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Introduction to Commercial Building Control Strategies and Techniques for Demand Response - Appendices

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Demand Response Research Center

Introduction to Commercial Building Control Strategies and Techniques for Demand Response

Appendices

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Appendix A
DR Strategies for HVAC Systems

Appendix A: DR Strategies for HVAC

This section provides additional technical details on HVAC DR strategies that are not covered in the main report. Although section 4.3 of the main report discusses statistical data from actual demand saving results, it does not clearly identify the demand savings results for some strategies, for reasons such as irregular whole building load shape, lack of sub-metering, or the application of multiple DR strategies. This appendix contains some actual demonstration results, which clearly illustrate the effects of the strategies. Table A.1 is a summary of the strategies discussed in this appendix.

Table A.1. Summary of DR strategies

Category	DR Strategy	Technical Details	Case Study
Zone control	Global temperature adjustment	X	X
	Passive thermal mass storage	X	
Air distribution	Duct static pressure decrease	X	
	Fan variable frequency drive limit	X	X
	Supply air temperature increase	X	
	Fan quantity reduction		X
	Cooling valve limit		X
Central plant	Chilled water temperature increase		
	Chiller demand limit		
	Chiller quantity reduction		
Rebound avoidance	Slow recovery		X
	Sequential equipment recovery		
	Extended DR control period		X

A.1. Global Temperature Adjustment (GTA)

Case Study

Site Name	**2530 Arnold (Martinez CA), government office**
DR Strategy	**Moderate Price (12:00 p.m. - 3:00 p.m.)** ▪ Zone setpoint increased 2°F (76°F to 78°F) **High Price (3:00 pm - 6:00 pm)** ▪ Zone setpoint increased 4°F (80°F)
Event Date	9/22/2005 (Max OAT: 82°F)

Figure A.1. Whole building power (global temperature adjustment) - 2530 Arnold shows the whole building power and baselines[1] of the building on a DR event day. This site used GTA, which has two levels of step increase (Pattern #1). The whole building demand dropped 100 kW immediately after the moderate price period started (transient savings). After about an hour the whole building demand increased and stabilized around 50 kW lower than the baseline (steady-state savings). This indicates that it took an hour to increase zone temperature from 76°F to 78°F with no cooling or a minimum level of cooling. 350 kW of whole building demand was required to maintain a 78°F setpoint, while 400 kW was required to maintain a 76°F setpoint.

When the high price period started, the demand dropped again from 350 kW to 300 kW (transient savings). After about an hour the whole building demand slightly increased. Around this time the whole building demand began to decrease towards the end of the occupancy period. The building did not have a rebound peak because the occupancy period ended at nearly the same time as the end of the curtailment period.

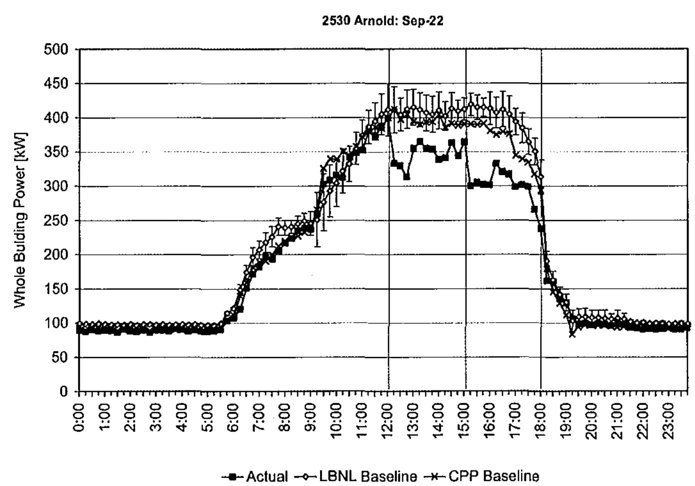

Figure A.1. Whole building power (global temperature adjustment) - 2530 Arnold

[1] LBNL's OAT regression baseline model and PG&E's CPP baseline (highest 3 days of the last 10 non-event working days) are plotted.

A.2. Passive Thermal Mass Storage

This section summarizes the results of a simulation analysis of passive thermal mass storage strategy conducted by Purdue University (Braun et al. 2001). Several thermal mass pre-cooling and discharge strategies were examined in the simulation.

Table A.2 shows details of the building for which the simulation model was developed. The simulation tool was used to estimate cooling season operation for a variety of DR strategies, utility rates, and locations. For these simulations, typical meteorological year (TMY) data were used for all locations. The acceptable range of occupied zone air temperatures was considered to be between 69°F to 77°F. This range was based on comfort studies specific to the field site (Keeney and Braun 1997).

Table A.2. Simulation building description

Building use	Headquarters office building
Building profile	• 1.4 million ft^2, 4-story • Heavy-weight concrete structure, energy-efficient windows • Total of 3,600 ton chillers, AHU with VAV, total 1,200,000 cfm • Occupancy period 7 a.m. to 5 p.m.
DR Strategy	Pre-cooling

Figure A.2. Weekday hourly zone temperature setpoints for night setup, light, moderate, and extended pre-cooling strategies shows zone setpoint temperature variations for four strategies where the on-peak occupied setpoint was held constant at 73°F. *Night setup* was the baseline used for comparing the alternative strategies. The *light pre-cooling* and *moderate pre-cooling* strategies are simple strategies that pre-cool the building at a fixed setpoint of 67°F prior to occupancy and then maintain a fixed discharge setpoint in the middle of the comfort range, 73°F, during occupancy. The light pre-cooling begins at 3 a.m., whereas moderate pre-cooling starts at 1 a.m. The *extended pre-cooling* strategy also starts at 1 a.m. and attempts to maintain the thermal mass cooled until the onset of the on-peak period. In this case, the setpoint at occupancy is maintained at the lower limit of comfort, 69°F, until the on-peak period begins at 9 a.m. At this point, the setpoint is raised to the middle of the comfort range (73°F).

Figure A.3 shows the simulated cooling loads for a sample day in mid-July in Chicago for each of the strategies. For all three strategies, night setup resulted in very little cooling during the unoccupied period, with a peak ocurring in the middle of the night. The cooling requirement was relatively flat during the day, with a second peak near the end of the occupied period. Each of the pre-cooling strategies resulted in reduced cooling requirements throughout the occupied period, particularly in the early morning. The greater the pre-cooling, the greater the on-peak period load reduction. For each strategy, although the on-peak <u>total</u> cooling requirement was reduced significantly, the peak cooling requirement during the on-peak period was only marginally reduced. These strategies tended to discharge the mass relatively early during the on-peak period.

The peak loads could be reduced further if up to the upper limit of comfort range were used throughout the on-peak occupied period.

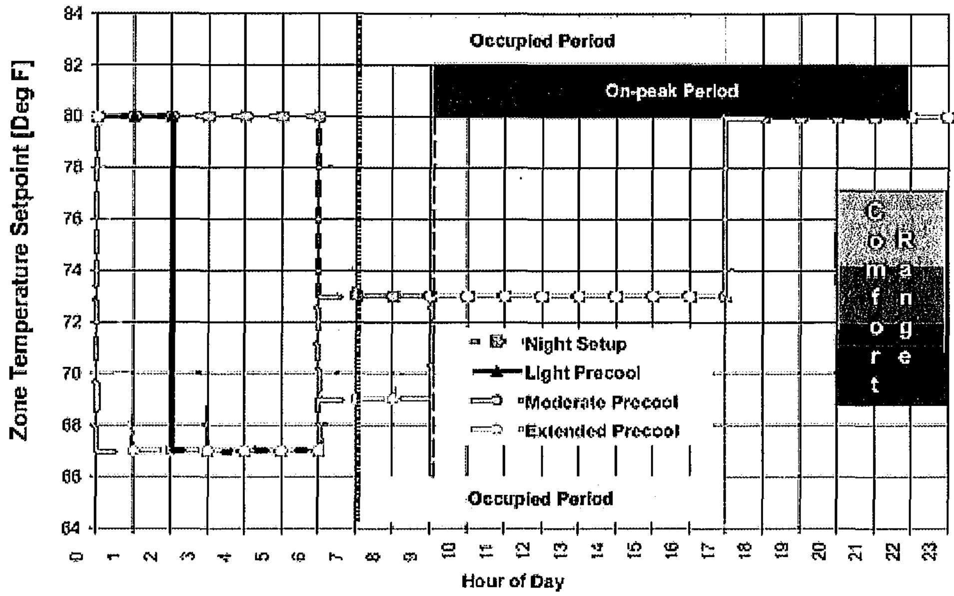

Figure A.2. Weekday hourly zone temperature setpoints for night setup, light, moderate, and extended pre-cooling strategies

