings (1993 \$)	Simple Payback (years)	Net Present Value (1993 \$)
				Peak	Off-Peak				
SDP IBM/Appb :									
Energy Awareness ^(a)	0	15	60	2	15	1.19	0.30	10.1	-63
Power Controller	125	5	188	23	17	3.75	1.47	23.9	-129
Energy Star ^(b)	100	0	150	18	14	3.00	1.18	23.9	-85
SDP-2 IBM/Appb :									
Energy Awareness	0	15	291	2	52	5.82	0.75	2.3	-44
Power Controller	125	5	520	23	62	10.41	2.03	6.9	-101
Energy Star	100	0	416	18	50	8.33	1.63	10.1	-63
SDP-3 IBM/Appb :									
Energy Awareness	0	15	540	2	97	10.81	1.31	1.2	-24
Power Controller	125	5	770	23	107	15.40	2.60	10.0	-81
Energy Star	100	0	616	18	86	12.32	2.08	6.9	-43

^(a) Actual savings will be less because participation will be less than 100% and will normally decrease with time.

^(b) Actual savings will be greater because an 80% power reduction is the minimum required for the Energy Star Program.

Table 9.3. Life-Cycle Cost Analysis for Westinghouse Hanford Company Electric Rates

Energy Savings Measure	Installed Cost (1993 \$)	Annual O&M Cost (1993 \$)	Annual Energy Savings (kWh)	Annual Demand Savings (W-mo)		Annual Energy Savings (1993 \$)	Annual Demand Savings (1993 \$)	Simple Payback (years)	Net Present Value (1993 \$)
				Peak	Off-Peak				
SDP IBM/Apple :									
Energy Awareness ^(a)	0	15	60	n/a	n/a	3.28	n/a	4.6	-56
Power Controller	125	5	188	n/a	n/a	10.32	n/a	12.1	-109
Energy Star ^(b)	100	0	150	n/a	n/a	8.26	n/a	12.1	-69
SDP-2 IBM/Apple :									
Energy Awareness	0	15	291	n/a	n/a	15.99	n/a	0.9	-9
Power Controller	125	5	520	n/a	n/a	28.62	n/a	4.4	-42
Energy Star	100	0	416	n/a	n/a	22.90	n/a	4.4	-15
SDP-3 IBM/Apple :									
Energy Awareness	0	15	540	n/a	n/a	29.73	n/a	0.5	43 ★
Power Controller	125	5	770	n/a	n/a	42.35	n/a	3.0	10 ★
Energy Star	100	0	616	n/a	n/a	33.88	n/a	3.0	37 ★

^(a) Actual savings will be less because participation will be less than 100% and will normally decrease with time.

^(b) Actual savings will be greater because an 80% power reduction is the minimum required for the Energy Star Program.

★ Star indicates recommended ECM.

Table 9.4. Life-Cycle Cost Analysis for Typical U.S. Electric Rates

Energy Savings Measure	Installed Cost (1993 \$)	Annual O&M Cost (1993 \$)	Annual Energy Savings (kWh)	Annual Demand Savings (W-mo)		Annual Energy Savings (1993 \$)	Annual Demand Savings (1993 \$)	Simple Payback (years)	Net Present Value (1993 \$)
				Peak	Off-Peak				
SDP IBM/Apple :									
Energy Awareness ^(a)	0	15	60	2	n/a	5.97	0.22	2.4	-45
Power Controller	125	5	188	23	n/a	18.77	2.71	5.8	-68
Energy Star ^(b)	100	0	150	18	n/a	15.02	2.17	5.8	-36
SDP-2 IBM/Apple :									
Energy Awareness	0	15	291	2	n/a	29.08	0.22	0.5	40 *
Power Controller	125	5	520	23	n/a	52.04	2.71	2.3	55 *
Energy Star	100	0	416	18	n/a	41.63	2.17	2.3	63 *
SDP-3 IBM/Apple :									
Energy Awareness	0	15	540	2	n/a	54.05	0.22	0.3	133 *
Power Controller	125	5	770	23	n/a	77.00	2.71	1.6	148 *
Energy Star	100	0	616	18	n/a	61.60	2.17	3.0	156 *

^(a) Actual savings will be less because participation will be less than 100% and will normally decrease with time.

^(b) Actual savings will be greater because an 80% power reduction is the minimum required for the Energy Star Program.

★ Star indicates recommended ECM.

Selective application of the power controllers and energy-efficient PCs will require a low-cost method of identifying high energy-consumption PCs. For PCs connected to LANs, software could be developed that uses the LAN to identify and record PCs that are actively connected during nonwork-hours. A simple survey of user operation may identify high energy-consumption PCs not connected to a LAN.

PNL's potential savings resulting from an intensive energy awareness program are 229,620 kWh/yr and \$7,793/yr. For all the Hanford Site contractors, the potential annual savings are 554,340 kWh/yr and \$18,814/yr. The LCC analysis recommends this ECM for targeted high energy-use PCs operating under Westinghouse electric rates only.

The actual savings for the energy awareness program will be less than those just listed because these savings estimates are based on 100% participation, with actual participation dependent on the strength of the program. A less intensive, and perhaps more realistic, energy awareness program that advocates turning off only PCs that are on during nonwork-hours (SDP-3_{IBM/Apple}) will capture 44% of the maximum cost savings while targeting only 12% of the total number of PCs.

PNL's potential savings from an intensive implementation of retrofit power controllers are 719,476 kWh/yr and \$25,934/yr. For all the Hanford Site contractors, the potential annual savings are 1,736,932 kWh/yr and \$62,610/yr. The LCC analysis recommends this ECM for targeted high energy-use PCs operating under Westinghouse electric rates only.

A policy requiring that the purchase of all new PCs be energy-efficient (based on Energy Star specifications) would result in a savings of 574,050 kWh/yr or \$20,763/yr for PNL, after approximately 5 years. Participation by all Hanford contractors would result in a savings of 1,385,850 kWh/yr and \$50,126/yr.

The actual savings for the energy-efficient equipment may be greater because an 80% power reduction is the minimum required for the Energy Star program. A less intensive, and perhaps more realistic, program that limits purchase of energy-efficient equipment to PCs that are on during nonwork-hours (SDP-3_{IBM/Apple}) will capture 44% of the maximum cost savings while targeting only 12% of the total number of PCs.

10.0 Conclusions

Field measurement of the electric demand of 222 personal computer workstations, network printers, and copiers, together with surveys of installed equipment at 1,231 locations in six buildings, have provided the real-world data necessary to gain insights into the behavior and impacts of personal computer workstations.

Detailed data was collected for each separate workstation component (e.g., computer, monitor, printer, modem, and other peripherals). This information was summarized as *standard PC*, *standard peripheral equipment*, and *standard workstation demand*, and workday and nonworkday demand profiles. Development of these standard conditions allows improved estimation of PC workstation demand and aids in managing the overall energy flows for other buildings.

Although the electric demand varies between and within computer models, 93% of PC workstations fell into a load class of 75 to 175 W. The *standard PC* had a demand of 144 W, and the *standard workstation* had a demand of 173 W. The peripheral equipment, such as printers and modems, accounted for only 16% of the overall workstation demand. This information indicates that energy conservation measures should target the computers (50% of total) and monitors (35% of total) first. Laser printers, which account for only 12% of total workstation demand, may also be important because they are typically powered on 24 h/day.

The comparison of nameplate ratings with measurements indicated that direct use of nameplate electric ratings will result in an overestimated demand (three to five times the actual demand). Use of a *standard power de-rate* of 0.23 multiplied by the rated values allows correction of the nameplate ratings.

The *standard workstation demand profile* provides a good estimate of the demand on a building's plug load attributable to all the PC workstation equipment. The *standard PC demand profile* works similarly. However, the IBM/Apple PC demand profile differs significantly from the SUN/DEC PC demand profile. Most users regularly turn off the IBM/Apple PCs during nonwork-hours. Most SUN/DEC PCs are left on continuously because they are a network resource. This has serious implications for ECM economics because the calculated energy savings potential for an IBM/Apple PC is significantly less for the IBM/Apple PC demand profile than it is for the workstation SDP.

The *standard workstation demand profile* can be adjusted to more accurately reflect the unique base and peak load of an individual building by using a walk-through audit. The building's unique operating characteristics would be estimated from information about computer, or computer and

monitor, fraction on-times. For adjustments based on computer and monitor fraction on-time, errors for the adjusted SDP are within 8% per building and 3% overall, instead of the 20% per building error when applying the SDP directly.

