Energy End-Use Metering in Two Modular Office Buildings at Fort Irwin, California

January 1994

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Pacific Northwest Laboratory
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Preface

The goal of the U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP) is to facilitate energy-efficiency improvements at federal facilities. This is accomplished by a balanced program of technology development, facility assessment, and use of cost-sharing procurement mechanisms. Technology development focuses on the tools, software, and procedures used to identify and evaluate efficiency technologies and improvements. For facility assessment, FEMP provides metering equipment and trained analysts to federal agencies exhibiting a commitment to improve energy-use efficiency. To assist in procurement of energy-efficiency measures, FEMP helps federal agencies devise and implement performance contracting and utility demand-side management strategies.

Pacific Northwest Laboratory (PNL)^(a) supports the FEMP mission. The Laboratory and its contractors work with federal facility energy managers to assess and implement energy-efficiency improvements at federal facilities nationwide.

The capabilities of the Mobile Energy Laboratory (MEL) provide onsite measurement and evaluation of energy conversion, distribution, and end-use efficiency at federal facilities. The results may be used to justify changes in operating procedures, maintenance efforts, system designs, or energy-using equipment. The MEL capabilities can subsequently be used to assess the results of energy-efficiency projects.

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Executive Summary

This report documents the application of the Mobile Energy Laboratory (MEL) at Fort Irwin for the period 21 December 1989 to 27 January 1992. The MEL capabilities are maintained and applied by Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP). The U.S. Army Forces Command (FORSCOM) has contracted with DOE to apply MEL energy-efficiency tests at FORSCOM installations.

Scope and Purpose

This test was conducted under the Mobile Energy Laboratory (MEL) Assignment Plan (MAP) IRWIN-002, attached as Appendix A. The purpose of the test was to monitor electrical demands in Buildings 567 and 571 by end use and to monitor the response of the HVAC systems to internal and external loads.

Results

Results of two years of monitoring are summarized below. The observed energy-use intensities (EUIs) were 13.7 kWh/ft²-yr for Building 567 and 10.4 kWh/ft²-yr for Building 571. The corresponding numbers for HVAC energy were 5.9 and 5.3 kWh/ft²-yr. Lighting used about 35%, primary HVAC 40% (heating 8%, cooling 32%), supply fans 3% and other equipment (mostly plug loads) about 20% of the total. Over 10% of the primary HVAC energy used in Building 567 was the result of simultaneous heating and cooling. Six energy conservation measures were evaluated: 1) delamping and retrofit of T-12 fluorescent fixtures with T-8 systems; 2) installation of two-speed fans with operation at the lower speed (67% of rated airflow) during occupied periods whenever a unit is not heating or cooling; 3) retrofit of heat pump compressors with two-speed compressors; 4) installation of controls that eliminate non-productive simultaneous heating and cooling and provide improved night and weekend setback; 5) coating the existing black roof material with a white reflective material; and 6) adding an economizer system to provide outside air cooling. The estimated energy savings as a percent of whole-building energy use are:

- Lighting HVAC Savings - 26%
- Two-Speed Fans - 2%
- Two-Speed Compressors - 11%
- Improved HVAC Controls - 5%
- White Roof Coating - 5%
- Economizer Cooling - 5%

The total energy savings that can be achieved through the measures is 49%.

Recommendations

Based on these findings and other information presented in the report, the following recommendations are made:

- Weekend setback controls should be installed;
- A heating/cooling arbitration control circuit should be installed to prevent simultaneous heating and cooling;
- Two-speed fans and associated controls should be installed;
- Optimal-start controls should be installed;
- Existing black roofing should be coated with reflective materials;
- Economizer cooling equipment and controls should be installed;
- New modular buildings should include the foregoing features;
- New modular buildings should be designed with central heat pumps that use variable-speed or two-speed compressors. This will simplify setback and economizer control, eliminate simultaneous heating and cooling, and increase distribution fan and heat pump seasonal efficiencies.

Energy Use Impact

The total estimated savings that can be achieved by implementing the recommended efficiency and conservation measures in all 47 modular office buildings at Fort Irwin is 1,346 MWh/yr, or \$128,000/yr.

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1.0 Introduction

Equipment from the Mobile Energy Laboratory (MEL) testing and application program supported by FEMP was applied to measure end-use loads in two modular office buildings at Fort Irwin, a U.S. Army Forces Command training facility near Barstow, California. Buildings 567 and 571 were selected as representative of the many modular office buildings in use at the site. The MEL equipment was operated throughout 1990 and 1991. MEL Test Procedure #5, *Electrical End-Use Metering* (Armstrong et al. 1993a) was followed in the installation and operation of the monitoring equipment.

The test involved monitoring electric loads and HVAC responses to internal and external loads and thermal conditions affecting Buildings 567 and 571. The monitoring objectives were to 1) provide information for recommending cost-effective energy efficiency measures and 2) provide a baseline for assessing energy savings resulting from any energy efficiency measures that are implemented in the monitored and similar buildings.

Results of the monitoring project are presented in the body of this report. Section 2 provides a brief description of the monitored facilities. Section 3 describes the monitoring hardware and application. Section 4 presents and interprets the monitored data. Section 5 evaluates six applicable energy resource opportunities. Section 6 provides the recommendations and conclusions of the study, and Section 7 contains the references.

The MEL Assignment Plan, MAP IRWIN-002, is attached as Appendix A. Appendix B is a glossary of terms, acronyms, and units of measure. Appendix C contains relevant portions of Southern California Edison Company's rate schedule used in the evaluation of energy resource opportunities. Appendix D contains a series of weekly end-use power demand and temperature histories, average day profiles and demand frequency distributions to give the interested reader deeper insight into how the modular buildings at Fort Irwin use energy.