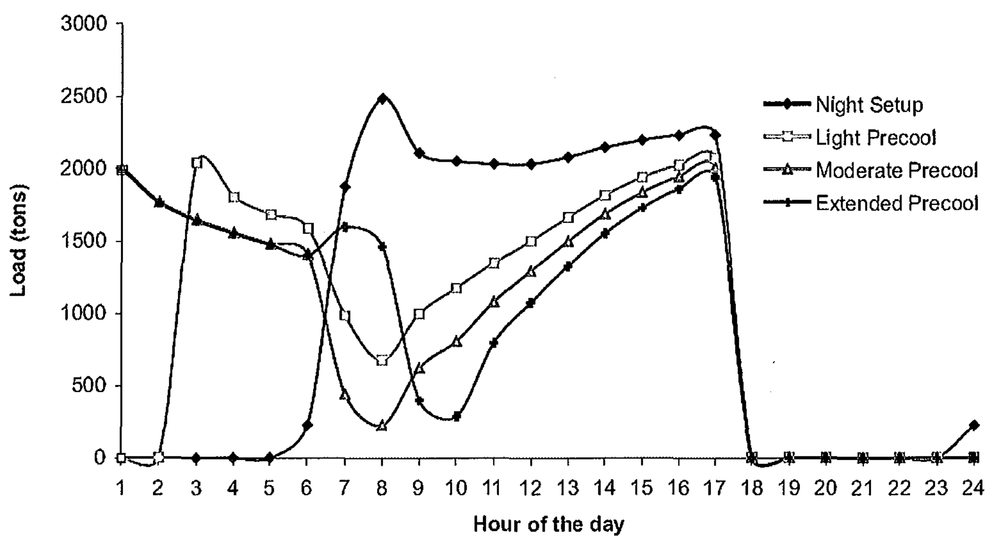

Figure A.3. Cooling load profiles for night setup, light, moderate, and extended pre-cooling strategies

Figure A.4 shows two additional strategies that have the same pre-cooling characteristics as the *extended pre-cooling* strategy, but that use the entire comfort range during the on-peak occupied period. The *maximum discharge* strategy attempts to discharge the mass as quickly as possible following the onset of the on-peak period. In this case, the setpoint is raised to the upper limit of comfort within an hour after the on-peak period begins. The maximum discharge strategy maximizes storage efficiency and load shifting but is not necessarily optimal in terms of peak load reduction. It tends to lead to low loads during the morning and a peak during the late afternoon. *Linear rise* strategies were also investigated as a means of leveling the load to further reduce peak loads. The *slow linear rise* strategy raises the setpoint linearly over the entire on-peak occupied period (nine hours in this case), whereas the *fast linear rise* strategy raises the setpoint over four hours.

Figure A.5 shows cooling load profiles for the night setup, maximum discharge, and linear rise strategies for the same day in mid-July. The maximum discharge strategy resulted in the lowest on-peak period <u>total</u> load. It also had a slightly lower peak load than the linear rise strategies during the on-peak period (after 9 am). The fast linear rise strategy had a flatter on-peak load profile but had its peak at the onset of the on-peak period. It is interesting to note that both the maximum discharge and the fast linear rise strategies resulted in minimum chiller loading at the onset of the on-peak period.

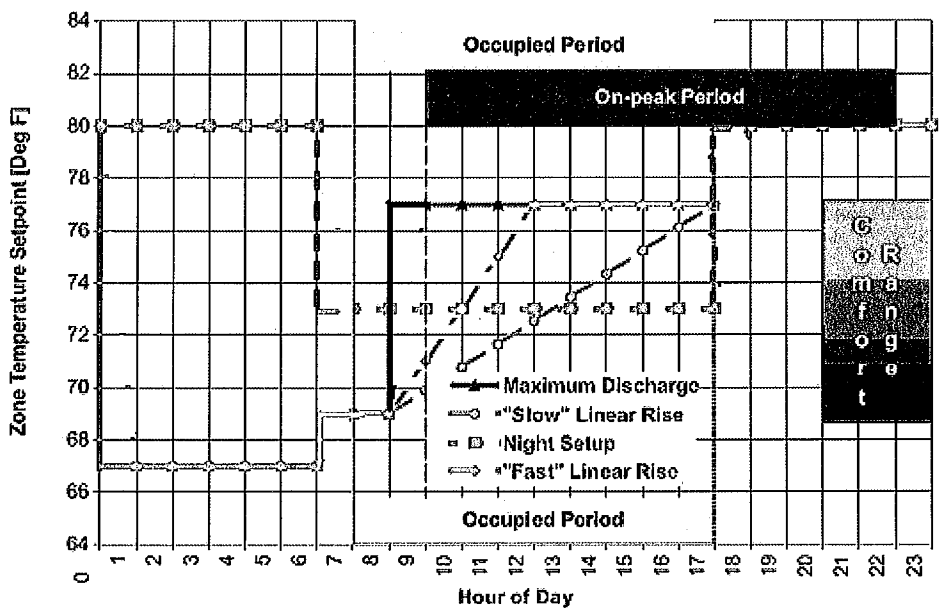

Figure A.4. Weekday hourly zone temperature setpoints for night setup, maximum discharge, and linear temperature rise strategies

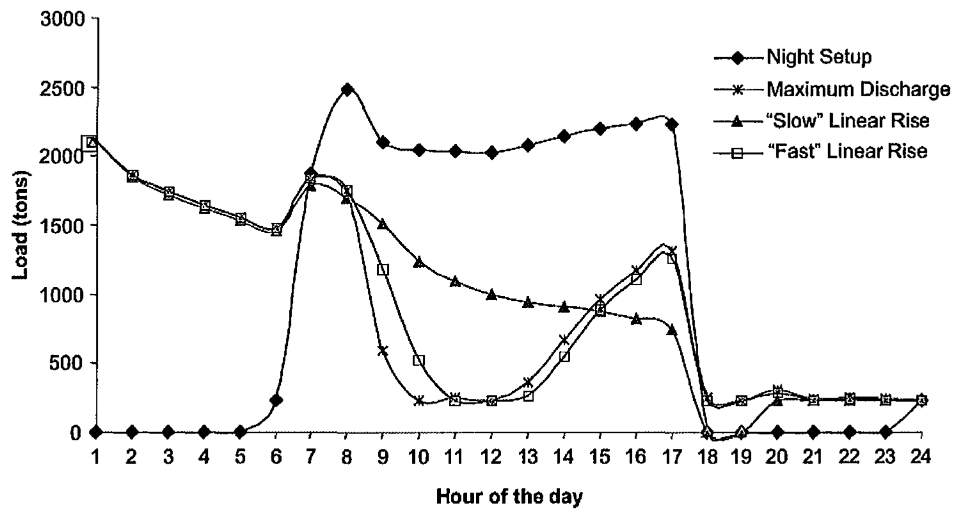

Figure A.5. Cooling load profiles for night setup, maximum discharge, and linear temperature rise strategies

A.3. Duct Static Pressure Decrease

This section describes the principle of controlling fan behavior using the *duct static pressure (DSP) decrease* strategy. Figure A.6 illustrates the concept of fan system parameter behavior when the DSP decrease strategy is applied. The fan characteristics curves based on the fan laws[2] and duct system characteristics are defined here (assuming fan size, gas density, and mechanical efficiency do not change during the DR strategy operation):

- ***fan curve***: Shows the relation between total pressure and airflow rate determined by fan VFD.
- ***system curve***: Shows the relation between total pressure and airflow rate determined by duct system resistance (from ducts and VAV dampers).
- ***power curve***: Shows the relation between airflow rate and fan power.

In the figure, the airflow rate and total pressure of the fan system are originally positioned at *point* ⓐ on ***fan curve 1*** as their normal settings. When the DSP setpoint is decreased, the system shifts from ***system curve 1*** to ***system curve 2***. Under this strategy, the fan variable frequency drive (VFD) speed is decreased to adjust the DSP, which causes conditions to shift from ***fan curve 1*** to ***fan curve 2***. The variable air volume (VAV) dampers open wider to deliver the same airflow rate for the lower DSP condition. The pressure-airflow relationship is stabilized with airflow rate and total pressure at *point* ⓑ on ***fan curve 2***, as shown. Power decreases as the fan speed is decreased and system conditions move from ***power curve 1*** to ***power curve 2***. The demand savings achievement by this strategy is represented by the shift from *point* ⓐ to *point* ⓑ on the power curves.