Power controllers on monitors provided a 21% demand savings and 57% consumption savings. Energy consumption savings during work-hours was only 39.9% of the overall savings, indicating that the main energy conservation potential is for computers that are on during nonwork-hours. Although power controllers on computers were not tested, similar savings would be expected from application of an appropriate power controller and software to automatically save and retrieve open applications. User acceptance of the monitor power controller was good.

Measurements showed that the built-in power-saver mode on 64% of the photocopiers was disabled. An enabled power saver will produce a 52% energy savings. The disabled power savers were probably the result of user dissatisfaction with the warm-up time required to use the photocopier during a sleep mode, incorrect power-saver mode setup, or no staff identified with responsibility for maintaining the power-saver mode.

Life-cycle costs of 27 energy conservation scenarios were analyzed to determine the cost-effectiveness of three ECMs. The ECMs were an energy awareness program, retrofit of existing PCs with power controllers, and purchase of new energy-efficient PCs. The LCC analysis recommended "no-action" for PCs that are operated according to the measured IBM/Apple PC demand profile. In fact, the costs of the ECMs would have to be dramatically lower to be recommended. For Richland electric rates, the costs could not exceed \$3/PC/yr for the energy awareness program, \$20 capital and no annual O&M for the retrofit power controller, and \$15 incremental cost for the purchase of new energy-efficient PCs. For Westinghouse electric rates, the costs could not exceed \$7, \$38, and \$31. And for the typical U.S. electric rates, the costs could not exceed \$13, \$80, and \$64. The low electric rates at the Hanford Site make ECMs for PCs unattractive at this time.

Selective application of the ECMs as shown in Table 10.1, will optimize the investment. When high energy-consumption PCs are targeted, the energy awareness program for the Westinghouse rates and all three ECMs for the typical U.S. electric rates are recommended actions. When targeting the highest energy-consumption PCs, all three ECMs for both Westinghouse and the typical U.S. electric rates are recommended actions. No ECMs are recommended for the low Richland electric rates under any electric demand profile.

Table 10.1. PC Energy Conservation Measure Recommendations

Energy Conservation Measure	Standard PCs (341 kWh/yr, 100% of PCs)			High Energy Use PCs (692 kWh/yr, 12% of PCs)			High Energy Use PCs (942 kWh/yr, 12% of PCs)		
	Richland Rates	WHC Rates	Typical US Rates	Richland Rates	WHC Rates	Typical US Rates	Richland Rates	WHC Rates	Typical US Rates
Energy Awareness						★		★	★
Power Controller						★		★	★
Energy Star PCs						★		★	★

★ Star indicates recommended action.



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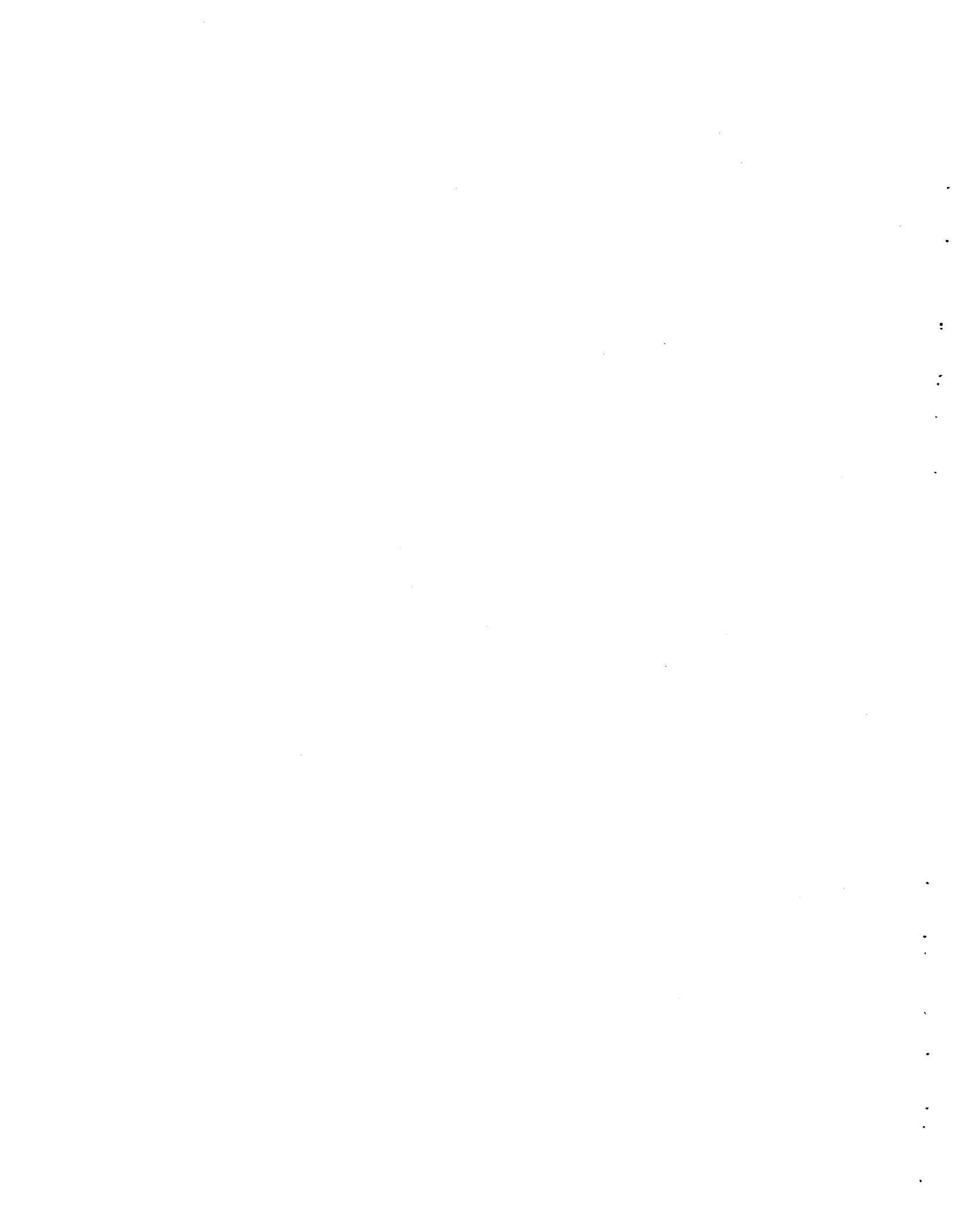
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Appendix A

Waveform and Harmonic Analysis



Appendix A

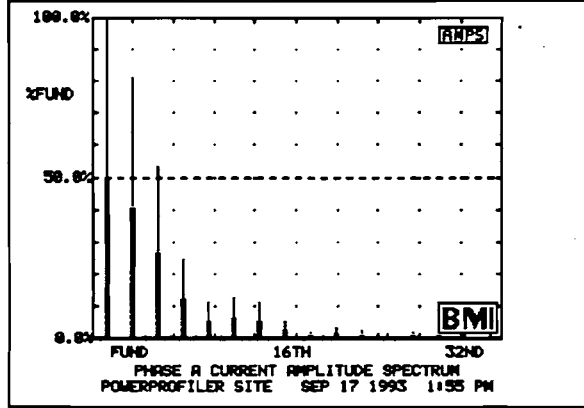
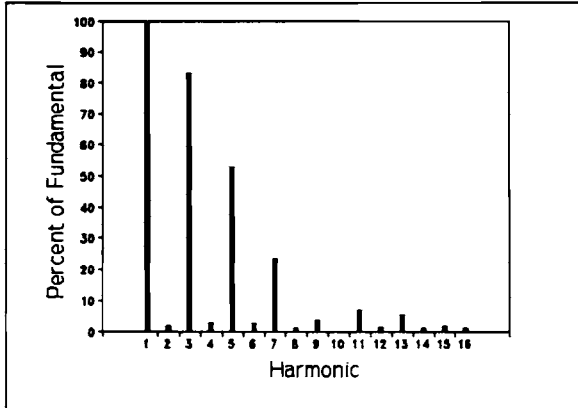
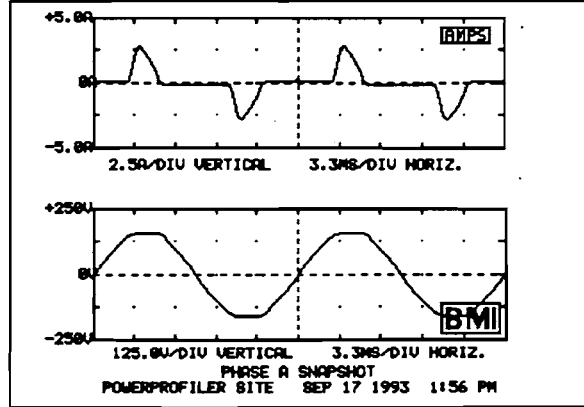
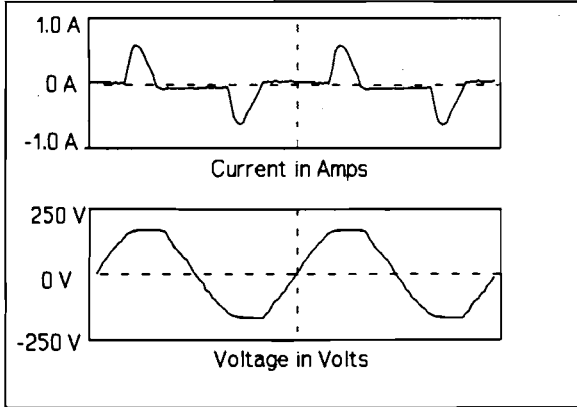
Waveform and Harmonic Analysis

Snapshot waveforms were taken from a Compaq LTE 386s/20 and a Texas Instruments MicroLaser printer using a C180E data logger and a BMI 3030A PowerProfiler[®].