2.0 Facility Description

Building 567 consists of eight 12- by 60-ft modules with an aggregate floor area of 5760 ft². The building contains offices, a conference room, and a break room and is occupied primarily by military personnel assigned to the Directorate of Logistics. Building 571 consists of seven 12- by 60-ft modules with an aggregate floor area of 5040 ft². This building contains offices and a break room and is occupied primarily by civilian personnel assigned to Finance. The two southeast-most modules of Building 571 were practically unoccupied when monitoring commenced.

At the outset of the end-use monitoring test Fort Irwin had 30 modular office/administrative buildings similar to Buildings 567 and 571 and 17 more such buildings were added in 1990. The aggregate floor area of these buildings is 223,920 ft². Modular buildings at Fort Irwin generally consist of four to eight modules connected side-by-side. The average floor area is equivalent to 6.6 modules per building. Construction, lighting type, and HVAC type are very similar across buildings. However, there are some differences among the modular buildings' furnishings and lighting layouts. Electrical energy use at Fort Irwin is thought to be particularly inefficient in modular buildings like Buildings 567 and 571.

3.0 Test Procedures and Equipment

The light and plug circuits of each building were divided into three groups of pure lighting loads, pure plug loads and mixed (light, plug, and small water heater) loads. The power drawn by each heat pump was monitored separately. Room temperatures were monitored at five locations in Building 567 and at four locations in Building 571. Outdoor temperature and solar radiation were monitored at Building 571. All eight supply air temperatures were monitored in Building 567 in order to distinguish between each heat pump's heating and cooling modes of operation.

A PNL 56-channel field data acquisition system (FDAS) and over 70 current transformers (CTs) were installed in each building. The CTs are wired in series for each similar group of loads and the leads from each series loop, which carry a voltage proportional to current for the whole group, connect to FDAS CT input terminals.

There is one two-phase (120/208 volt) electrical distribution panel per module. Thus, Building 567 has eight panels and Building 571 has seven panels. Each panel has four types of loads: lights, plugs, mixed lights and plugs, and a heat pump. Four pairs of CTs were installed in each panel with each pair corresponding to one of the four load types and the CTs of each pair corresponding to the two power phases. A fifth pair of CTs was installed in each panel to measure the total current into the panel. The CTs for a given load type and phase were connected in series across all panels except in the case of the heat pumps, which were monitored individually. The CT channels for the two loggers are enumerated in Table 3.1.

Table 3.1. CT Channel Assignments for End-use Metering Test

Building 567	Building 571	
Main A, B	Main A, B	(sum across all panels)
Lights A, B	Lights A, B	(sum across all panels)
Plugs A, B	Plugs A, B	(sum across all panels)
Mixed A, B	Mixed A, B	(sum across all panels)
HP1 A, B	HP1 A, B	
HP2 A, B	HP2 A, B	
HP3 A, B	HP3 A, B	
HP4 A, B	HP4 A, B	
HP5 A, B	HP5 A, B	
HP6 A, B	HP6 A, B	
HP7 A,B	HP7 A,B	
HP8 A,B		

Thermistors were installed to sense room and supply air temperatures. A linearized YSI thermistor senses outdoor temperature and a LiCor silicon cell pyranometer senses solar radiation on a horizontal surface.

The instruments were installed in late December 1989, and monitoring officially commenced January 1, 1990. The buildings were monitored for two years except for a few periods when data were lost for a week or two due to phone line or modem problems. The analysis presented here covers only periods when both loggers were operating.

4.0 Observations and Analysis

Building 567 was instrumented with supply air temperature sensors that made it possible to distinguish between the heating and cooling modes of each heat pump. Long-term HVAC and non-HVAC loads and average-day profiles are reported for both Buildings 567 and 571.

4.1 Short-Term Observations

A typical winter week (22-28 January) in the power demand history of Building 567 is shown in Figures 4.1 through 4.7. Figure 4.1 shows the non-HVAC loads. The lighting loads are very predictable and regular. The plug and mixed loads vary more but are still fairly predictable. Weekend loads and nighttime loads are very low and constant.

The aggregate electric loads for heat pumps operating in cooling mode and the aggregate electric loads for heat pumps operating in heating mode are shown in Figure 4.2. Heating power demand is greatest in the morning during recovery from night setback. Heating usually stops when occupants arrive and turn lights and equipment on at 0800 because the internal gains are usually sufficient to maintain the heating setpoint. Cooling usually commences at about noon and continues until occupants depart at 1700. This pattern is apparent even in cold weather, such as occurred during the week of January 15-21, 1990. Heat pumps operated throughout the nights of 17 and 18 January but cooling was still called for on the afternoons of January 18 and 19, as shown in Figure 4.3.

There are times (e.g., the morning of 26 January) when heating and cooling occur simultaneously. Most of this simultaneous heating and cooling is due to thermostat or operator error (e.g., a heating setpoint in one module that is higher than the cooling setpoint in an adjacent module). This condition is wasteful and should be eliminated.

Heating and cooling demand distributions are shown in Figures 4.4 and 4.5 to help assess part load operation of the heat pumps.

Figure 4.4 shows the distribution of average 15-minute demands for the heat pumps in Building 567. Both heating and cooling distributions have a peak at about 4 kW, corresponding to the nominal, full-capacity load of one heat pump unit. Note that cooling actually has two peaks, indicating variation in capacity which may be due to different refrigerant charges in different units or to the normal variations in operating conditions. The points that fall between zero and full nominal capacity result whenever a unit cycles on or off during the 15-minute demand averaging interval. The areas under the fractional-capacity parts of the curves are typically greater than the areas under the full-capacity peaks, indicating that most of the heating and cooling effect is delivered in cycles of less than 15-minutes duration. Note that the heating distributions are consistent with reports that strip heaters (i.e., in-duct electric resistance heaters) have been disabled in most or all of the modular buildings at Fort Irwin. A typical 3-ton heat pump would be equipped with 5- to 10-kW strip heaters but no such mode appears in the frequency distribution curve.

