Title
Register Closing Effects on Forced Air Heating System Performance

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Executive Summary

Closing registers in forced air heating systems and leaving some rooms in a house unconditioned has been suggested as a method of quickly saving energy for California consumers. This study combined laboratory measurements of the changes in duct leakage as registers are closed together with modeling techniques to estimate the changes in energy use attributed to closing registers.

The results of this study showed that register closing led to increased energy use for a typical California house over a wide combination of climate, duct leakage and number of closed registers. The reduction in building thermal loads due to conditioning only a part of the house was offset by increased duct system losses; mostly due to increased duct leakage. Therefore, the register closing technique is not recommended as a viable energy saving strategy for California houses with ducts located outside conditioned space.

The energy penalty associated with the register closing technique was found to be minimized if registers furthest from the air handler are closed first because this tends to only affect the pressures and air leakage for the closed off branch. Closing registers nearer the air handler tends to increase the pressures and air leakage for the whole system.

Closing too many registers (more than 60%) is not recommended because the added flow resistance severely restricts the air flow though the system leading to safety concerns. For example, furnaces may operate on the high-limit switch and cooling systems may suffer from frozen coils.

TABLE OF CONTENTS

Background

It has been proposed that conditioning less space in a house by closing registers in rooms that are unoccupied has the potential to save considerable amounts of energy and peak power in California. This reduction in load needs to be balanced with potential decreases in distribution system efficiency due to increased duct losses and changes in house infiltration. If duct systems had no leaks, then closing registers would just increase system pressures and reduce total air flow. This would lead to slightly lower heat exchanger efficiencies that would cancel out some of the savings. However, duct systems tend to be leaky and the effect of register closing on increasing duct leakage will have a much greater impact. It has been well documented that California duct systems have typical air leakage between 20% and 30% of total air handler flow. This air leakage occurs through holes in the duct system and is a function of the system operating pressures. As registers are closed, the duct system pressures will increase and the duct leakage will also increase. Because this duct leakage is to outside the conditioned space it represents a loss of energy that would also tend to cancel out the gains in energy efficiency due to conditioning less of the home by closing registers.

The testing discussed in this report attempts to quantify the changes in forced air heating and cooling system performance that occur for a system with closed registers. This research aims to experimentally quantify the changes in leakage and air handler flow and the resulting changes in distribution system performance so that the balance between increased losses and decreased demand can be analyzed.

For the laboratory study, a complete duct system with ten supply registers and a single return was connected to a test chamber and the registers were systematically closed. The duct system was carefully constructed to be essentially air tight and then leaks were deliberately added. These added leaks were calibrated and monitored so that they could be used as flow meters. This allows the detailed monitoring of leakage changes during the experiment. They were also specially designed to have a pressure exponent of about 0.6 – typical of residential duct system leaks, rather then the exponent of 0.5 that most air flow meters have. The total system air flow, plenum and boot pressures and leak flows were recorded as each register was closed to show how the system pressures and leakage increase as more registers are closed.

The overall effect on the energy consumption of a house (including both the reduction in building load and the changes in air conditioner and thermal distribution system performance) was determined using the REGCAP simulation model for California Climate zones 3, 12 and 16 (Oakland, Sacramento and Mt. Shasta). Additional calculations were used to estimate the changes in steady-state distribution system efficiency using the calculation methods in proposed ASHRAE Standard 152 for three locations in California: Sacramento, Bakersfield and Los Angeles. Both the ASHRAE 152 and REGCAP calculations were performed for a Title 24 reference house (CEC 1998).

Test Apparatus

The test chamber

The test chamber is a 32 ft. long × 8 ft. wide × 8 ft. high (9.5 m×2.5 m×2.5 m) wood framed structure (see Figure 1). The wood framed walls and ceiling are covered with gypsum wallboard and plywood, with carefully taped seams and joints to minimize envelope leakage. To reduce the leakage further, additional caulking was used at joints in the structure. The chamber is mounted above a four-foot high crawl space that contains the duct system. The chamber has one well weather-stripped door and no windows. Although the interior is currently a single zone, it may be possible in future experiments to add interior partitions to investigate interzonal pressure differences caused by register closing. The test chamber is located inside a warehouse and is completely sheltered from any outdoor weather. Two blower door fans were mounted in one wall of the chamber – one to pressurize the structure and one to depressurize it.