Compaq LTE 386s/20 Computer

Synergistics C180E Data Logger

BMI 3030A PowerProfiler



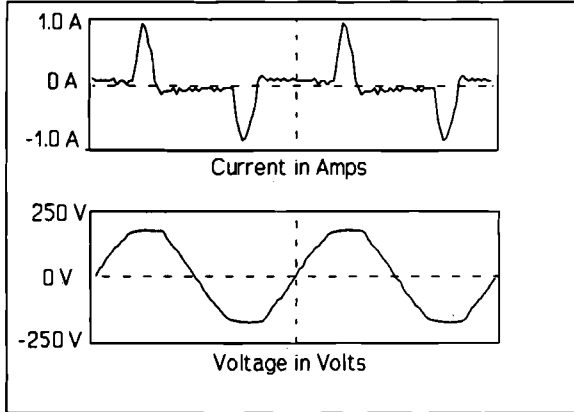
122.1 V_{rms}
 807 mA_{rms}
 61 W
 98.53 VA
 0.62 PF
 N/A dPF
 112% THD

Voltage, Volts_{rms}
 Current, Amps_{rms}
 Power, watts
 Apparent Power, VA
 Power Factor
 Displacement Power
 Factor
 Total Harmonic
 Distortion

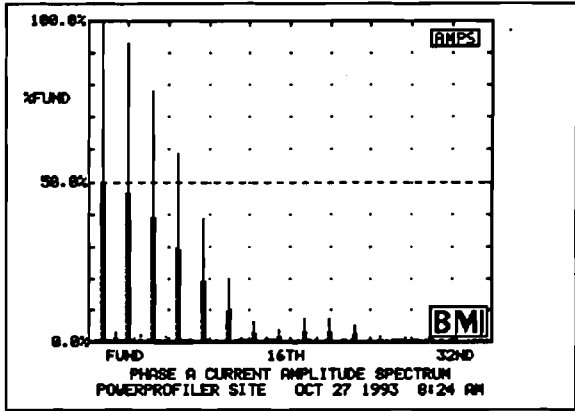
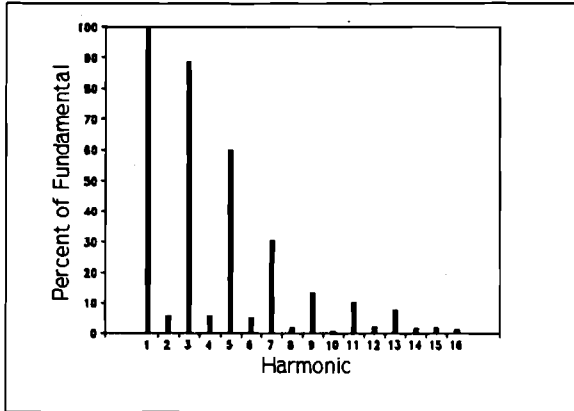
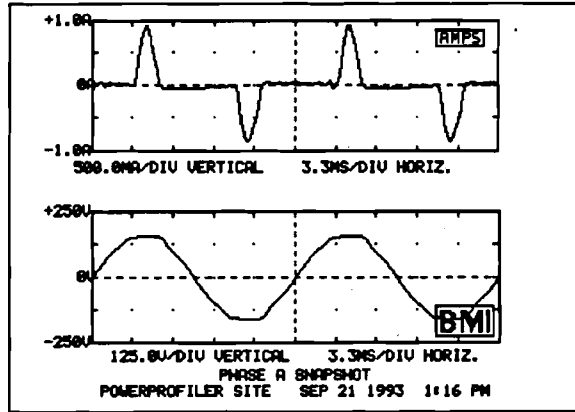
121.6 V_{rms}
 811 mA_{rms}
 65.15 W
 99.47 VA
 0.66 PF
 0.99 dPF
 107.1% THD

Texas Instruments Laser Printer

Synergistics C180E Data Logger



BMI 3030A PowerProfiler



120.6 V_{rms}
 300 mA_{rms}
 21 W
 36.47 VA
 0.59 PF
 N/A dPF
 136% THD

Voltage, Volts_{rms}
 Current, Amps_{rms}
 Power, watts
 Apparent Power, VA
 Power Factor
 Displacement Power
 Factor
 Total Harmonic
 Distortion

120.1 V_{rms}
 305 mA_{rms}
 21.65 W
 36.24 VA
 0.60 PF
 1.00 dPF
 129.3% THD



Appendix B

Equipment Surveyed and Monitored

Appendix B

Equipment Surveyed and Monitored

A form (Figure B.1) was used to survey equipment items monitored in the sample buildings on the Hanford Site. In Table B.1, workstations are shown by power consumption class. Tables B.2 through B.6 list each individual piece of equipment identified.

PC Metering Study

Data Start Time: _____ Data Stop Time: _____

Metering Identification Information

C180 S/N: _____ Metered By: _____
Building: _____ Room: _____
User Name: _____ Phone: _____
Position: _____ Company: _____

Equipment Information

CPU Type / Model: _____
Monitor Type: _____
Internal Disks: _____
External Disks: _____
Printer: _____
Accessories: _____
Other Comments: _____

Connection	Type of Device	Rated Power
1	_____	_____
2	_____	_____
3	_____	_____
4	_____	_____
5	_____	_____
6	_____	_____
7	_____	_____

Figure B.1. Sample Survey Form

Table B.1. Inventory of Workstations Found in Sample Buildings

WORKSTATIONS:	Federal Building		TCPC		2400 Stevens		OSB		Sigma I		Sigma IV	
	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed
Class I	0	20	1	2	1	2	0	0	2	14	0	7
Class II	45	869	37	289	34	193	15	141	27	100	0	120
Class III	4	27	6	14	6	15	3	9	1	7	0	2
Class IV	0	0	3	5	0	0	0	0	0	0	0	0
TOTALS	49	916	47	310	41	210	18	150	30	121	0	129

Table B.2. Inventory of CPUs Found in Sample Buildings

CPU TYPE:	Federal Building		TCPC		2400 Stevens		OSB		Sigma I		Sigma IV	
	Monitored	Surveyed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed
(network terminal)	0	3										
AST	1	2										
AST Premium 386/33	0	1	2	3								
CLJB	2	2										
Compaq 286 Deskpro	0	21										
Compaq 386/20			2	3								
Compaq 386/20e	4	38	3	11								3
Compaq 386/25	4	8	1	23	0	3						
Compaq 386/33L	1	1										
Compaq LTE 286					0	1	0	1				
Compaq LTE 386a/20	0	1			1	2	1	6	0	1		4
Compaq Portable 3												1
Compaq SLT	0	1										
Dell 486/50									0	1		
Digital DECstation 3100			10	62								
Digital DECstation 5000			0	2								
Digital VAXstation 2000			0	2								
Digital VAXstation II			1	1								
Digital VT 240									0	1		
Gateway 2000					0	4						12
Gateway 2000 386/25									3	9		
Gateway 2000 386/25C									0	1		
Genelec 286	4	23	3	36	0	6			0	1		8
HP 9836C					1	1						
HP Vectra	0	1	2	2								
Helikon 286 Laptop									0	1		
IBM 5155 Portable							0	2				
IBM PC	1	21	0	5	3	10	0	3	1	5		25
IBM PC AT	6	24	3	28	8	19	0	3	6	13		21
IBM PC XT	0	3	1	5	1	2	0	2				7
IBM PS/2 30									0	1		
IBM PS/2 50	3	7					2	6				3
IBM PS/2 50ex							0	1				
IBM PS/2 55ex	3	4			1	1	1	9	0	1		4
IBM PS/2 60	1	1			1	2	1	5	1	6		6
IBM PS/2 65ex							1	1				
IBM PS/2 70	5	35	2	20	5	23	9	107	5	11		9
IBM PS/2 80	2	4			5	5	3	8	1	7		2
ISO 286			0	1								
ISO B/T			0	3								
MAC II	1	4	1	1	4	4			0	6		
MAC Ix	1	2	1	3	2	2			4	11		12
MAC Ixx									1	6		2
MAC Ixx	1	2	0	2	1	2			0	2		
MAC Plus	1	6	1	2	1	3			0	4		2
MAC Quadra 700							0	1	0	1		
MAC SE									2	10		5
MAC SE/30									2	3		
NCR												1
Northgate 386					1	1						
Northgate Elegance 425i									1	1		
PC Limited 286							0	3				
Sun 3/50									0	4		
Sun 3/60									0	1		
Sun 386i			1	11								
Sun Microsystems									0	1		
Sun Sparcstation I					5	5			1	7		
Sun Sparcstation I/PC									1	2		
Sun Sparcstation II									1	3		
Tektronix	0	1										
Televideo 955	0	1										
Texas Microsysteme					1	1						
Tohiba T3100 Laptop												2
UZI												
WIN 286			0	3								
WIN 386	1	7	2	6								
WIN 386ex	4	23	6	31								
WIN Turbo AT	3	56	2	44								
Xerox	0	1										
Zenith Laptop	0	1					0	1				
TOTALS	49	305	44	310	41	87	18	180	30	121	0	129