Figure 4.5 shows the distribution of demand obtained by taking the average of 15-minute demands over all eight heat pump units in Building 567. Note discrete peaks corresponding to 1, 2, 3 or 4 units operating

simultaneously in cooling mode. The heating demand distribution shows a similar behavior with up to six or seven units operating simultaneously. The simultaneous heating mode operation of several units occurs regularly during morning recovery from night setback.

Indoor air temperature histories for the week are shown in Figure 4.6. A sharp temperature rise is evident each morning. Internal gains cause temperatures to continue to rise after heating demand is satisfied until the cooling setpoint is reached. The behavior in Figure 4.6 indicates heating setpoints of around 24°C and cooling setpoints of around 26°C. Note that the heat pumps operated all day on the Saturday, 27 January, and Sunday, 28 January, indicating that there was no weekend setback strategy in effect. Thermostat "droop" is also evident: daytime indoor air temperatures are about 23°C instead of 24°C.

Figure 4.7 shows histories of the average of the five indoor temperatures measured in Building 567, the average of the four indoor temperatures measured in Building 571, and the outdoor air temperature. Here the different thermostat types used in the two buildings is apparent. The electronic thermostats in Building 571 appear to have a smaller deadband and appear to be programmed for weekend heating setback. The apparent lower rate of temperature decay at night in Building 571 may be the result of one or more of the thermostats failing to enter night setback mode. Indeed, average weekend HVAC energy use over the entire 2-year monitoring period (see Tables 4.1 and 4.2, discussed later) indicates that weekend setback was more effective in Building 567 than in Building 571.

The lack of an aggressive night and weekend setback strategy, and the occurrence of simultaneous heating and cooling, point to a need for improved controls and improved operation and maintenance.

Figure 4.1. Non-HVAC Loads in Building 567 for the Week of 22 January 1990

Figure 4.2. Primary Heating and Cooling Power in Building 567 for the Week of 22 January 1990

Figure 4.3. Primary Heating and Cooling Power in Building 567 for the Week of 15 January 1990

Figure 4.4. Frequency of 15-Minute Average Heat Pump Power in Building 567

Figure 4.5. Frequency of 15-Minute Average Power for All Heat Pumps Together in Building 567 (expressed in kW per heat pump unit)

Figure 4.6. Indoor Air Temperature Histories in Modules 1, 2, 5, 6 and 8 of Building 567 for the Week of 22 January 1990

Figure 4.7. Outdoor Temperature and Average Indoor Air Temperatures in Buildings 567 and 571 for the Week of 22 January 1990

4.2 Long-Term Observations

The long-term histories of daily energy use by separately monitored loads are shown in Figures 4.8 through 4.15.

Figures 4.8 and 4.9 show the heating and cooling energy for Buildings 567 and 571 on workdays. Note that for Building 567 there is a breakdown into primary heating, primary cooling and fan energy. There is also a history of daily energy waste due to simultaneous heating and cooling by heat pumps in adjacent modules. Figures 4.10 and 4.11 show the same data for non-workdays.

Figures 4.12 and 4.13 show the lighting loads, plug loads and mixed loads for Buildings 567 and 571 on workdays. Note that the loads (lighting in particular) are not as constant as expected for an office/administrative type building. The first shift in energy use occurs at the end of May 1990. This correlates with a change in work schedule adopted to reduce on-peak energy use. To gain more insight into changing energy use patterns, the daily load profiles were plotted; the profiles are discussed in the next section. Figures 4.14 and 4.15 show the historical light, plug, and mixed load data for non-workdays. The non-workday loads are much lower than workday loads and the variability is low as is typical for this building type.

Table 4.1 gives the average daily energy use and the corresponding energy-use intensity (EUI) by load for Building 567. Table 4.2 gives the corresponding data for Building 571.

Figure 4.8. Workday Average Primary HVAC Loads in Building 567

Figure 4.9. Workday Average Primary HVAC Loads in Building 571

Figure 4.10. Non-Workday Average Primary HVAC Loads in Building 567

Figure 4.11. Non-Workday Average Primary HVAC Loads in Building 571

Figure 4.12. History of Workday Average Non-HVAC Loads in Building 567

Figure 4.13. History of Workday Average Non-HVAC Loads in Building 571

Figure 4.14. Non-Workday Average Non-HVAC Loads in Building 567

Figure 4.15. Non-Workday Average Non-HVAC Loads in Building 571

Table 4.1. Energy Use in Building 567 by End Use

Bldg 567 (5760 sf)	Energy Use (kWh/day)										
Workdays:	Total	Lights	Plugs	Mixed	HVAC	nonHVAC	Heat	Cool	Fan	sHC[a]	EC[b]
01/01/90 - 05/24/90	294.6	131.0	33.1	36.7	94.9	200.8	15.1	70.8	9.0	3.9	22.79
06/01/90 - 12/19/90	240.2	79.0	24.0	27.2	109.0	130.2	8.9	91.7	8.4	6.3	11.58
01/09/91 - 09/24/91	298.0	114.0	30.6	28.3	125.2	172.9	13.6	108.6	3.0	10.1	19.8
11/25/91 - 01/27/92	292.6	111.8	20.6	30.8	130.8	163.2	64.8	62.9	3.1	41.3	38.85
All Workdays	277.7	105.9	27.7	29.6	114.4	163.2	18.5	89.9	6.1	11.0	19.61
All Non-Workdays	80.0	16.7	9.5	9.1	44.7	35.3	15.6	25.2	3.9	3.7	5.51