If the DSP setpoint is too low to deliver enough air to some zones, the VAV boxes at these zones will open 100% and starve for air. Even if some VAV boxes are starving, the fan VFD will not speed up as long as the DSP setpoint is maintained. If the DSP setpoint is not met, then the airflow rate becomes lower than required to maintain comfort in the space. This reduction in airflow reduces the chilled water flow to maintain the supply air temperature. Consequently, cooling demand is saved under such conditions, but airflow may fall below design levels in some zones. Therefore, careful consideration to avoid a shortage of fresh air supply should be taken in selecting a DSP setpoint.

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[2] The fan laws relate the performance variables for any dynamically-similar series of fans. The variables are fan size, rotational speed, gas density, volume flow rate, pressure, power, and mechanical efficiency (ASHRAE System and Equipment Handbook 18.4).

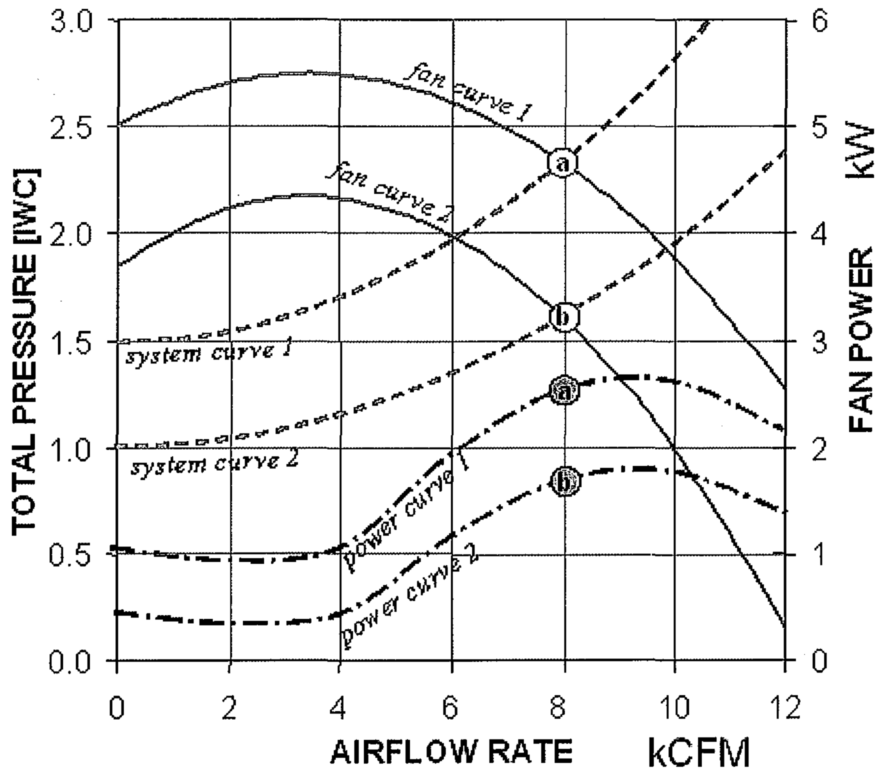


Figure A.6. Fan performance curve for DSP decrease strategy

A.4. Fan VFD Limit

This section describes the principle of controlling fan control behavior by the *fan variable frequency drive (VFD) limit* strategy. Figure A.7 illustrates the concept of fan system parameter behavior when the fan VFD limit strategy is applied. In the figure, the airflow rate and total pressure of the fan system are originally positioned at *point* ⓐ on f***an curve 1*** as their normal settings. When fan speed is lowered by the DR control, system conditions shift from ***fan curve 1*** to ***fan curve*** 2. To maintain the duct static pressure (DSP) setpoint the system conditions have to be on ***system curve 1***. When the strategy is applied the total fan pressure moves to *point* ⓑ on ***fan curve*** 2, with a corresponding reduction in airflow rate. On the fan power side, when the fan speed is lowered the system moves from ***power curve 1*** to ***power curve*** 2. Due to the airflow rate reduction the fan power is reduced to *point* ⓑ on ***power curve*** 2.

However, the VAV boxes are not satisfied with the reduced airflow and start opening the damper positions. From this point, the system can no longer maintain the DSP setpoint, because the fan speed is locked. The condition rides on ***fan curve 2*** as the DSP decreases while the airflow increases. In the figure, conditions move from ***system curve*** 1 towards ***system curve*** 2 (DSP 1.0 IWC (inches water column)), and the airflow rate is satisfied at *point* ⓒ on ***system curve*** 2. The demand savings is represented by ⓐ – ⓒ on the fan power curves.

If the VFD limit is too low to maintain sufficient DSP, the VAV boxes at some zones open 100% and starve for air. Even if some VAV boxes are starving, the fan VFD will not speed up because the fan speed is locked, causing DSP to drop. This strategy may provide essentially the same result as the DSP decrease strategy. However, when the fan VFD limit strategy is used, the resulting DSP cannot be predicted, while DSP can be specified with the DSP decrease strategy.

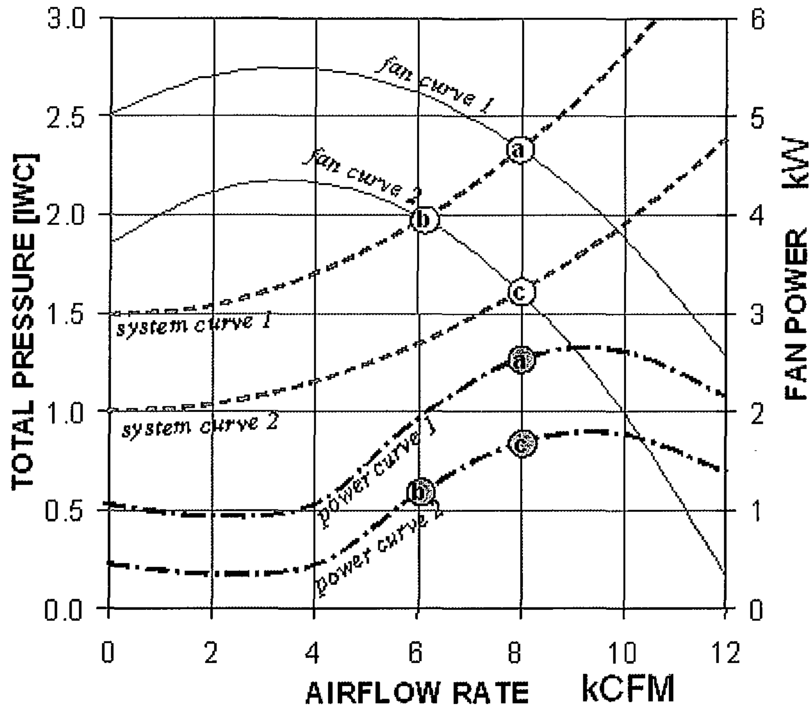


Figure A.7. Fan performance curve for fan VFD limit strategy

Case Study

Site Name	**UC Santa Barbara (Santa Barbara CA), Library**
DR Strategy	**Moderate Price (1:15 p.m. - 2:15 p.m., 3:15 p.m. - 4:15 p.m.)** Supply fan VFD 70% limit Economizer 100% open **High Price (2:15 p.m. - 3:15 p.m.)** Supply fan VFD 60% limit Duct static pressure reset 0.4 IWC (partial) Heating/cooling valve closed
Event Date	11/19/2003 (Max OAT: 69 °F)

Figure A.8 shows the fan power demand of a university library that employed the fan VFD limit strategy in a mixture of multiple strategies. The fan power shed was mostly accomplished by the fan VFD limit strategy. During normal operation most fans were operated at 100% VFD. During the moderate price period the fan VFD was limited to 70% achieving approximately 17% fan power reduction. During the high price period the fan VFD was lowered to 60% resulting in approximately 35% of fan power shed compared to the baseline operation.