Table B.3. Inventory of Monitors Found in Sample Buildings

MONITORS:	Federal Building		YPCP		2400 Stevens		OSB		Sigma I		Sigma IV	
	Number	Serial	Number	Serial	Number	Serial	Number	Serial	Number	Serial	Number	Serial
Amberchrome	0	1					0	1				5
Apple Color	3	7	2	5	8	10	0	1	1	17		12
CIT-101									0	1		
Compaq	0	1										
Compaq Deskpro	0	1	1	3								3
Dell Ultraseam									0	1		
Digital			10	63								
Digital II			1	3	0	1			0	1		
E-Machines												1
E-Machines 19"									1	1		
Evershion					0	2						
Gateway 2000					0	2			1	3		10
Gateway 2000 Crystal									2	7		
HP Color			1	1	1	1						
HP Enhanced Graphics			0	1								
Hyundai					0	1	0	1	0	1		
IBM Enhanced Color Disp.					5	15			2	2		10
IBM PC Color Display	1	4			1	5			1	7		13
IBM PC Mono Display					0	1						1
IBM P8/2 Color Display	11	31	0	9	11	25	17	110	3	17		24
IBM P8/2 Monochrome									0	1		
IM TEC 1438E												1
IM TEC Super VGA					0	1						
Intellync 2s												1
Leading Technology					0	1						
MAC Portrait Display												1
MAG Colorview/14s												2
Magnavox	0	2	0	4			0	3				2
Magnavox Professional												1
Mega Graphics									0	2		
Mitsubishi 19"			0	6								
Mitsubishi Color			0	1	1	4						
Mitsubishi Diamond Scan					0	1						
Monoferm Viking												1
NEC CZ 805A												1
NEC Multisync	0	31	3	30	1	4	1	8	1	2		3
NEC Multisync +												2
NEC Multisync 2s							1	11				1
NEC Multisync 3D	25	132	17	83	1	4	1	10	4	7		4
NEC Multisync 3Ds	1	1	3	14	0	1	0	5				
NEC Multisync 3FGx							0	2				
NEC Multisync 4D	1	1	0	1								
NEC Multisync 4Ds	1	1							1	1		
NEC Multisync 4FG	1	1										
NEC Multisync 8D			2	11	0	1						
NEC Multisync II	1	9	4	44	1	1	0	1	0	1		2
NEC Multisync Plus					0	1						
NEC Multisync sI	0	1	0	3	0	1						
Northgate Color					1	1						
Packard Bell					0	3						
Packard Bell VCG Display					0	1						1
Princeton Graphic System									1	1		3
Princeton HD-12			0	1								
Quadchrome II	1	20	1	12	2	8			1	3		11
Radius									0	2		1
SACO Instruments	0	1										
Samsung												1
Semtron					0	1						
Selenar Graphics									0	1		
Sony	0	5			0	1						
Standard Technology												1
Sun Color			1	11	6	9			2	17		
Sun Color 16"									1	1		
SuperMAC			0	1					3	6		
TVM MD System	0	33										
TVM Supersync 2A	0	3										
TVM Supersync 3A			0	2								
Texan					0	2			0	1		
Texan (monochrome)					1	1						
Texan 620	0	3										
Teomar					1	2						
Televideo	3	24	0	3								
Uniflex	1	6										
VGA AOC												2
WIN	0	2										
Xerox	0	1	0	1								
Zenith					1	1			0	1		
Zenith Data Systems							0	1	1	2		
TOTALS:	80	322	46	323	42	123	20	184	26	107	0	121

Table B.4. Inventory of Printers Found in Sample Buildings

PRINTERS:	Federal Building		TCPC		2400 Stevens		OSB		Sigma I		Sigma IV	
	Monitored	Surveyed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed
Alpe Allegro 24	0	18										
Alpe Allegro 500	0	1										
Apple ImageWriter	0	1							0	3		
Apple ImageWriter II			1	4	1	3			1	2		
Apple LaserWriter	0	2							0	2		1
Apple LaserWriter II	1	1					0	1	1	4		2
Apple LaserWriter II NTX									0	1		
Apple LaserWriter Plus	1	1							1	1		
Canon PC Printer 80									0	1		
Canon PC Printer 70							1	1				1
Citizen 120D					0	1						
Daisywriter					0	1						
Dataproducs	0	1			2	3	5	8				
Epson	2	11	1	14	0	1			1	4		4
Epson EPL-7500									1	1		
Epson FX-1050	3	9	0	9								
Epson FX-185	1	4	0	2					0	1		
Epson FX-225			0	1								1
Epson FX-285			0	1								
Epson FX-298	3	7	0	4	0	3	1	1	0	1		5
Epson FX-298e	2	10	3	11	0	3			0	1		
Epson FX-80												1
Epson FX-85	1	3	0	1					0	2		
Epson FX-850	3	10										
Epson FX-88e	1	14										
Epson LQ-850	1	1										
Epson LQ-1050			0	1								
Epson MX 80F/T												1
Genicom 4410												1
HP 2583B							0	1				
HP LaserJet	3	8	1	3								
HP LaserJet +	0	1										
HP LaserJet 2000					0	1	2	2				1
HP LaserJet II	7	27	7	31	3	11			1	5		8
HP LaserJet III	4	43	4	38	5	13	7	42	5	13		8
HP LaserJet IIIi	0	1			0	1						
HP LaserJet IIIp					0	1						1
HP LaserJet IIIe											1	1
HP PaintJet			2	4								
HP ThinkJet					1	2						
IBM Laser Printer									0	1		
IDS Model 80					1	1						
Imagin 3308					1	1						
Integral Data Systems	1	2										1
Itoh 8510					0	1			1	1		
JDL 850			0	2								
Minolta EP300	1	2										
NEC SpinWrite	0	1										
Panasonic IX-P108i					0	1						
Prism 132							1	2				
QMS PS-810					0	1						
QMS PS-815			1	1								
QMS Printer	0	1										
TI Laser Printer					1	1						
TI MicroLaser					0	1						
Talaris	0	1			0	1						
Talaris 810							0	2				
Talaris 811							0	5	2	2		
Talaris System					0	1						
Talaris T810	0	1			0	3	1	14	2	7		11
Talaris T811							1	1				
Tektronix 4898	0	1										
Tektronix Phaser II									0	2		
TOTALS:	35	183	20	126	15	58	19	78	18	55	1	48