Bldg 567	Energy Use Intensity (kWh/sf-yr)										
Workdays:	Total	Lights	Plugs	Mixed	HVAC	nonHVAC	Heat	Cool	Fan	sHC[a]	EC[b]
01/01/90 - 05/24/90	18.7	8.3	2.1	2.3	6.0	12.7	1.0	4.5	0.6	0.2	1.4
06/01/90 - 12/19/90	15.2	5.0	1.5	1.7	6.9	8.3	0.6	5.8	0.5	0.4	0.7
01/09/91 - 09/24/91	18.9	7.2	1.9	1.8	7.9	11.0	0.9	6.9	0.2	0.6	1.3
11/25/91 - 01/27/92	18.5	7.1	1.3	2.0	8.3	10.3	4.1	4.0	0.2	2.6	2.5
All Workdays	17.6	6.7	1.8	1.9	7.3	10.3	1.17	5.69	0.39	0.70	1.24
All Non-Workdays	5.1	1.1	0.6	0.6	2.8	2.2	0.99	1.60	0.25	0.23	0.35
Std DayType Mix	13.7	4.9	1.4	1.5	5.9	7.8	1.11	4.41	0.34	0.55	0.96
		36.1%	10.2%	10.7%	42.9%	57.1%	8.1%	32.2%	2.5%	4.0%	7.0%

[a] primary energy for simultaneous heating and cooling

[b] primary cooling energy that can be saved with economizer cooling

Table 4.2. Energy Use in Building 571 By End Use

Bldg 571 (5040 sf)	Energy Use (kWh/day)					
	Total	Lights	Plugs	Mixed	HVAC	nonHVAC
Workdays:						
01/01/90 - 05/24/90	250.7	91.2	24.7	46.7	86.4	162.6
06/01/90 - 12/21/90	163.7	34.4	10.2	31.0	91.7	75.6
01/09/91 - 09/24/91	140.5	39.3	12.4	26.9	69.7	78.6
11/21/91 - 01/27/92	184.0	87.3	11.4	36.3	59.1	134.9
All Workdays	172.2	51.2	13.6	32.6	79.8	96.9
All Non-Workdays	80.6	2.8	3.0	13.5	59.9	19.2

Bldg 571	Energy Use Intensity (kWh/sf-yr)					
	Total	Lights	Plugs	Mixed	HVAC	nonHVAC
Workdays:						
01/01/90 - 05/24/90	18.2	6.6	1.8	3.4	6.3	11.8
06/01/90 - 12/21/90	11.9	2.5	0.7	2.2	6.6	5.5
01/09/91 - 09/24/91	10.2	2.8	0.9	1.9	5.0	5.7
11/21/91 - 01/27/92	13.3	6.3	0.8	2.6	4.3	9.8
All Workdays	12.5	3.7	1.0	2.4	5.8	7.0
All Non-Workdays	5.8	0.2	0.2	1.0	4.3	1.4
Std DayType Mix	10.4	2.6	0.7	1.9	5.3	5.3
		25.1%	7.2%	18.5%	51.3%	50.6%

4.3 Average Daily Demand Profiles

Figures 4.16 through 4.20 show the lighting and non-HVAC (aggregate of light, plug, and mixed) load profiles for the four periods defined by the distinct changes in average non-HVAC load.

Weekday demand profiles for lighting circuits are shown in Figures 4.16 and 4.17. In Building 567, Figure 4.16, the change in workday schedule is apparent but there are also large changes in the heights of the profiles. These changes can only be explained by delamping or office vacancies. Note that daytime lighting power density is highest during 1/90 - 5/90, is lowest during 6/90 - 12/90, returns almost to the 1/90 - 5/90 power level during 1/91 - 9/91 but drops again for 11/91 - 1/92. In Building 571, Figure 4.17, the change in workday schedule is also apparent. Here there are even larger changes in the heights of the profiles. These changes can only be explained by delamping or office vacancies. Note that daytime lighting power density is highest during 1/90 - 5/90, lowest during 6/90 - 12/90, and returns almost to the 1/90 - 5/90 power level during 11/91 - 1/92.

Non-HVAC demand profiles for the entire monitoring period are shown in Figures 4.18 and 4.19. The weekday non-HVAC (including lights) and pure lighting profiles have very similar shape in both buildings and are also similar between buildings. However, the weekday (Figure 4.18) power densities are about 50% higher for Building 567, consistent with the observations presented earlier in Tables 4.1 and 4.2. The weekend profiles, Figure 4.19, show occasional daytime use of Building 567 but rare weekend daytime use of Building 571. Note that both buildings have a non-HVAC equipment baseload of about 0.15 W/ft² (1.3 kWh/ft²-yr); these baseloads would include small service water heaters and break room refrigerators.

The relation between weekday and weekend non-HVAC demand profiles can be seen clearly in Figure 4.20.

Figure 4.16. Daily Average Demand Profile in Building 567 for Pure Lighting Circuits During Four Distinct Monitoring Periods

Figure 4.17. Daily Average Demand Profile in Building 571 for Pure Lighting Circuits During Four Distinct monitoring periods

Figure 4.18. Average Weekday Demand Profiles for the Entire Monitoring Period-

Figure 4.19. Average Non-weekday Demand Profiles for the Entire Monitoring Period

Figure 4.20. Weekday and Weekend Non-HVAC Demand Profiles for Buildings 567 and 571

5.0 Energy Resource Opportunities

An energy resource opportunity (ERO) is any conservation, efficiency, or fuel-switching measure that will save energy at the site or at the primary energy source (e.g., involving the serving electric utility's raw energy mix). Six such opportunities have been evaluated for the modular buildings at Fort Irwin and are discussed in this section.