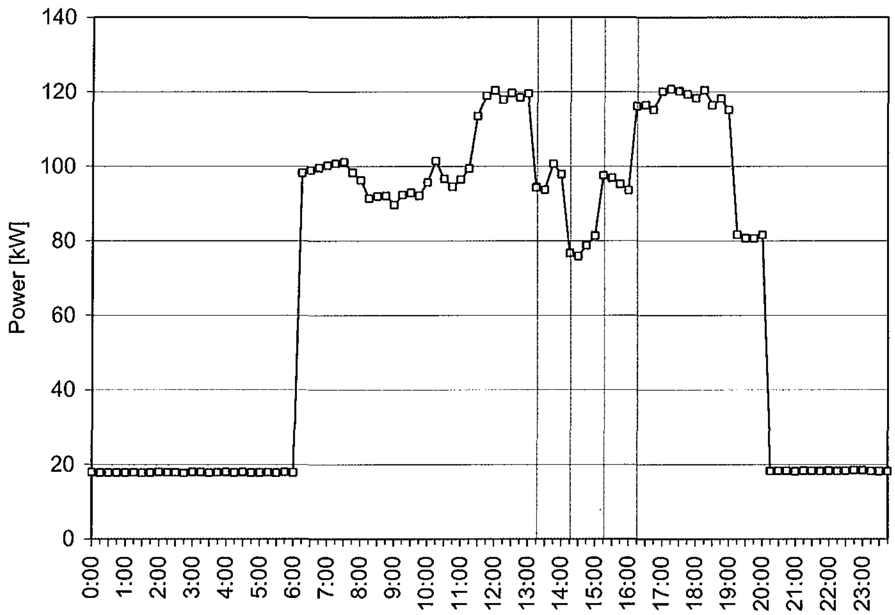


Figure A.8. Fan power (fan VFD limit) - UCSB

A.5. Supply Air Temperature Increase

This section describes the controls behavior for the supply air temperature (SAT) increase strategy for VAV systems. When the SAT is raised, the VAV boxes require more airflow and open the dampers wider. This causes the DSP to drop. The fan speeds up to maintain the DSP setpoint resulting in a fan power increase. Therefore, locking the fan VFD or IGV at their positions prior to curtailment is required to avoid a significant fan power increase. However, even when the fan VFD or IGV is locked, the airflow increases until it satisfies the VAV boxes (when DSP is lowered airflow rate can increase even without increasing fan speed). Along with the airflow increase, the fan power may or may not increase depending on its location on the power curve (no power reduction is expected). Therefore, fan power demand savings cannot be achieved by this strategy.

The increased airflow requires the same amount of chilled water flow as would be required at the original SAT setting. Therefore, this strategy will not save or may even increase fan power demand, nor will it save chiller power demand, while the DSP setpoint is maintained.

To achieve cooling demand savings, the SAT setpoint has to be raised until the VAV system loses control of the DSP setpoint. As in the fan VFD limit strategy, when some VAV boxes open 100% and begin to starve for air, the DSP setpoint can no longer be maintained if the VFD is locked. Then the airflow rate becomes smaller than required. This reduction in airflow reduces the chilled water flow to maintain the SAT. Consequently, the cooling demand is saved.

For reheat load reduction an SAT increase strategy will be beneficial for both CAV and VAV systems. If the building has a large reheat load, since many VAV boxes are running at minimum damper position, the airflow increase caused by the SAT increase will be minimal. Technically, the same amount of cooling energy will be reduced as reduced reheat energy.

The best practice for reheat control for a VAV system is to increase the SAT until the first VAV box damper goes to the fully-open position. If the building is operated in this manner the SAT increase will cause some VAV boxes to starve immediately. If the SAT is controlled at a fixed temperature, the SAT increase may not cause a significant zone temperature increase if most of the VAV boxes are operated below 100% open. If the building tends to have a large reheat load, fine tuning of this strategy results in worthwhile demand savings without a severe reduction in service.

A.6. Fan Quantity Reduction

Case Study

Site Name	**Roche Pharmaceutical (Palo Alto CA),** **Office, Auditorium, and Cafeteria**
DR Strategy	**Moderate Price (1:15 p.m. - 2:15 p.m., 3:15 p.m. - 4:15 p.m.)** ▪ Auditorium - supply fans off (50%) **High Price (2:15 p.m. - 3:15 p.m.)** ▪ Auditorium - supply fans off (50%) ▪ Cafeteria - supply fans off (50%) ▪ Office - supply fans off (50%)
Event Date	11/19/2003 (Max OAT: 66°F)

A pharmaceutical laboratory campus used fan quantity reduction for its DR strategy at three buildings -- an office, an auditorium, and a cafeteria. Half of the constant volume AHUs were turned off for 3 hours in the auditorium and for 1 hour in the cafeteria and the office. Figure A.9 shows the whole building power (not including the cooling demand) and the aggregated OAT regression baseline of all three buildings. The levels of demand shed due to the different price signals can be clearly seen in the demand profile. After the first $0.30/kWh signal at 1 p.m., the whole building power dropped by 71 kW at 1:15 p.m. from the implementation of the fan quantity reduction strategy in the auditorium. After the $0.75/kWh signal at 2 p.m., the demand dropped further by 57 kW at 2:15 p.m. when half the fans were also shut off in the cafeteria and the office. Roche achieved maximum 164 kW demand savings (28%) from 2:45 p.m. to 3:00 p.m. After the end of the moderate price signal at 3:00 p.m., the cafeteria and office fans were returned to 100% operation, while half the auditorium fans remained shut off.

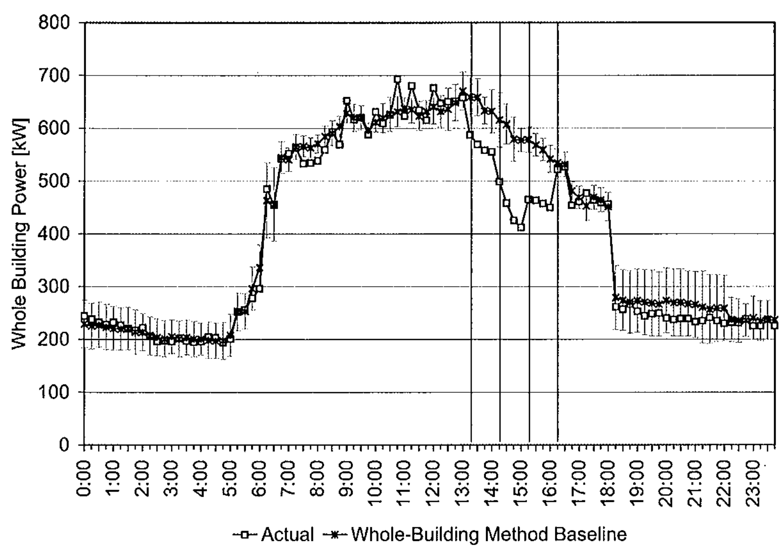


Figure A.9. Total whole building power (fan quantity reduction) - Roche

A.7. Cooling Valve Limit

Case Study

Site Name	UC Santa Barbara (Santa Barbara CA), Library
DR Strategy	**Moderate Price (1:15 p.m. - 2:15 p.m., 3:15 p.m. - 4:15 p.m.)** ▪ Supply fan VFD 70% limit ▪ Economizer 100% open **High Price (2:15 p.m. - 3:15 p.m.)** ▪ Supply fan VFD 60% limit ▪ Duct static pressure reset 0.4 IWC (partial) ▪ Heating/cooling valve closed
Event Date	11/19/2003 (Max OAT: 69°F)

Cooling valve limit was another strategy employed by the university library. Chilled water is supplied from a campus-wide chilled water network, and during the DR event the cooling valve was completely shut off to reduce chiller demand at the central plant. The fan was kept operating at lower speed to deliver fresh air to zones.

Figure A.10 shows the library's cooling demand, which was calculated from chilled water consumption at the library and the ratio of the central chiller plant electric demand to total chilled water supply Btu/h. Cooling power dropped significantly at the beginning of the high price period because of the strategy. However, the cooling power demand had a rebound peak at the end of the shed period and was greater than the baseline demand for that time period. A rebound avoidance strategy should be considered when this strategy is applied.