Table B.5. Inventory of PC Accessories Found in Sample Buildings

ACCESSORIES:	Federal Building		TCPC		2400 Stevens		OSB		Sigma I		Sigma IV	
	Monitored	Surveyed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed
680 mB Ext. Harddisk					1	1						
ARTECON									0	4		
Apple HD	1	1										
Apple 20SC Ext. Drive	1	1										1
Apple Datafile					4	4			1	4		1
Apple Scanner			0	1					0	1		
Autocad			11	79								
Bernoulli 10+10			1	1								
Bernoulli 20+20	0	2	1	11	2	4						1
Bernoulli 20+20 Ext. Drive					1	1						
Bernoulli Box					0	1						
Bernoulli Box II					3	3			1	4		
Bernoulli Box II 44			0	1					0	3		
CMS Ext. Drive												
Canon Scanner					1	1						
Color Digital Scanner					1	1						
Converter					1	1						
Core Ext. Drive			0	2								
Core Ext. Drive			0	2								
Dataframe 20			1	1					2	3		1
Dataframe XP-30									0	1		1
Daymate			1	2					0	2		
Digital Storage Expansion			0	2								
Dolphin Ext. Drive									1	1		1
Dolphin Matchmate									1	1		
HP 7470A	0	1			1	3			1	1		
HP 7475A	0	2	0	3	2	3			1	3		2
HP 7550 Plus	0	3	0	1								
HP 7550A	0	3	1	5								
HP 7580B					1	1						
HP 9111A Graphics Tablet					1	1						
HP 9133 Ext. Drive					1	1						
HP Draftmaster I					0	1						
HP ScanJet			0	2	1	1						
HP ScanJet Plus	0	2										
HP Scanner					1	1						
Hayes Modem					3	4						
IBM 3363 Optical Drive									1	1		
IBM 4869	2	8	0	4	3	9	2	42	4	12		9
Ideal Context FSS 3012			0	1								
Image Processor					1	1						
Jasmine DirectDrive 100									0	1		
MASS Microsystems									0	2		
Mayntream Tapedrive	2	5										
Microtek MSF-300G Scan									0	1		
Telebit Modem	1	1										
NEC Discdrive	0	1										
PLI Infinity 40 Turbo									1	1		
Print Contender					1	1						
Prometheus	1	1										3
REO-130 Optical Drive									1	1		
Recal Vadic Modem			1	1								
Realistic Micrographics												1
Reference Tech. CD Drive									0	1		
Sony Ext. Drive									1	1		
Summagraphics Digitizer					0	1						
SummaSketch					0	1			1	1		
Sun CD ROM Ext. Drive									0	1		
Sun Tapedrive												
Sygen Ext. Drive	2	3	1	2			0	1				
Tallgrass 20+20												1
Tallgrass TG-1040e Tapedrive					0	1						
Tallgrass TG-5025 Tapedrive	0	2			1	1						4
TOTALS:	10	36	18	121	31	48	2	43	17	51	0	26

Table B.6. Inventory of Auxiliary Office Equipment Found in Sample Buildings

AUXILIARY OFFICE:	Federal Building		TCPC		2400 Stevens		OSB		Sigma I		Sigma IV	
	Monitored	Surveyed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed
3M Thermofax	0	1										
3M Transparency Maker	0	1										1
AMBruning PD-4400 Copier			0	2								
Black & Decker 4 cp Coffee									0	1		1
Black & Decker Coffeematic	0	1							0	1		
Braun Coffee Maker												2
Bunn Pour-O-Matic & Warmer	0	1										
Bunn Pour-O-Matic Coffee Mak			0	1								1
Canon Copier	0	1										
Canon FAX & Typewriter					0	1						
Canon FAX-270S							0	1	0	1		
Canon FAX-270S & Copier	1	1										
Canon FAX-270S & Typewriter	0	1	0	2								
Canon FAX-L770							0	3				1
Coffee Cup Warmer	2	2							1	1		
Coffee Pots (3)	1	1										
Dayton 16" Oscillating Fan	1	2										
Dictaphones (2)	0	1										
Digital DecWriter									1	1		
FaxWriter 2225												1
HP Scientific Calculator					1	1						
Hamilton Beach Coffee												1
Harris/3M 2110 Fax			0	1					1	1		
Harris/3M 2225 FAX	0	1					1	2				
IBM Selectric II Typewriter	1	25	3	18	0	6	1	5	1	3		3
IBM Wheelwriter 10					0	1	0	1				
Krupa Coffee Maker									0	1		1
Lamp			3	3								
Lanier Fax & Typewriter	1	1										
MITA Copier & Shredder	1	1										
MITA DC-2254 Copier			0	1								
MITA DC-313Z Copier			0	1								
MITA DC-3285 Copier	1	1	1	2								
MITA DC-4085 Copier	1	1	0	1								
Melitta Coffee Maker									0	1		1
Melitta Gevalia Coffee												
Minolta EP 470Z Copier									0	1		
Minolta EP-4230 Copier											1	1
Mr. Coffee			0	5					0	1		2
Mr. Coffee International			1	2								
Mr. Coffee Jr			1	5								1
Mr. Coffee Br									0	1		1
Mr. Coffee Ultrasonic												1
NEC NEFAX BIT-I			0	1								
NEC FAX 1010L							1	1				
NEC NEFAX-BITV	1	2	0	1					0	1		
NEC PC-VCR & Sony TV			0	3								
Norelco Coffee Maker			1	7					0	1		1
Olivetti ET 121 Typewriter	1	3										
Olivetti ET-225 Typewriter			0	2								
Panasonic IX-E7000 Typewrite	1	1	0	3			0	1	0	4		
Panasonic IX-E700m Typewrit	0	2	0	5								1
Panasonic IX-E708 Typewriter	0	1	0	1	0	3			0	2		11
Proctor Sillex ADC Coffee									1	1		
Proctor Sillex Coffee Maker			0	2								3
RICOH FAX 1010L							1	1				
RICOH FT-4030 Copier			0	1								
RICOH FT-4085 Copier									1	1		
RICOH FT-4430 Copier					1	1						
RICOH FT-4480 Copier									0	1		
RICOH FT-5580 Copier					1	1						
RICOH FT-6085 Copier			0	1			1	2				1
RICOH FT-6620 Copier					1	1						
RICOH FT-7870 Copier							2	2				

AUXILIARY(cont):	Federal Building		TCPC		2400 Stevens		OSB		Sigma I		Sigma IV	
	Monitored	Surveyed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed	Monitored	Installed
Regal & Norelco Coffee Makers			0	1								
Regal Coffee Maker			0	2								
Royal 130 Copier			1	1								
Royal 1803 ZMR Copier	0	1										
Russell Hobbs Electric Teapot									0	1		
Salton Coffee Maker			0	1								
Sharp QS-2188 Calculator			1	1								
Sharp SF-8550 Copier	0	1										
Sharp VX-2852 Calculator			1	1								
Sunbeam Hot Shot Coffee Mak	0	1							0	1		
West Bend Hot Pot (coffee)			0	1								
Westbend Brewtime Coffee Ma												1
Westbend Coffee Maker	0	1										
Xerox 627 Memorywriter			0	2								
Xerox 630 Memorywriter			0	1								
Xerox Copier			0	1								
TOTALS:	13	56	13	81	4	15	7	18	6	27	1	37

Appendix C

Building Workstation Demand Profiles



Appendix C

Building Workstation Demand Profiles

Figure C.1 shows the workstation demand profiles (non-normalized) for the five sample buildings. This plot shows the electric demand in kilowatts as calculated by extrapolating the monitored set of workstation equipment to the surveyed building total. This plot gives an indication of the variability among the sample buildings. Figure C.2 shows the workstation demand profiles (non-normalized) for the weekends during the study period.