5.1 Improved HVAC Controls

Primary HVAC energy can be saved by implementing night and weekend setback schedules with an optimal start feature. Additional energy can be saved by including controls to prevent simultaneous heating and cooling.

Description. The modular buildings currently use separate thermostats to control the heat pumps in each module. The large number of thermostats makes implementation of night setback a difficult operation and maintenance problem. An attractive solution is to add a central controller to each building. The controller will enable heating or cooling based on the average temperature sensed by multiple sensors. This will allow the heat pumps to heat or cool but not both. With a central control deadband of 1°C and module thermostat deadbands of 3 to 4°C, there will be ample margin for variation in individual setpoints to satisfy occupants' comfort criteria. At night and on weekends the central control will operate with a lower heating setpoint of 12 to 15°C and will disable cooling entirely. Time to recover from night setback will be estimated by an optimal start algorithm based on average indoor temperature, outdoor temperature, and day-time heating setpoint. This will allow a low night heating setpoint to be used without the penalty of having to initiate recovery on a fixed, early morning (worst case) schedule. A lower-cost alternative to the EMCS-type controller described above is a full-featured electronic thermostat wired to enable the heating and cooling modes of the individual module thermostats. Another alternative is to include sufficient inputs with the central control to measure the air temperature at each zone and completely replace the existing thermostats.

Assumptions. Elimination of simultaneous heating and cooling will save 3,200 kWh/yr in Building 567 and 2,000 kWh/yr in Building 571. Based on the current non-workday HVAC consumption of 37,000 kWh/yr and the workday night heating consumption of 10,000 kWh/yr, night and weekend setback with optimal start should save at least 16,000 kWh/yr. Setback and optimal start savings accrue at a rate of \$0.05/kWh and \$2.15/kW-mo; simultaneous heating and cooling prevention accrues savings of \$0.10/kWh and about \$6.00/kW-mo. A load factor of 0.5 is assumed for demand savings calculations.

The annual energy saved by night and weekend setback costs \$800, with associated demand charges of \$50; the annual energy saved by prevention of simultaneous heating and cooling costs \$500, with associated demand charges of \$250. The total annual savings in the two buildings is therefore about \$1,600.

The small commercial building EMCS control market is large and very competitive. A number of manufacturers offer 16-point (e.g., 8 analog in, 8 digital out) units for under \$1,500. Four temperature sensors and one outdoor temperature sensor will cost \$300, and installation labor and programming will cost \$500 per building assuming 10 or more buildings are involved. Wiring to existing thermostats will cost about \$100, and thermostat replacement (if necessary) will cost about \$100 each, including labor. Maximum total cost is therefore about \$3,200 per building. Note that the cost to expand the EMCS

controller and add four additional room temperature sensors may be no more than the cost to replace all thermostats.

Result. The first cost to implement improved controls in the two buildings is about \$6,400. Annual energy savings of about 13,000 kWh and about \$350/yr in demand charges will result. The net present value^(a) (NPV) of the measure is \$12,967 and the savings-to-investment ratio^(b) (SIR) is 3.03.

5.2 Two-Speed Fan Motors

Description. Each heat pump has a supply air fan that operates continuously during occupied hours. A two-speed fan can be operated at two-thirds speed during occupied hours when there is no heating or cooling load. The measure requires replacement of the fan motor and installation of a relay to select high speed only when the heat pump compressor is on.

Assumptions. The fans use over 4,000 kWh/yr during fan-only operation. This can be reduced by 2,600 kWh/yr by replacing the fan motors with two-speed motors. The value of the energy savings is \$260, but the associated demand savings is only about \$25/yr because most of the fans will be running at high speed during the summer monthly basewide peaks.

Result. The first cost to retrofit the heat pump units with two-speed supply air fans in the two buildings is about \$3,450. Annual energy savings of about 2,600 kWh and about \$25/yr in demand charges will result. The NPV of the measure is \$1,144 and the SIR is 1.33.

5.3 Two-Speed Compressors

Description. The existing heat pumps have single-speed compressors. A heat pump equipped with a two-speed compressor operates more efficiently at part load by obtaining much closer approach temperatures in the evaporator and condenser heat exchangers and by dissipating less energy in the form of refrigerant loop friction losses. A two-stage expansion valve and two-stage room thermostat controls must also be provided with this retrofit.

Assumptions. Heat pumps can satisfy the loads 90% of the time at 60% of current capacity. Energy use under these conditions will be reduced by 25% in heating mode and 30% in cooling mode. This will reduce annual HVAC energy in the two buildings from 60,000 kWh to 44,000 kWh, for a savings of \$1,500. The cost of a two-speed, three-ton compressor is \$400; installation labor cost is \$150; additional controls will cost about \$200, installed, per heat pump unit. The retrofit will therefore cost \$11,250 for Buildings 567 and 571.

-
- (a) Net present value (NPV) is the difference between the present value (PV) of net savings over the life-cycle cost analysis period and the initial cost of the measure. The PV of net savings is the difference between the sum of PVs of all costs, including energy, to operate and maintain the base-line plant and the sum of PVs of all costs to operate the alternative plant.
 - (b) Savings-to-investment ratio (SIR) is the ratio of first cost to the PV of gross savings. The PV of gross savings equals the first cost plus the NPV.