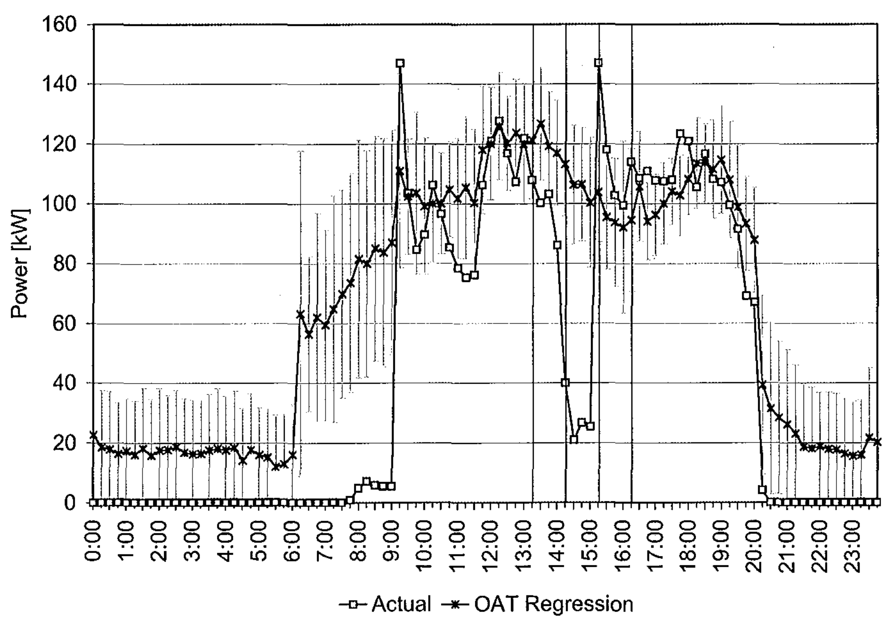


Figure A.10. Cooling demand (cooling valve limit) - UCSB

A.8. Slow Recovery Strategy

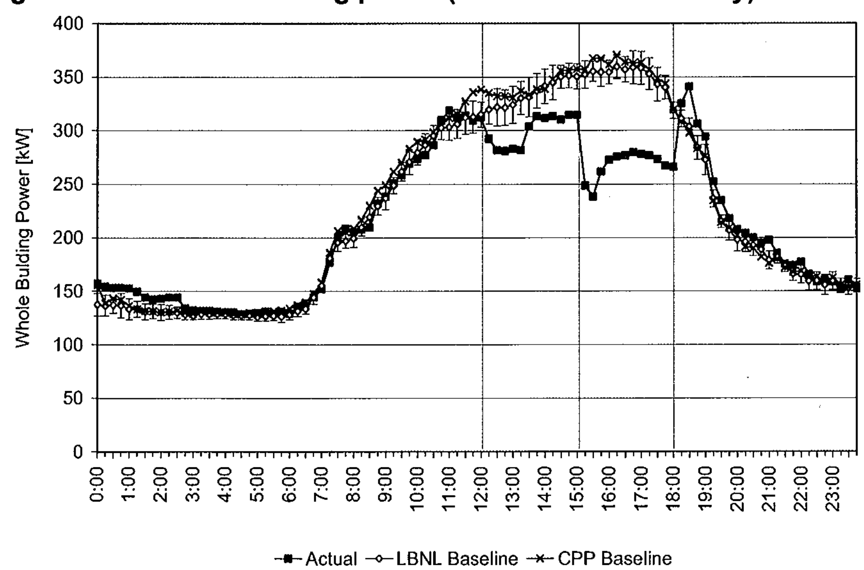
This section introduces a case study of the slow recovery strategy, one of the rebound avoidance strategies.

Case Study

Site Name	**Echelon (San Jose CA), Corporate headquarters office**
DR Strategy	**Moderate Price (12:00 p.m. - 3:00 p.m.)** ▪ Hallway lighting turned off where ambient light present ▪ Daylit office lights turned off ▪ Inner office lights dimmed to 20% **High Price (3:00 p.m. - 6:00 p.m.)** ▪ 1 of 3 RTU turned off ▪ DSP reduced from 1.5" to 0.8" ▪ SAT increased from 55 to 65°F **Rebound avoidance** ▪ Ramp-up DSP in 0.2 IWC increments every 5 minutes (manual)
Event Dates	10/13/2005 (Max OAT: 83 °F), 10/25/2005 (Max OAT: 69 °F)

Figure A.11 shows the whole building power and OAT regression baselines of an office building that employed a set of HVAC DR strategies for the high price period. Due to limitation of the control system's capability, the rebound peak avoidance strategy was not programmed for the first test. After the DR period, all the HVAC operations were set back to normal at once, and this caused rebound peak.

Figure A.11. Whole building power (without slow recovery) - Echelon



For the second test, to avoid the high rebound peak right after the shed period, the operator did manual slow recovery by ramping up the duct static pressure from 0.8 IWC to 1.5 IWC in increments of 0.2 IWC every 5 minutes. It took about 20 minutes to get the DSP back to normal. The building operator also manually ramped down the supply air temperature from 65°F to 55°F gradually over 30 minutes after the end of DR period. Figure A.12 shows the whole building power of the site when the slow recovery strategy was applied. Use of this strategy mitigated the high rebound peak.

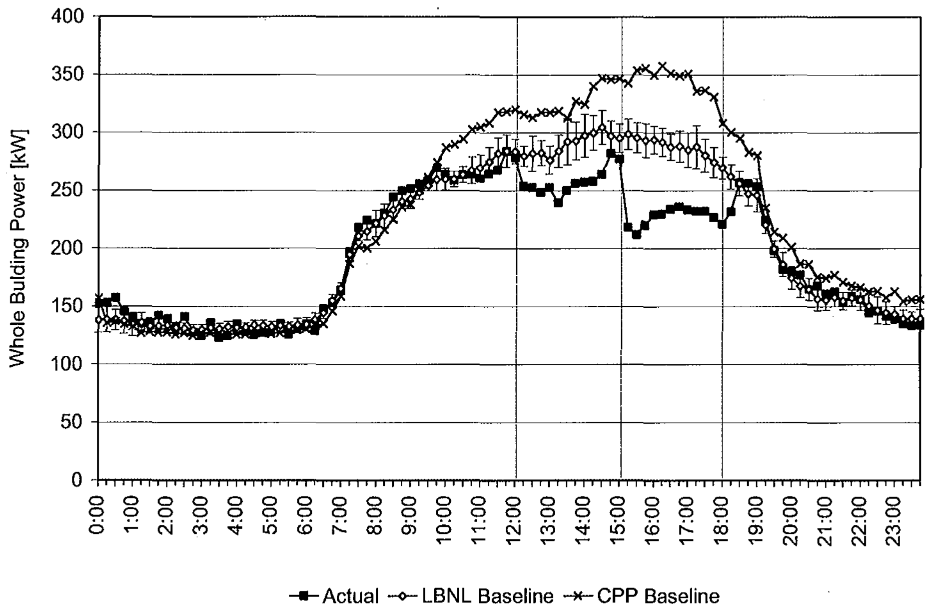


Figure A.12. Whole building power (with slow recovery) - Echelon

A.9. Extended DR Control Period

This section introduces a case study of the extended DR control period strategy, one of the rebound avoidance strategies.

Case Study

Site Name	**Alameda County Water District (Fremont CA), Office**
DR Strategy	**Moderate Price (12:00 p.m. - 3:00 p.m.)** ▪ Boiler disabled ▪ CHW setpoint raised to 50°F ▪ Current limiting to 70% ▪ SAT increased from 55°F to 65°F for AHUs 1, 2, 3, and Lab AHU ▪ DSP setpoint decreased from 1.5" to 1.0" ▪ Zone setpoint increased to 75°F **High Price (3:00 p.m. - 6:00 p.m.)** ▪ Zone setpoint increased to 78°F **Rebound Avoidance** ▪ Extend shed control 2 hours (until 8 p.m.)
Event Date	9/29/2005 (Max OAT: 87°F), 10/6/2005 (Max OAT: 75°F)

Figure A.13 shows the whole building power and OAT regression baselines of an office building that employed multiple HVAC DR strategies. At the beginning of the demonstration this site did not have any rebound avoidance strategy programmed. At the end of the DR period a high rebound peak occurred due to the sudden recovery of HVAC operation.