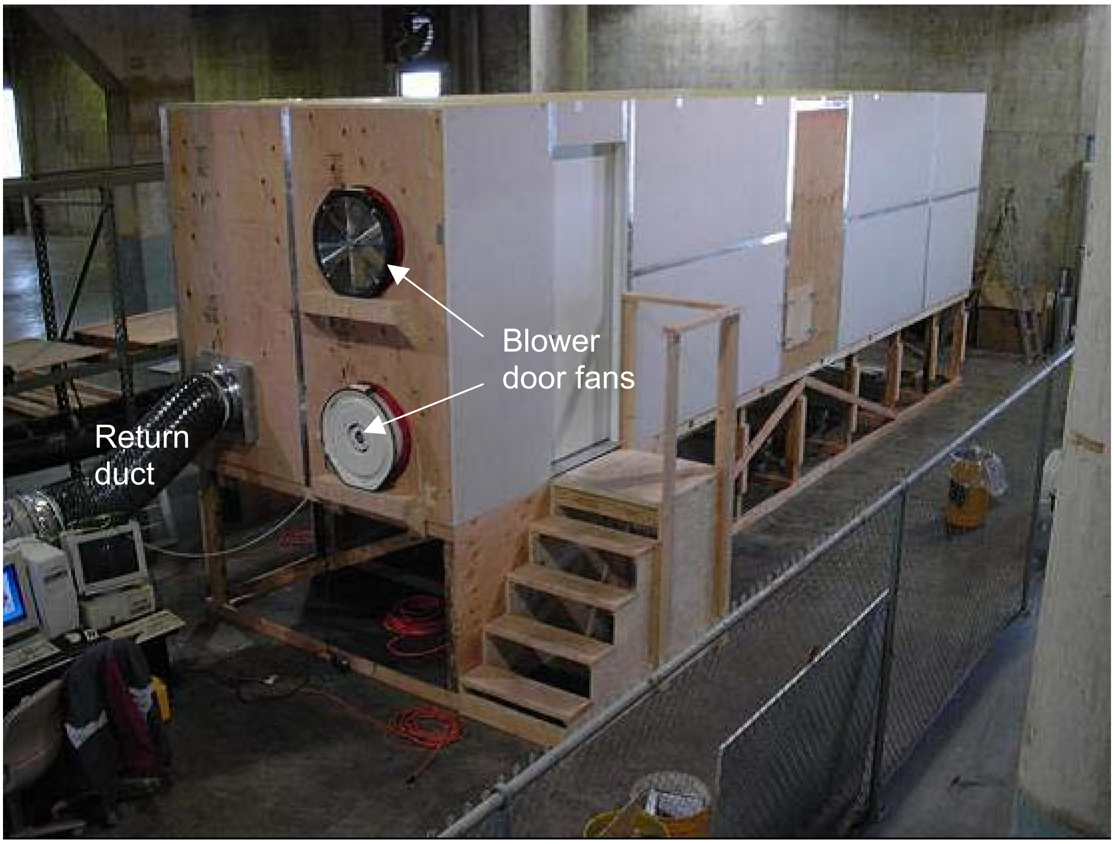

Figure 1. Completed test chamber inside warehouse showing the return duct connection and blower door fans (before supply duct installation).

Test chamber leakage

The background leakage of the test chamber, measured using standard fan pressurization techniques, had an air leakage coefficient of 4.8 L/sPa^n (10.1 cfm/Pa^n) and a pressure coefficient of 0.56. This is equivalent to 29 L/s (61 cfm) at 25 Pa.

Additional pressurization tests were performed (see appendix A) that show that about two-thirds of this leakage was through the second blower door and only one-third was through the chamber envelope and duct system. Six deliberate holes were added that allow the evaluation of measurements under a wide range of house envelope leakage conditions. The air leakage flow information for these holes is summarized in Table 1. These holes were created by cutting circular holes in the building envelope and covered using plywood plates as illustrated in Figure 2. In the register closing experiments holes 1, 2, and 6 were opened for a combined total of about 1460 L/s (2280 cfm) at 25Pa. This makes the leakage very close to the default value given in the California State Energy Code (Title 24) as discussed in Appendix B.

Table 1. Summary of additional envelope holes

Hole Number	Diameter, m (in)	Air Flow at 25Pa, L/s (cfm)
1	0.15 (6)	236 (500)
2	0.23 (9.1)	604 (1280)
3	0.18 (7.1)	358 (760)
4	0.18 (7.1)	358 (760)
5	0.23 (9.1)	604 (1280)
6	0.15 (6)	236 (500)

Figure 2. Open hole number 1 next to covered hole number 2.

The duct system

The duct system has 10 supply registers and a single return grille. The supply ducts are made of flexible insulated duct (with R4 insulation) mostly mounted in the crawlspace below the test chamber (see Figure 3). The supply duct system has two main branches from the supply plenum: one 0.31 m (12 inches) in diameter and one 0.36 m (14 inches) in diameter. The return duct, air handler and the two main supply branches are located beside the test chamber. The registers are placed in the floor of the test chamber in the layout illustrated in Figure 4. The flows from each register range from about 25 L/s to 125 L/s (50 cfm to 250 cfm). The total air handler flow is about 566 L/s (1200 cfm) with all the registers open. The air handler flow is measured using a large 0.41 m (16 inch) diameter flow nozzle in line with the return duct. The duct system had mastic sealant at all connections, and the register boots are screwed and taped to the floor to make sure the system has little or no leakage (see Appendix A, Table A1).

Duct system pressures were measured at each boot and at the plenums. The static pressure drop across the air handler was measured between the return plenum and a point between the air handler and the heat exchanger, rather than using the supply plenum. This gives a more accurate representation of the pressure change through the fan when making fan power and efficiency calculations.

Figure 3. Ducts in the crawlspace below the test chamber.