Result. The first cost to retrofit with two-speed compressors in the two buildings is about \$11,600. Annual energy savings of about 16,000 kWh and about \$370/yr in demand charges will result. The NPV of the measure is \$21,743 and the SIR is 2.87. Use of smaller compressors, based on the peak load data reported herein, should be considered if this ERO is implemented. Another option to be considered is replacement of each entire heat pump unit by a high-efficiency unit with a two-speed or variable-speed compressor and fans. Though not evaluated in this study, utility incentives may be available for this option.

5.4 Lighting Retrofit

Description. Lighting use during occupied periods was initially 3.0 W/ft². The potential for delamping observed in a lighting survey (Armstrong 1990) appears to have been achieved for about six months but the lighting load intensity later increased, indicating that the reduced intensity was probably due to office vacancy rather than delamping. The lighting level reductions recommended in Armstrong (1990), together with conversion of the fixtures to T-8 technology will reduce the power density for lighting to about 1.8 W/ft². The lighting technology retrofit should be undertaken, and its evaluation is presented in a forthcoming assessment report.^(a)

5.5 White Roof Coating

Description. The existing roof is a black synthetic rubber membrane. White reflective roof coating materials are available to reduce heat gains from absorbed solar radiation.

Assumptions. Solar energy incident on the two buildings amounts to about 2,000,000 kWh per year. About 2% of this, or 40,000 kWh/yr, contributes directly to the cooling load. The measured annual cooling load for the two buildings is 113,000 kWh, based on an assumed COP of 2. White roofs will eliminate at least half of the 40,000 kWh/yr thermal load, for an annual—mostly on-peak—electric load savings of 8,000 kWh, which corresponds to energy bill savings of \$800 and associated demand savings of \$250. The cost of coating the roof is estimated to be \$1.00/ft²; the total cost for the two buildings is therefore \$10,800. Renewal of the coating at 5-year intervals is assumed.

Result. The first cost to apply a reflective roof coating to both buildings is about \$10,800. Annual energy savings of about 8,000 kWh and about \$250/yr in demand charges will result. The NPV of the measure is \$6,125 and the SIR is 1.57.

5.6 Economizer Cooling

Description. Economizer cooling can be added to the existing system in a number of ways. The simplest system would involve one economizer damper retrofit package per heat pump. However, such a retrofit may not be feasible due to the compact nature of the heat pump units. We therefore consider a system that adds a filtered outdoor air fan unit, an exhaust fan unit, and an EMCS unit and variable-speed

(a) Hadley, D. L., D. R. Dixon, J. M. Keller, E. E. Richman, S. A. Shankle, R. R. Wahlstrom, *Fort Irwin Integrated Resource Assessment—Volume 3: Resource Assessment*, Draft Report (1993), Pacific Northwest Laboratory, Richland, Washington.

motor controller for each four modules. A back-draft damper will be provided at each heat pump supply air outlet and a motorized damper will be installed where the outside air duct branches to each of the four supply air ducts. Each exhaust fan will be located at the center of the roof area of the module it serves and will remove air directly from the ceiling plenum. The EMCS will monitor the existing thermostat signals, as well as exhaust and outside air temperatures and relative humidities and will control the new supply and exhaust fan speeds and open or close the motorized dampers accordingly.

Assumptions. Energy and demand savings were calculated from the monitored compressor loads, after eliminating simultaneous heating and cooling, by applying a nominal cooling COP of 2.5 and assuming a supply air flow rate of 1000 cfm per supply fan. On this basis, economizer cooling will save about 7,140 kWh/yr on workdays and 2,020 kWh/yr on non-workdays in Building 567. Workday savings accrue at the rate of \$0.092/kWh, and the non-workday savings accrue at the rate of \$0.052/kWh. Demand savings of about 70 kW-months per year will also accrue at a weighted average rate of \$4.55 per kW-month.

The costs for the economizer system are as follows: outside air fan (2): \$1,700; outside air ductwork, installed: \$2,160; motorized dampers (8): \$1,600; exhaust fan with backdraft damper and curb, installed (2): \$2,140; variable-speed drive, installed (2): \$2,376 (Armstrong et al. 1993b); temperature and RH sensors, installed (3): \$375; EMCS unit (2) \$3,000; EMCS sensor and actuator interface: \$850.

Result. The estimated first cost for the retrofit is \$14,200. Annual energy and demand savings are \$762 + 318 = \$1,080/yr. The NPV of the measure is \$83 and the SIR is 1.01.

5.7 Summary of EROs

Life-cycle costs of the five EROs evaluated above are summarized in Table 5.1. The NPVs and SIRs were computed using BLCC (building life-cycle cost) version 3.2 for 1993 (Petersen 1992; Ruegg and Petersen 1987; NBS 1987; NIST 1993). There are some interactions that will reduce the attractiveness of some EROs and increase the attractiveness of others. Estimates of these interactive effects are reflected in the modified SIR (MSIR) values.

Table 5.1. Present Value of Alternative Projects Shown in Ascending Order of Initial Cost

Project Name	Initial Cost (PV)	Net Present Value (NPV)	SIR	MSIR
Modular Building Base Case	\$0	\$0		
Two-Speed Supply Fans	\$3,450	\$1,144	1.33	1.4
Improved HVAC Controls	\$6,400	\$12,967	3.03	2.5
Two-Speed hp Compressors	\$11,625	\$21,743	2.87	2.0
Reflective Roof Coating	\$10,800	\$6,125	1.57	1.2
Economizer Cooling (B567)	\$14,200	\$83	1.01	1.5

6.0 Conclusions and Recommendations

The electric demand monitoring results of Section 4 and the analysis of Section 5 indicate that substantial savings are possible by lighting retrofits, two-speed compressor and fan retrofits, improved HVAC controls, reflective roof coatings, and economizer cooling.