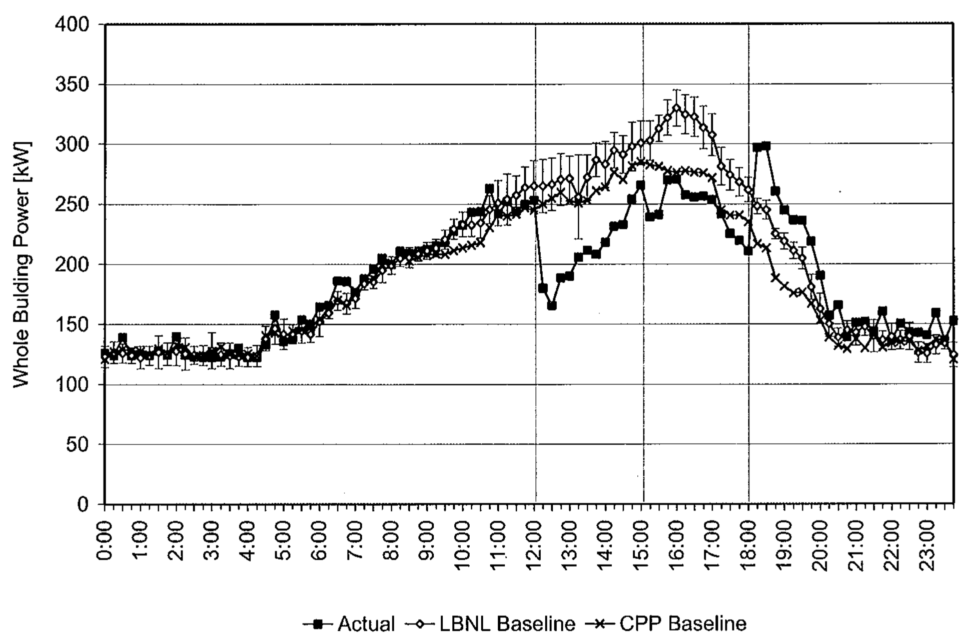


Figure A.13. Whole building power (without extended DR period) - ACWD

After experiencing the rebound peak during the first test, the building operator added an extended DR control period. Since the occupants start to leave around 6 p.m., the operator assumed that there would be no significant impact on occupant comfort even if the DR strategies were continued after the end of the work day. The new sequence of operation initiated the original DR strategies when the DR event was triggered and continued the strategies until 8 p.m.

Figure A.14 shows the demonstration results after implementation of the extended DR period strategy. For this event all the strategies were successfully operated and rebound peak did not occur.

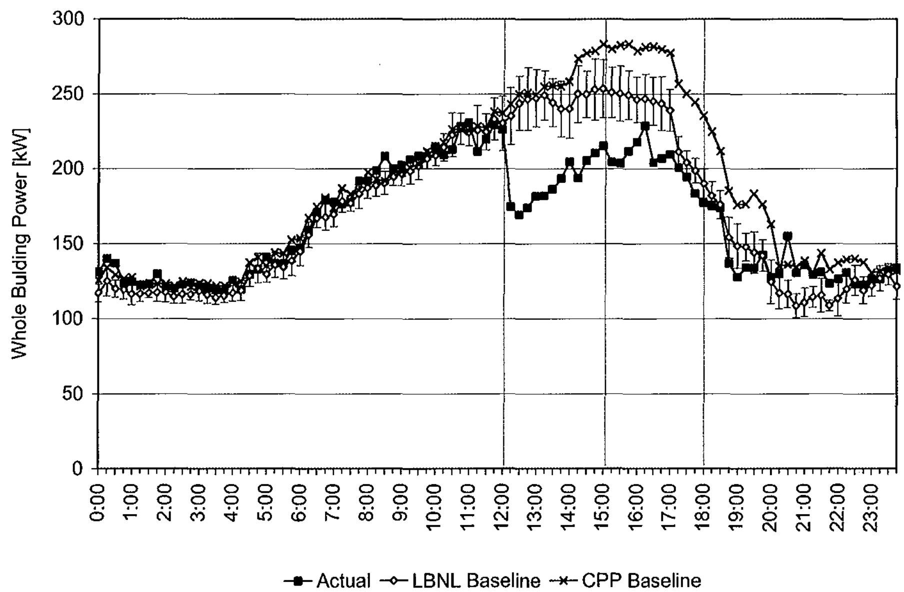


Figure A.14. Whole building power (with extended DR period) – ACWD

References

ASHRAE 2004. ASHRAE Handbook – HVAC Systems and Equipment. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. 18.4. Atlanta GA.

Braun, J.E., K.W. Montgomery, and N. Chaturvedi. 2001. *Evaluating the Performance of Building Thermal Mass Control Strategies.* International Journal of Heating, Ventilating, Air-Conditioning and Refrigeration Research, Vol. 7, No. 4, pp. 403-428. October.

Keeney, K.R. and J.E. Braun. 1997. *Application of Building Precooling to Reduce Peak Cooling Requirements*. ASHRAE Transactions, Vol.103, No.1, pp. 463-469.

Appendix B
Summary of DR Strategies

Appendix B: Summary of DR Strategies

This section summarizes the DR control strategies chosen for each participation site in the LBNL Auto-DR studies over three years (Piette et al. 2005a, 2005b, 2006) and other case studies (see section 1.5 of the main report).

B.1. DR Strategies of LBNL Auto-DR Studies

Table B.1 summarizes the DR strategies chosen for the Auto-DR participant sites in 2003 and 2004. Albertsons, Bank of America, OFB, Roche and UCSB participated in the 2003 and 2004 studies and rest of the sites in the table participated in the 2004 study.

In these tests the moderate price period was from 1 p.m. to 2 p.m. and from 3 p.m. to 4 p.m. The high price period was from 2 p.m. to 3 p.m. The strategies chosen for the moderate price period were continued during the high price period, with greater increase or decrease of parameter setpoints chosen for the moderate price period.

Table B.1. DR strategies by site for LBNL Auto-DR studies, 2003 and 2004

Site Name	Moderate Price	High Price
300 Capitol Mall - Office	▶ CHW temp increase 44°F → 47°F ▶ GTA cooling 1.5°F increase ▶ Supply fan VFD lock ▶ Fountain pump off ▶ Fan quantity reduction at loading deck ▶ Zone switching at lobby	▶ CHW temp increase → 55°F ▶ GTA cooling 3°F increase
Albertsons - Supermarket	▶ Bi-level switching 35% off at store area	▶ Anti-sweat door heater in night-mode
B of A - Office, Data Center	▶ SAT reset 55°F → 59°F ▶ DSP decrease 2.2" → 1.8"	▶ SAT reset → 59°F ▶ DSP decrease → 1.4"
Cal EPA - Office	▶ DSP decrease 1.0" → 0.5"	▶ Zone switching in daylit space
CETC - Research Lab	▶ Unload chiller and cool with ice storage ▶ Fan quantity reduction (2 AHU off) ▶ Electric humidifier off	
Cisco - Office, Data Center	▶ GTA cooling 2°F increase ▶ Boiler pump off & stairwell fan coils off ▶ Zone switching in daylit space ▶ Zone switching in stairwell, lobby, hallway	
50 Douglas - Office	▶ GTA cooling 76°F → 78°F	▶ GTA cooling → 80°F
Summit Center - Office	▶ GTA cooling 76°F → 78°F	▶ GTA cooling → 80°F
Echelon - Office	▶ GTA cooling individually setup by zones ▶ Continuous dimming at office	▶ RTU quantity reduction (2 of 3 off) ▶ Zone switching in common area ▶ Bi-level switching up to 50% off in hallway
450 Golden Gate - Federal Office	▶ GTA cooling 72°F → 74°F ▶ GTA heating 70°F → 68°F	▶ GTA cooling → 78°F ▶ GTA heating → 66°F
NARA - Federal Archive Storage	▶ GTA cooling 75°F → 76°F ▶ GTA heating 70°F → 68°F	▶ GTA cooling → 78°F ▶ GTA heating → 66°F
Oakland Federal - Office	▶ GTA cooling 72°F → 76°F ▶ GTA heating 70°F → 68°F	▶ GTA cooling → 78°F ▶ GTA heating → 66°F
Kadant - Material Processing	▶ Transfer pump off	
Monterey - Office	▶ Bi-level switching 33% off at lobby	

Table B.1. DR strategies by site for LBNL Auto-DR studies, 2003 and 2004 (continued)

Site Name	Moderate Price	High Price
OSIsoft - Office	▶ GTA cooling 72°F → 76°F ▶ GTA heating 70°F → 68°F	▶ GTA cooling → 78°F
Roche - Office, Cafeteria	▶ Supply fan quantity reduction (50%) in Bldg-A	▶ Supply fan quantity reduction (50%) in Bldgs-B&C
UCSB - Library	▶ Supply fan VFD limit 70%	▶ Supply fan VFD limit 60% ▶ DSP decrease 0.4" (partial) ▶ Heating/cooling valve closed
USPS - Distribution Center	▶ Chiller demand limit 75%	▶ Chiller demand limit 50%

CHW: chilled water, GTA: global temperature adjustment, VFD: variable frequency drive
SAT: supply air temperature, DSP: duct static pressure, RTU: rooftop unit

Table B.2 summarizes the DR strategies chosen for the Auto-DR participant sites in 2005. The major additions from the 2003 and 2004 studies were passive thermal mass storage and rebound avoidance strategies. In the table, pre-cooling for passive thermal mass storage and other strategies started prior to the DR period and are noted as "Pre-event" in the Moderate Price column. Rebound avoidance strategies are noted as "Rebound" in High Price column.