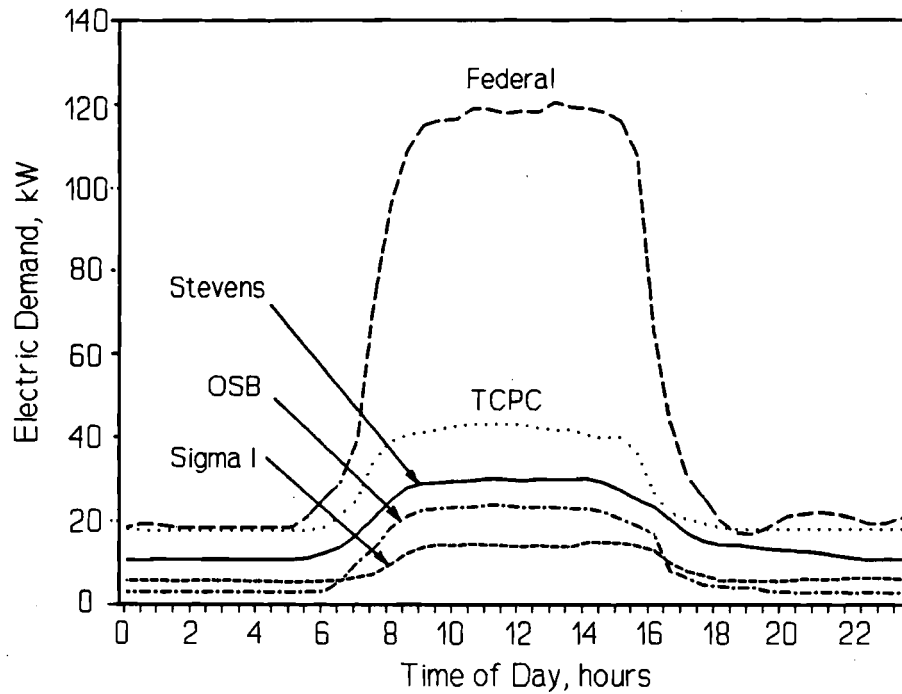


Figure C.1. Weekday Workstation Demand Profiles

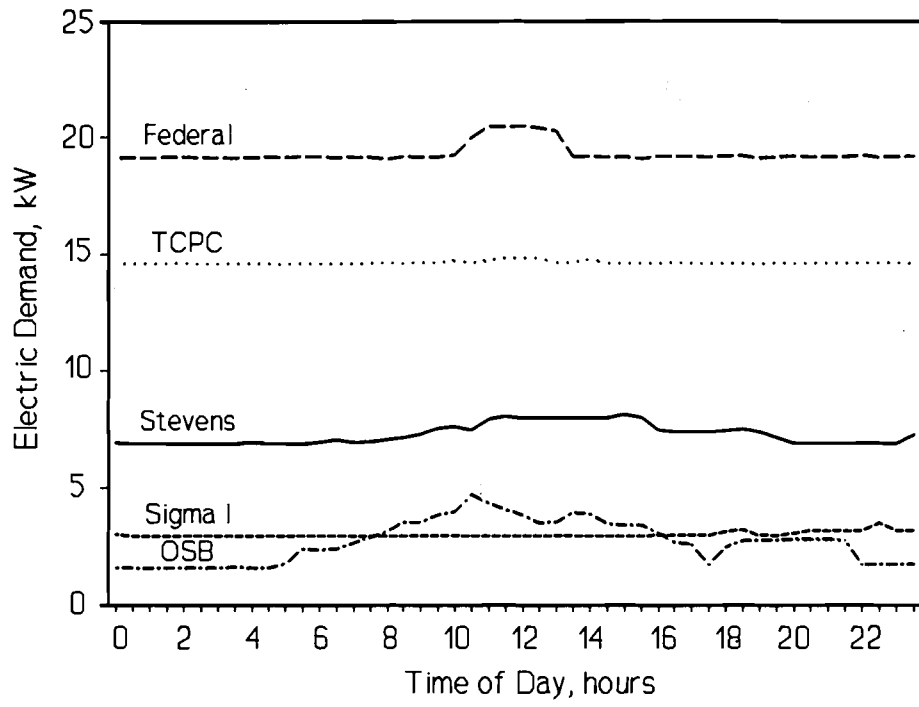


Figure C.2. Weekend Workstation Demand Profiles

Appendix D

Workstation Demand Profiles

Appendix D

Workstation Demand Profiles

In this appendix, the total workstation demand profile for each building is presented normalized to the maximum possible demand value. By normalizing the demand, the profile maintains its shape while allowing us to identify what percentage of the maximum demand is reached at a specific time during the day. In addition to total workstation demand (shown as the solid line in the plots that follow), the total demand for the PC (CPU and monitor) is also shown (dotted line). By plotting the demand attributable to CPUs and monitors, the electric demand attributable to all the peripheral equipment appears as the area between the two curves. Peripheral equipment includes printers, plotters, external disk drives, external modems, and autoCAD devices.

The first plot, Figure D.1, shows the *standard* demand profile (SDP) constructed by combining all the test buildings, followed by the building demand profile (BDP) for each of the test buildings.