6.1 Existing Buildings

The following conservation measures are recommended for existing office buildings:

- T-8 system lighting retrofit
- improved HVAC controls including weekend setback, heating/cooling arbitration, and optimal-start controls
- two-speed fan retrofit.

6.2 New Buildings

Some of the improvements that are attractive in new buildings, such as use of reflective roof materials, can be achieved at virtually no cost when included as part of the new building design specification. Others should be subject to payback analysis by the building designer or design/build team before they are adopted. Based on our analysis the following are recommended:

- New modular buildings should be designed with high-efficiency heat pumps that use variable-speed or two-speed compressors. Utility rebates may be available for this equipment.
- Each new modular building should be equipped with a central controller that provides separate thermostatic control for each unit based on average air temperature at two or three representative points. The controller should also implement night, weekend and holiday setback, optimal start control, and weekend override by unit.
- Small-scale, high-efficiency heat pump-based VAV systems should be considered for new modular buildings; optimal start and enthalpy economizer controls should be included in the HVAC package. Utility rebates may be available for this equipment.
- New modular buildings should be provided with economizer cooling.
- New modular buildings should be designed with reflective roof materials.

- Water heating by desuperheaters should be considered in new buildings that have significant water heating loads.
- Small-scale district cooling tower loops with diurnal storage should be considered for new modular buildings with water source heat pump-based HVAC systems. Utility rebates may be available for this equipment.

7.0 References

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Appendix A

MEL Assignment Plan

MEL Assignment Plan (MAP) - Test Identification

Date: September 26, 1989

Completed By: Don Hadley

Site: Ft. Irwin, California

Test No. IRWIN-002

Test Objective: Determine the electric end use profiles of 2 "typical" new modular office buildings. One building will be monitored "as-is." In the second building, the thermostats will be operated with an evening/weekend setback, and possible temporary shut down of some of the heat pumps.

The modular office buildings are equipped with a three-ton heat pump for each 12' x 60' (720 ft²) section and it is suspected there is excess cooling capacity for the combined units. The buildings may be using more electric energy than necessary and contributing significantly to the total electric use for the base. Electric use will also be compared to other office buildings previously monitored in the ELCAP study.

Test Description: Collect time-series electric end use data (heat pump, lighting, convenience outlets) for each office building using PNL commercial FDAS loggers. Indoor and outdoor temperatures will be monitored.

Test Procedure(s): Test Procedure 1 - Building Energy Monitoring

Schedule Requirements: The equipment should be installed in time to monitor energy consumption during the period of maximum demand (July and August). Data should be collected for a minimum of 4 months to account for unusual short-term conditions caused by abnormal weather.

Installation of a single dedicated phone line near the point of installation of each data logger is required for routine data collection.

Cost Estimate: PNL personnel, equipment, and reporting: \$23,400 to \$27,000
DEH support: 24 manhours

Approvals:

Richard Szydlowski
MEL Tech Coordinator

Date

Graham Parker
MEL Project Manager

Date

John R. Wright
LTC, ENG
Ft. Irwin

Date

Jim Vasiloff
FORSCOM

Date

Appendix B

Glossary

Appendix B

Glossary

Terms and Acronyms

ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
CT	current transformer—a device which senses alternating current
load	the power or apparent power required by a building or end-use
baseload	constant part of a time-varying electrical load
desuperheater	a heat exchanger used to remove heat from superheated refrigerant that leaves a heat pump compressor and (usually) heat domestic water
economizer	a system to cool by use of outside air when conditions permit
EMCS	Energy Management Control System—describes a variety of general purpose, usually microprocessor-based, HVAC (and other facility) controls
energy-use intensity (EUI)	annual energy consumption divided by gross floor area
end-use	a class of energy using devices that serve a specified function
ERO	energy resource opportunity—a potential efficiency, conservation or fuel-switching measure
FEDS	federal energy decision screening—the federal-sector IRP process
FEMP	Federal Energy Management Program—the umbrella program under which the MEL operates
heat pump	a refrigeration machine that can operate in reverse to provide heating as well as cooling
HVAC	heating, ventilating, and air conditioning
IES	Illuminating Engineers Society
IRP	integrated resource planning—least cost planning process that considers all energy, conservation, and efficiency resource options

LCC	life-cycle cost--the PV of owning and operating a facility
MEL	Mobile Energy Laboratory
NPV	Net Present Value--the difference between the present value (PV) of net savings over the life-cycle cost analysis period and the initial cost of the measure; the PV of net savings is the difference between the sum of PVs of all costs, including energy, to operate and maintain the baseline plant and the sum of PVs of all costs to operate the alternative plant
PV	present value--the value of a series of costs or savings, distributed over time, adjusted for the time-value of money to the present
primary heating (cooling) energy	the energy required to operate a heating (cooling) plant
retrofit	energy resource option in which equipment is wholly or partly replaced
SCE	Southern California Edison--Fort Irwin's electric utility
setback	a change in setpoint that results in lower energy use during unoccupied periods, e.g., a lower heating or higher cooling temperature setpoint
SIR	Savings-to-Investment-Ratio--the ratio of first cost to the PV of gross savings where the PV of gross savings equals the first cost plus the NPV
source energy	the energy required by a power plant to satisfy a given energy end-use or service
TOU	time of use--a type of electric rate structure
VAV	variable-air volume--a type of forced air HVAC distribution system
VSD	variable-speed drive--a power controller used to modulate motor speed
workday	day when a commercial building is fully occupied, e.g., most weekdays