Table B.2. DR Strategies by site for LBNL Auto-CPP study, 2005

Site Name	Moderate Price	High Price
ACWD - Office, Lab	▶ Boiler disabled ▶ CHW temp increase → 50°F ▶ Cooling valve limit 70% ▶ SAT increase 55°F → 65°F ▶ DSP decrease 1.5" → 1.0" ▶ GTA cooling → 75°F	▶ GTA cooling → 78°F ▶ ***(Rebound)*** *Extended DR control period 2 hours (until 8 p.m.)*
B of A - Office, Data Center		▶ DSP decrease 2.2" → 1.4" ▶ Fan VFD lock 3 minutes after DSP decrease ▶ CHW temp increase 5°F at secondary loop ▶ Cooling valve lock at AHU
Chabot - Museum	▶ ***(Pre-event)*** *Free cooling when OAT is below 62°F. Pre-cooling until noon at 70°F average zone temperature.* ▶ GTA cooling → 74°F (4/3°F/h step-by-step)	▶ GTA cooling → 78°F (4/3°F/h step-by-step)
2530 Arnold - Office	▶ GTA cooling 76°F → 78°F	▶ GTA cooling → 80°F ▶ ***(Rebound)*** *Sequential recovery: VAV boxes released one by one over a short interval*
50 Douglas - Office	▶ GTA cooling 76°F → 78°F	▶ GTA cooling → 80°F ▶ ***(Rebound)*** *Sequential recovery: VAV boxes released one by one over a short interval*
Echelon - Office	▶ Zone switching at hallway with ambient light ▶ Zone switching in daylit spaces ▶ Continuous dimming 20% off in offices	▶ RTU quantity reduction (1 of 3 off) ▶ DSP decrease 1.5" → 0.8" ▶ SAT increase 55°F → 65°F
Irvington - High School	▶ ***(Pre-event)*** *GTA 72°F until 11:50 a.m. for pre-cooling* ▶ GTA cooling → 78°F	▶ Turn off HVAC system at 2:50 pm (school closes at 3 pm)
Gilead 300 - Office	▶ ***(Pre-event)*** *Shed control starts at 11 a.m.* ▶ SAT increase 55°F → 65°F.	▶ Same as moderate price
Gilead 342 - Office, Lab	▶ ***(Pre-event)*** *Shed control starts at 11 a.m.* ▶ SAT increase 55°F → 65°F ▶ GTA cooling → 75°F (70 - 75°F normal)	▶ Same as moderate price
Gilead 357 - Office, lab	▶ ***((Pre-event)*** *Shed control starts at 11 a.m.* ▶ SAT increase 55°F → 65°F ▶ GTA cooling → 75°F (70 - 75°F normal)	▶ Same as moderate price

Table B.2. DR strategies by site for LBNL Auto-CPP study, 2005 (continued)

Site Name	Moderate Price	High Price
IKEA - Retail	▶ GTA cooling 2°F increase	▶ GTA cooling → 76°F
LBNL OSF - Office, Data Center	▶ ***(Pre-event)*** *GTA 0 to 2°F in morning for pre-cooling* ▶ GTA cooling 2 - 6°F increase	▶ GTA cooling up to 6°F increase
Oracle - Office	▶ DSP decrease 20%	▶ GTA cooling 3°F increase
Target - Retail	▶ RTU quantity reduction (3 of 12 off; Increased to 5 on Oct 6th to end of summer)	▶ Bi-level switching 1/4 off in sales area
USPS - Distribution Center	▶ Chiller demand limit 80%	▶ Chiller demand limit 65% ▶ ***(Rebound)*** *Slow recovery: increase chiller demand limit by 5% every 15 minutes*

B.2. DR Strategies of Other Case Studies

This section summarizes the DR strategies chosen in the other case studies listed in section 1.5 of the main report. Due to lack of data, technical details of some of the strategies, including whether control setpoints were in normal or DR mode, were not included. These DR strategies were either manually or semi-automatically operated.

Table B.3. DR strategies by site for other case studies

Building	HVAC	Lighting	Others
Facility - Office	▶ Fan VFD limit 40, 60, or 80% ▶ GTA cooling ▶ CHW temp decrease		
Facility 2 - Office	▶ GTA cooling ▶ Chiller demand limit ▶ Shut off one condenser water pump ▶ CHW temp increase 3 to 5°F ▶ Fan VFD limit to minimum speed ▶ DSP decrease	▶ Bi-level switching ▶ Zone switching in common area	
Facility 3 - Food Processing	▶ Chiller quantity reduction: 40 & 60-ton chiller, 10 &20-ton chillers in packaging room, chillers in freezer warehouse	▶ Zone switching in daylit area including central warehouse and second floor packaging area	▶ Shut off 150-hp mixers (1 of 2)
Facility 4 - Glass Processing			▶ Shut off air compressors, glass transfer equipment motors, dissolver, conveyors, mixers, fans, and tank farm pumps
Facility 5 - Chemical Pepackaging	▶ Unload two 20-ton package unit in production area	▶ Bi-level switching 40% off in production area	
Facility 6 - Packaging & Cold Storage		▶ Main building lighting reduction (details unknown)	▶ Shut off cold storage and selected process and packing lines from noon to 2:30 p.m.
Facility 7 - (Packaging & SCold storage)			▶ Shut off cold storage for maximum allowed period without spoilage ▶ Shed misc. process loads

Table B.3. DR strategies by site for other case studies (continued)

Building	HVAC	Lighting	Others
New York Times Building - Office	▶ GTA level 1: 74 → 76.5°F ▶ GTA level 2: 76.5 → 78.5°F ▶ Reduce perimeter fan boxes to 30% capacity from 2 p.m. to 6 p.m. ▶ ***(Pre-event)*** *SAT decrease 54°F until 2 p.m. for pre-cooling* ▶ SAT increase 59.5°F from 2 p.m. until 6 p.m.	▶ Level 1: Continuous dimming to 50% in core, 70% in PC-dominated interior and perimeter zones ▶ Level 2: Continuous dimming to 50% in core, 70% in interior zones, and 0% in perimeter zones	
Home Depot - Retail		▶ Bi-level switching 1/2 off in sales area and display light	
Rockefeller Center - Office	▶ CHW temp increase ▶ Fan VFD reduction		▶ Elevator & escalator cycling
Lafarge Building Materials - Material Process			▶ Shut off rock crushers
MCWA - Irrigation			▶ Irrigation pump peak shifting
Wesleyan University		▶ Turn off unnecessary lighting	▶ Turn off unnecessary equipment
Ganahl Lumber - Lumber Processing		▶ Continuous dimming	
LA County - Office	▶ GTA cooling	▶ Continuous dimming	

References

Piette, M.A., O. Sezgen, D.S. Watson, N. Motegi, and C. Shockman. 2005a. *Development and Evaluation of Fully Automated Demand Response in Large Facilities.* Lawrence Berkeley National Laboratory. CEC-500-2005-013. LBNL-55085. Berkeley CA, January. Available at http://drrc.lbl.gov/drrc-pubs1.html. Accessed November 10, 2006.

Piette, M.A., D.S. Watson, N. Motegi, N. Bourassa, and C. Shockman. 2005b. *Findings from the 2004 Fully Automated Demand Response Tests in Large Facilities.* Lawrence Berkeley National Laboratory. CEC-500-03-026. LBNL-58178. Berkeley CA, September. Available at http://drrc.lbl.gov/drrc-pubs1.html. Accessed November 10, 2006.