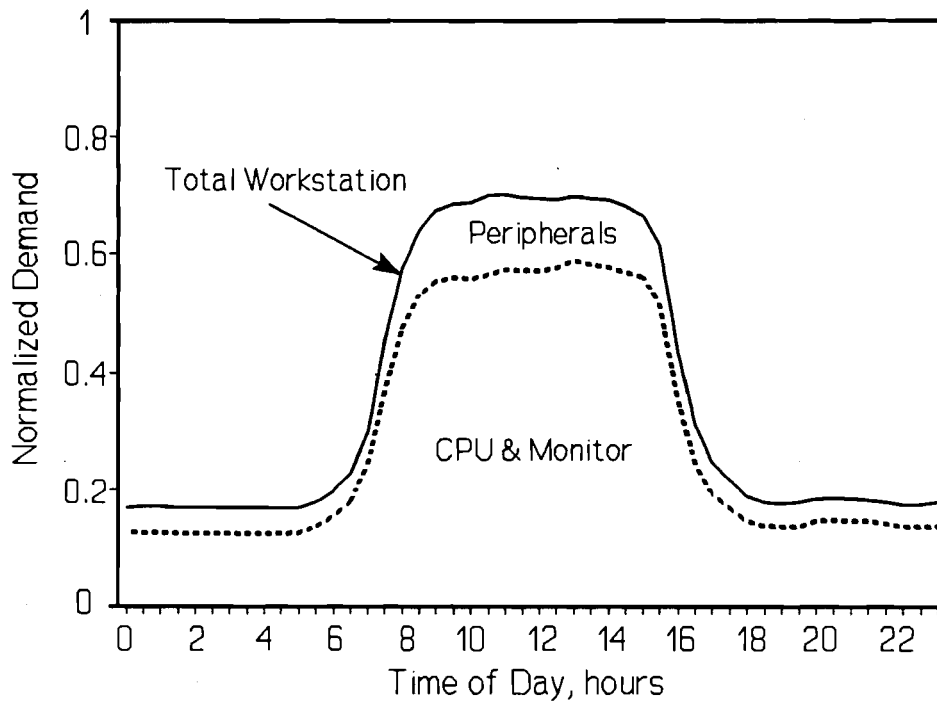


Figure D.1. Standard Demand Profile

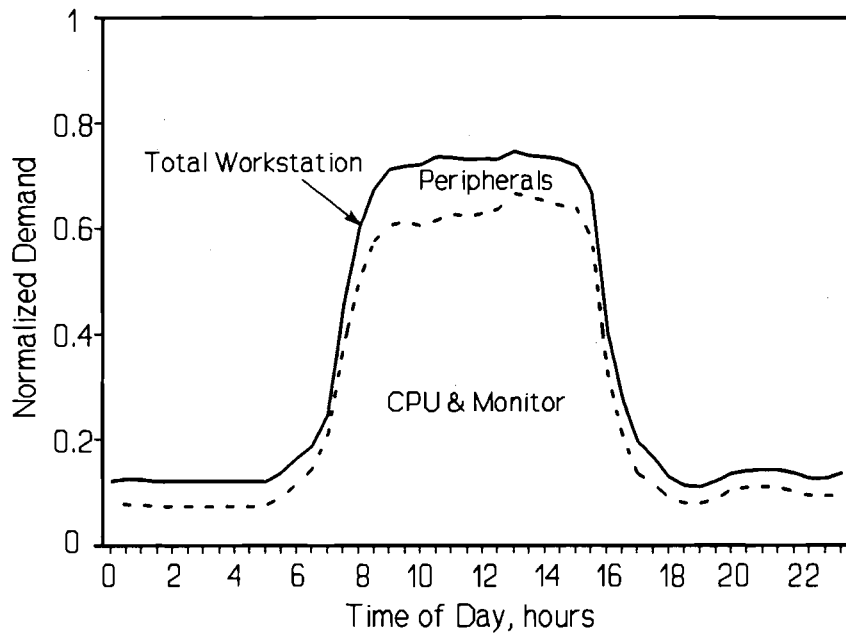


Figure D.2 Federal Building Demand Profile

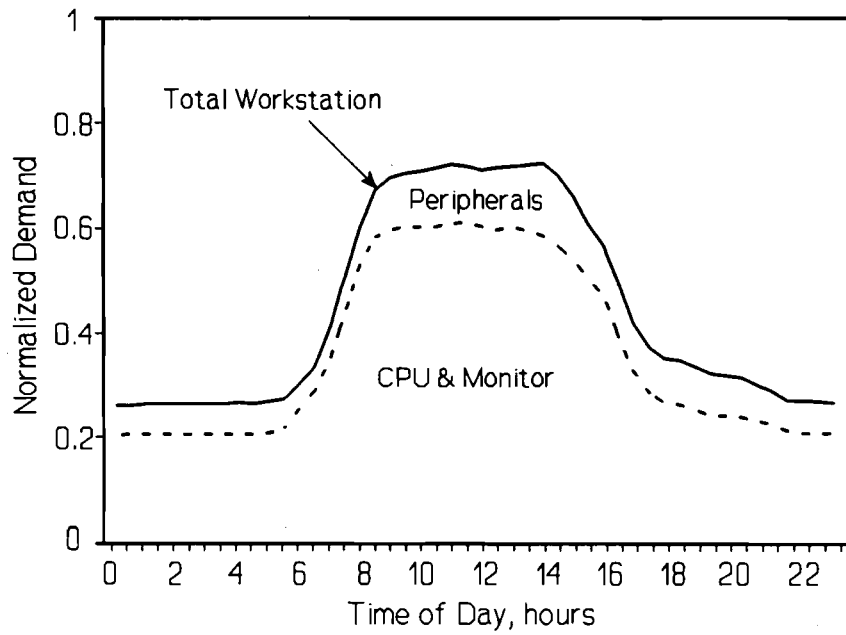


Figure D.3. Stevens Building Demand Profile

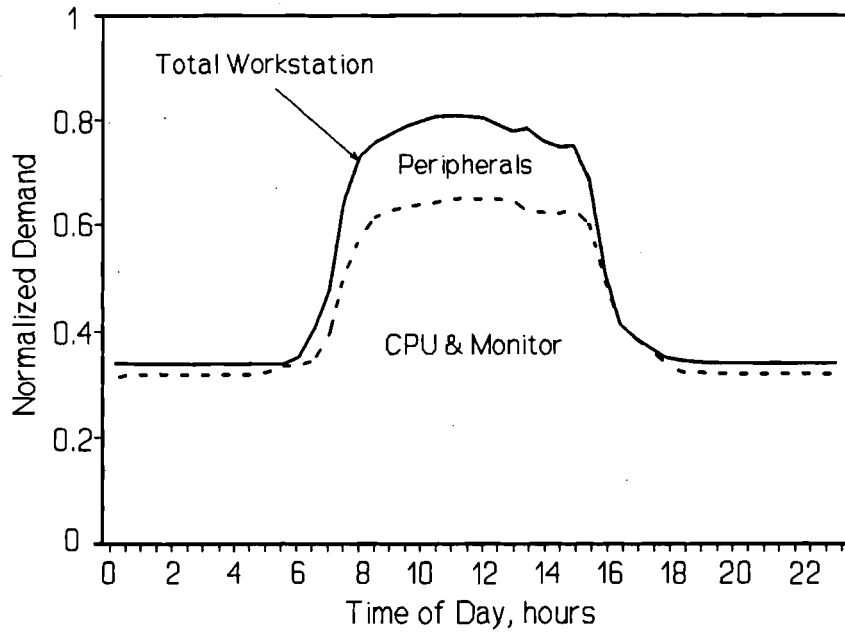


Figure D.4. TCPC Building Demand Profile

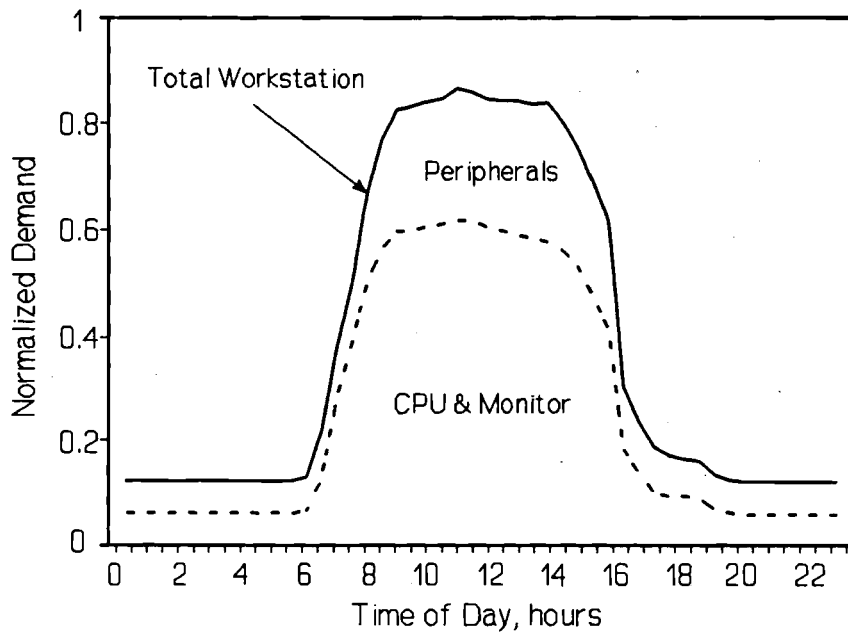


Figure D.5. OSB Demand Profile

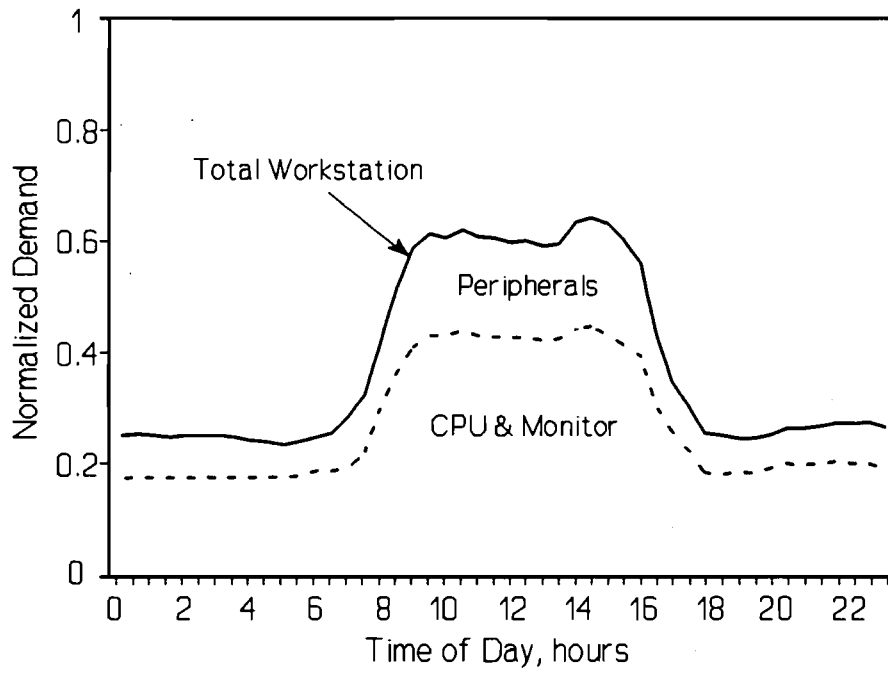


Figure D.6. Sigma I Building Demand Profile

Appendix E

Estimating Workstation Demand Profiles

Appendix E

Estimating Workstation Demand Profiles

This appendix demonstrates the methods used to approximate a building demand profile (BDP) using the *standard* demand profile (SDP) and adjusting the baseload and peak load values using PC fraction on-time (FOT_{PC}) information.

The least accurate approximation is to simply assume that the SDP fits the BDP in question. This is a rough approximation. A better method is to adjust the SDP to fit the peak load and baseload as determined from FOT_{CPU} , which yields SDP'_{CPU} . Slightly more accurate than SDP'_{CPU} is the SDP'_{PC} , which uses FOT_{PC} instead of FOT_{CPU} . The errors for each building, average error, and standard deviation for each estimation technique are given in Table E.1. Figures E.1 through E.5 show the actual monitored BDP for each of our monitored buildings in addition to the profiles used to estimate the BDP.

Table E.1. Errors for Workstation Demand Profile Estimation Techniques

	SDP	"Hat"	SDP' _{Measured}	SDP' _{CPU}	SDP' _{PC}
Stevens	-10.3	-11.4	-3.9	13.2	1.8
Federal	14.3	12.9	1.1	-1.3	-5.6
TCPC	-20.0	-21.0	1.6	-10.2	-7.7
Sigma I	-8.8	-10.0	2.6	8.4	-1.3
OSB	7.6	6.3	1.0	-9.5	-1.8
Average	-3.4	-4.7	0.5	0.1	-2.4
Standard Deviation	12.5	12.4	2.3	9.4	3.8