Units of Measure

A	Ampere (electric current)
V	Volt (electric potential)
kW	kilowatt (electric power)
kWh	kilowatt-hour (electric energy)
MWh	megawatt-hour (electric energy)
kVA	kilovolt-Ampere (apparent electric power)
Btu	British thermal unit (thermal energy)
W/ft²	power density in watts per square foot of floor area
kWh/ft²-yr	average power density in kilowatt-hours per square foot per year
cfm	cubic foot per minute (volumetric flow rate)
ton	A measure of cooling plant capacity equal to 12,000 Btu/hr

Appendix C

SCE Rate Schedule

Appendix C

SCE Rate Schedule

The rate schedule in effect during the monitoring period is shown below. The summer billing period for Southern California Edison (SCE) runs from the first Sunday in June to the first Sunday in October. This period will be 17 weeks long in 4 of every 7 years and 18 weeks long in 3 of every 7 years. The average number of working days in the summer billing period is therefore:

$$(4*17 + 3*18) * 5/7 - 2 = 85.14$$

and the average number of working days in the winter billing period is:

$$252.89 - 85.14 = 167.75$$

Rates and times for SCE's time-of-use (TOU) billing periods are summarized below:

SCE TOU Billing Period	Ft. Irwin Office Hr	Hours	\$/kW	\$/kW
Summer On-Peak 12:00-1800	12:00-17:00	5.0	.10216	14.15
Winter On-Peak 12:00-18:00	8:00-12:00	4.0	.08268	2.15
Winter Mid-Peak 8:00-12:00	12:00-17:00	5.0	.09288	2.15
Off-Peak	7:30-8:00	0.5	.05012	2.15

The annual direct cost per baseload kW is therefore:

Days	hr/day	\$/kWh	Mos.	\$/kW	\$/kWb
85.14	* 5.0 *	.10216	+ 4 *	14.15	= 100.09
85.14	* 4.0 *	.08268	+ 4 *	2.15	= 36.43
167.75	* 5.0 *	.09288	+ 8 *	2.15	= 95.10
167.75	* 4.0 *	.09288	+ 8 *	2.15	= 79.52
252.89	* 0.5 *	.05012	+ 12 *	2.15	= 32.14
					343.29

The additional cost for cooling at a coefficient of performance (COP) of 2.5 is $(100.09 + (4+8+8+12) * 2.15)/2.5 = \$67.56/\text{yr}$. This gives a total energy cost of \$410.84/yr per baseload lighting kW.

The on-peak demand charge is \$14.15 per kW per month during the four summer months. There is an additional savings of 1/2.5 kW in cooling demand for every 1 kW of avoided lighting load. The annual savings per kW of avoided on-peak summer lighting load is therefore:

$$\$14.15 * 4 * (1 + 1/2.5) = \$79.24$$

The on-peak demand charge is \$2.15 per kW per month during the eight winter months. There is an additional savings of 1/2.5 kW in cooling demand for every 1 kW in lighting load. The annual savings per kW of avoided on-peak winter lighting load is therefore:

$$\$2.15 * 8 * (1 + 1/2.5) = \$24.08$$

Appendix D

Additional Data

Appendix D

Additional Data

Weekly data plots from December 1989 and January, February, March 1990 are presented in this appendix.

The first set of plots, pages D.2 through D.14, shows load histories for five end-uses monitored in Building 567. The load histories for lights, plugs, and mixed circuits are shown in the upper figure on each page. The aggregate electric loads for heat pumps operating in the cooling mode and the aggregate electric loads for heat pumps operating in the heating mode are shown in the lower figure on each page.

Heating and cooling demand distributions for Building 567 are shown in the second set of plots, pages D.15 through D.27. The lower figure on each page shows the distribution of demand obtained by taking the average of 15-minute demands over all eight heat pump units.

Indoor air temperature histories are shown in the third set of plots, pages D.28 through D.35. The upper figure on each page shows the five room temperatures measured in Building 567. The lower figure on each page shows the four room temperatures measured in Building 571.

Additional temperature histories are shown in the fourth set of plots, pages D.36 through D.43. The upper figure on each page shows the average of five room temperatures in Building 567, the average of four room temperatures from Building 571, and outdoor temperature measured at Building 567 (measured outside the north wall just below the roofline). The lower figure on each page shows two additional temperature histories. The outdoor temperature measured by a shielded thermistor outside of Building 571 closely tracks the outdoor temperature measured outside of Building 567. The jagged line that alternately rises above and falls below the average Building 567 room temperature is the average of eight supply air temperatures measured in Building 567.

The last page, D.44, shows average-day heat pump and non-heat pump loads in the two buildings for late December 1989 through early March 1990. The upper plot is for weekdays and the lower plot is for weekends.

Building 567 Power Demand by End Use

PNL 90/03/21

Building 567 Heating and Cooling Power

Building 567 Power Demand by End Use

PNL 90/03/21

Building 567 Heating and Cooling Power

PNL 90/03/21

Building 567 Power Demand by End Use

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Building 567 Heating and Cooling Power

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Building 567 HP Power Distributions

(All Units)

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Room Temperatures--Bldg 567

PNL 90/03/15

Room Temperatures--Bldg 571

PNL 90/03/15

Room Temperatures--Bldg 567

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- Tmod1 Tmod2 Tmod5 Tmod6 Tmod8

Room Temperatures--Bldg 571

PNL 90/03/15

Tmod2 Tmod3 Tmod4 Tmod5

Room Temperatures--Bldg 567

PNL 90/03/15

Room Temperatures--Bldg 571

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Room Temperatures--Bldg 567

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Room Temperatures--Bldg 571

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Monitored Temperatures--Bldgs 567 & 571

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Monitored Temperatures--Bldgs 567 & 571

PNL 90/03/15

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