Piette, M.A., D.S. Watson, N. Motegi, S. Kiliccote, and P. Xu. 2006. *Automated Critical Peak Pricing Field Tests: Program Description and Results.* Lawrence Berkeley National Laboratory. LBNL- 59351. Berkeley CA, April. Available at http://drrc.lbl.gov/drrc-pubs4.html. Accessed December 3, 2006.

Appendix C
Case Study of Advanced Demand Response

Appendix C: Case Study of Advanced Demand Response

This section presents a unique case study of commissioning of DR control strategies that was planned from the new construction system design phase. In 2005 Lawrence Berkeley National Laboratory (LBNL) researchers worked with the design of the new New York Times Headquarters building in Manhattan to integrate control of lighting and shading devices, to commission the lighting systems, and to develop DR strategies and DR controls specifications for the building. LBNL developed a detailed energy simulation model to design the optimal DR strategy[3].

C.1. DR Strategies Plan at New York Times Headquarters

The building systems and the owner's preferences provided a framework and identified constraints for DR strategy development. The owner requested that any common equipment, such as the chiller plant, and common spaces would be exempt from DR work. In addition, the DR strategies would be implemented floor-by-floor depending on occupancy and other priorities. DR control strategies were initially proposed as follows:

- **HVAC system**: Increase the cooling setpoint 3°F for moderate demand reduction and an additional 3°F for further demand reduction. The 3°F change was proposed as a starting point for the simulations. Iterations of the temperature gradient were expected depending on the simulated temperatures within the zones.
- **Lighting system**: Employ two stages of lighting control. Stage 1 involved lowering the lighting power in all perimeter daylight configuration zones by 70% and in all zones close to the central core by 50%. During Stage 2 perimeter lights were turned off. Anytime the lighting system reached 10% output it was automatically turned off.

A detailed energy simulation model was used to evaluate dynamic DR control strategies during the new construction design process. A custom version of the EnergyPlus [4] program was developed by NaturalWorks [5] and utilized for this simulation. The modeling and simulation effort was conducted in two phases that involved some iteration. In the first phase, a basic building model was developed and a limited set of DR strategies was simulated, such as window shade control (control angle of window shades to optimize daylighting and solar heat gain) and global temperature adjustment (GTA). To refine the model the owner and LBNL researchers assisted in providing accurate estimation parameters.

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[3] This section is a summary of a paper presented at the 2006 ACEEE Summer Study (Kiliccote 2006).

[4] EnergyPlus is a building energy simulation program for modeling building heating, cooling, lighting, ventilating, and other energy flows.

[5]NaturalWorks (San Diego CA) offers consultancy and research services in the field of building physics. http://www.natural-works.com

During the second phase NaturalWorks delivered a more complete model including the ability to simulate lighting shed strategies. For lighting management during DR events the space is divided into three zones based on use and daylight availability: core, interior, and perimeter. The model included two strategies for the lighting system, two levels for GTA setup, and two additional HVAC strategies: 1) decrease supply air temperature (SAT) for thermal mass pre-cooling until 2 p.m. and increase SAT during the demand peak period, and 2) reduce fan coil units' capacity on the perimeter. Table C.1 lists the DR strategies modeled in the simulations. These DR strategies were combined in six different operation schedules described in Table C.2.

Table C.1. DR strategies for second phase simulation, New York Times building

Type	Strategies	Definition
HVAC	GTA-1	Cooling setpoint increase to 76.5°F
	GTA-2	Cooling setpoint increase to 78.5°F
	FCU	Reduce perimeter fan coil units to 30% capacity from 2 p.m. to 6 p.m.
	SAT	SAT 54°F for pre-cooling until 2 p.m. and then raised to 59.5°F
Lighting	Light-1	Reduce lighting power to 50% in core zone and to 70% in PC dominated interior and perimeter zones
	Light-2	Reduce lighting to 50% in core, to 70% in interior zones, and off in perimeter zones

Table C.2. Simulation sequence of DR strategies, New York Times building

A	Lighting	None
	HVAC	None
B	Lighting	None
	HVAC	FCU SAT
C	Lighting	Light-1 Light-2
	HVAC	GTA-1 GTA-2 FCU SAT
D	Lighting	Light-1 Light-2
	HVAC	GTA-1 GTA-2 FCU SAT
E	Lighting	Light-1 Light-2
	HVAC	GTA-1 GTA-2 FCU SAT
F	Lighting	Light-2 Light-1
	HVAC	GTA-1 GTA-2 FCU SAT

13:00 13:30 14:00 14:30 15:00 15:30 16:00 16:30 17:00 17:30 18:00 18:30 19:00

C.2. Preliminary Results of Simulation Study

Figure C.1 displays the preliminary results from the simulation model analysis. This chart shows the baseline with overnight pre-cooling and the demand profile of the building under pattern F, the DR sequence shown to provide the most demand savings in the most recent simulation results. Demand savings estimated from this simulation was approximately 600 kW. The simulation study also revealed that the overnight pre-cooling strategy should be refined. The results indicate that morning pre-cooling may be as effective as overnight pre-cooling while consuming less energy.

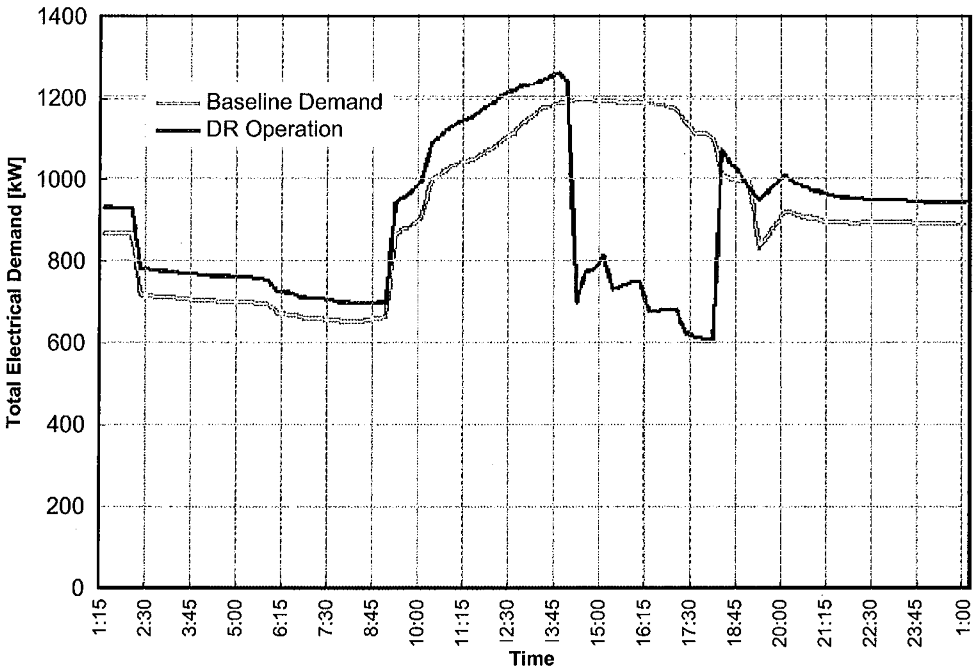

Figure C.1. Total demand profile of occupied floors, New York Times building

For any building, the owner must decide how aggressively the DR strategies will be implemented, based in part on occupant comfort. The current simulation results display potential demand savings but do not provide occupant comfort indicators. NaturalWorks has planned to examine predicted mean vote[6] (PMV) and temperatures in the building that will provide indicators of conditions in the space under different sequences of operation. Further simulation studies are needed to provide more accurate estimates for the owner to make a decision on the most efficient DR strategies.

The study also examined the financial impact of the demand response activities in different scenarios.

C.3. Conclusion

DR strategy planning from the early phase of new construction design can reduce the risk of missing effective DR strategies or programming unwanted strategies. Performing building simulations will reduce costs and efforts to manually demonstrate the effect of DR strategies and/or to reprogram the EMCS. Analysis of the combination of demand, energy, comfort, and economics is important to achieve the best DR strategy for any building.

[6] The average comfort vote predicted by a theoretical index for a group of subjects when subjected to a particular set of environmental conditions.

References

Kiliccote, S., M.A. Piette, and G. Hughes. 2006. "Dynamic Controls for Demand Response in New and Existing Commercial Buildings in New York and California." Presented at the ACEEE 2006 Summer Study on Energy Efficiency in Buildings: Less is More: En Route to Zero Energy Buildings, Asilomar, Pacific Grove CA, August 13–18.