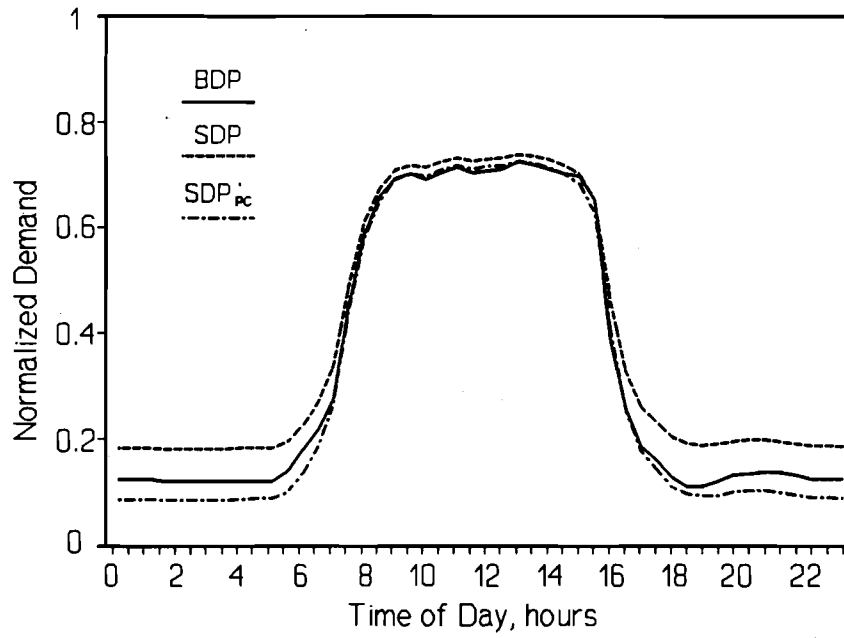


Figure E.1. Federal Building Normalized Demand

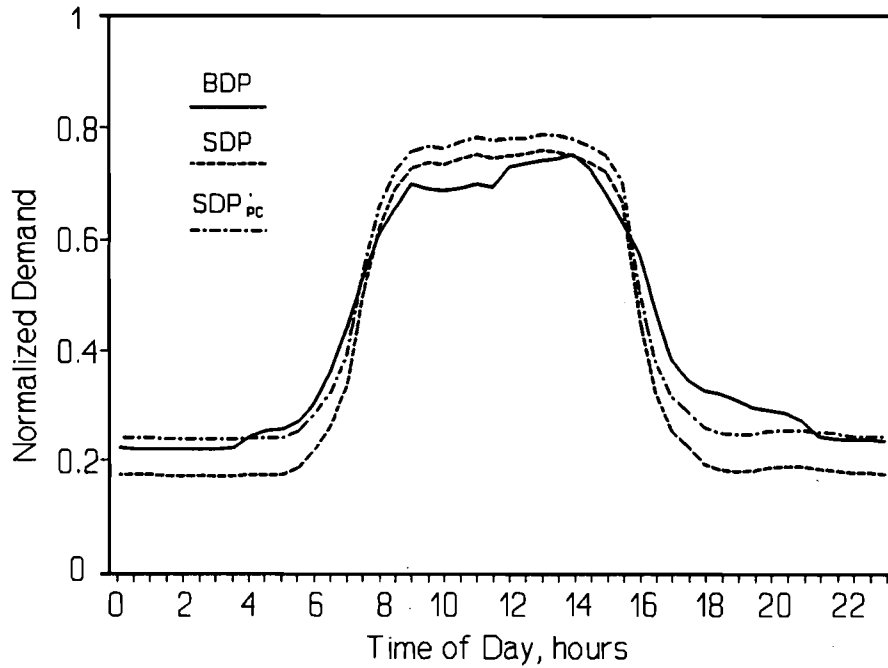


Figure E.2. Stevens Building Normalized Demand

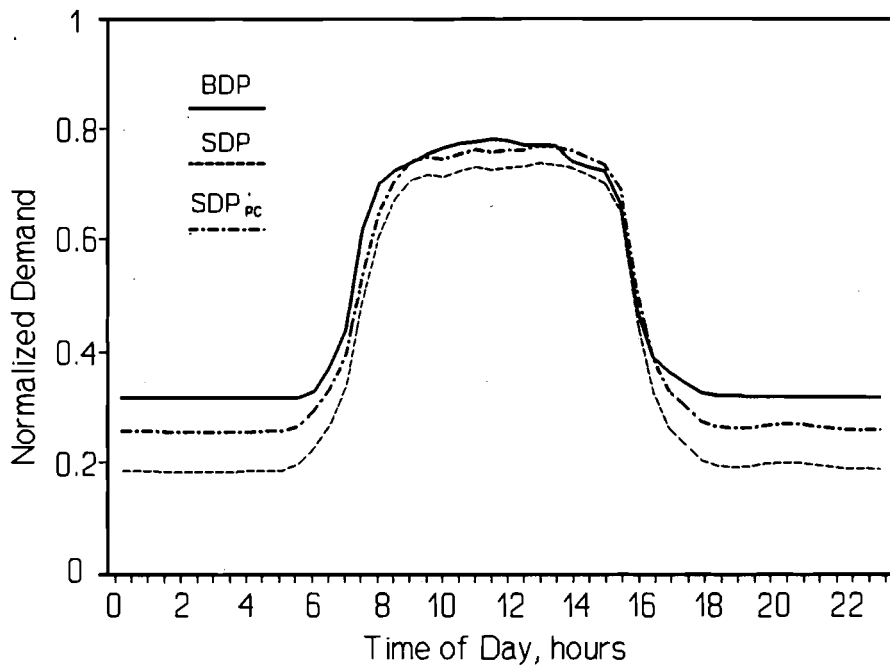


Figure E.3. TCPC Building Normalized Demand

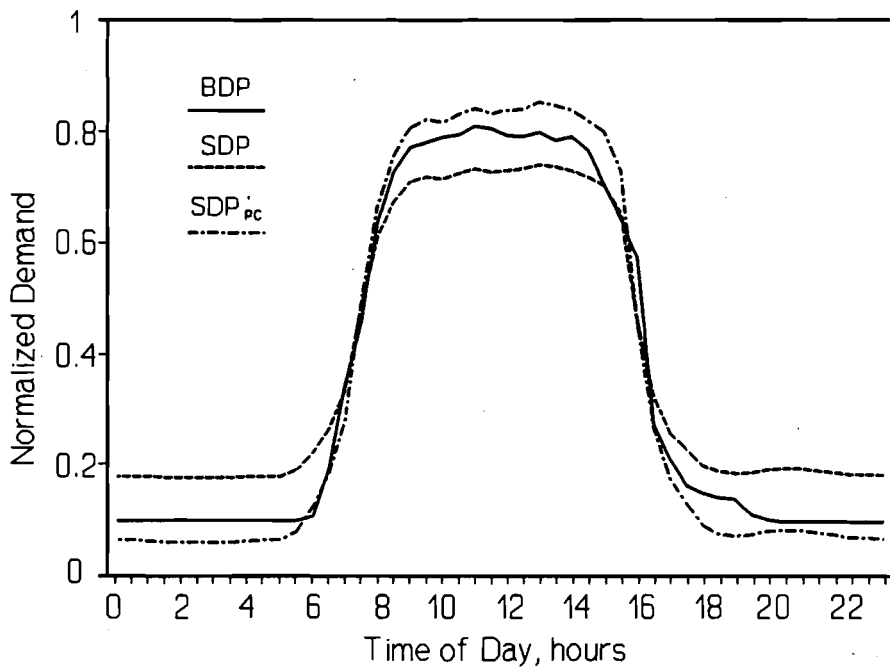


Figure E.4. OSB Normalized Demand

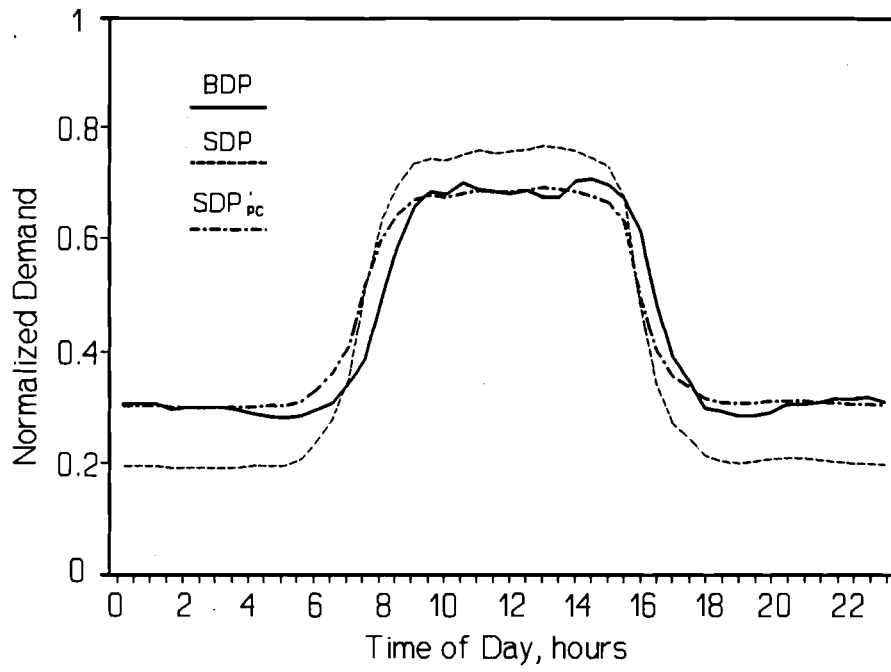


Figure E.5. Sigma I Building Normalized Demand

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