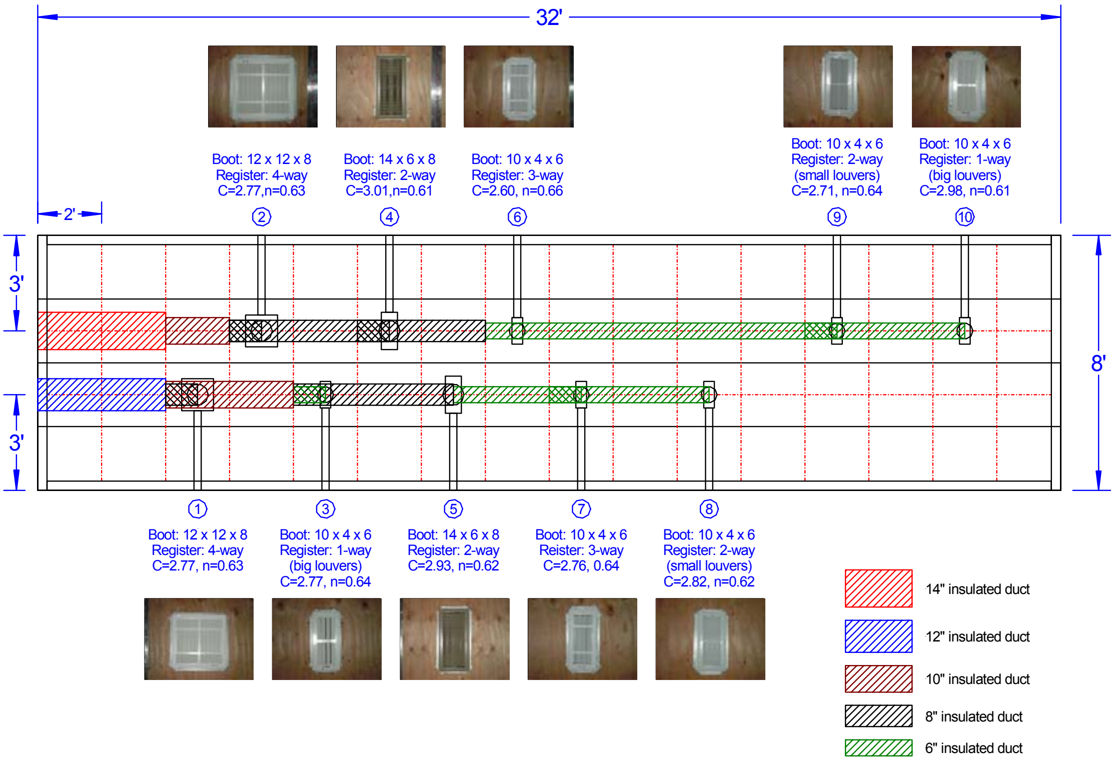

Figure 4. Floor plan of test chamber showing supply duct system layout, register location and duct leakage location

Supply boot leaks

The supply boot leaks were specially designed to have a pressure exponent of about 0.6, rather than the 0.5 that is typical of most flow meters. A range of example leaks was constructed and calibrated using high accuracy (±0.5%) flow meters. The pressure drop across the leak and the reference flow were recorded over a range of flow rates. The target leak flow rates were selected to be close to the range of flow rates found in residential systems: 2.5 to 10 L/s (5 to 20 cfm). Between eight and ten target flow rates were used during the calibration process. The pressure exponent and flow rate were controlled by varying the diameter and length of arrays of holes placed inside the duct leaks. These arrays were created using several techniques, using plastic straws and tubing of different lengths and diameters inside the main leakage pipe. Details of leak construction and calibration for each technique are given in Appendix A. The final versions of the calibrated leaks used holes drilled in PVC plugs – with 55 holes across the cross section of the main duct leakage pipe. The use of these identical CNC milled PVC plugs made the leak construction more consistent to ensure that all ten added boot leaks (one added to each boot) were the same. The PVC plugs with 55 holes had a pressure exponent of 0.61 and a flow coefficient of 1.42 L/sPa^n (3.01 cfm/Pa^n). The calibrated leaks were installed at the boots as shown in Figures 6 and 7. These boot leaks were closed for tests requiring no boot leakage by placing a cap over the end of the pipe, as shown in Figure 7.

Figure 6. End view of boot leak showing the PVC plug used for the register closing tests.

Figure 7. Boot leak showing end cap and attachment to boot.

Supply and return plenum Leaks

The supply plenum and the return plenum each had a single measured leak added. The added leaks were made by connecting a duct to the plenum. The supply plenum leak duct contains a 0.15 m (six inch) nozzle and the return plenum leak duct contains a 0.10 m (four inch) orifice, so that the airflow through each plenum leak can be measured. As with the register boot leaks, the leaks could be closed by capping their ends. The calibrations for these flow meters are given in Appendix C.

Register Closing Experiments

For each register closing test, the register closing pattern was noted and the following were measured:

- Duct leakage flow (all the individual boot leaks plus the return and supply plenum leaks),
- boot pressures,
- plenum pressures,
- envelope pressures (and the resulting envelope leakage flow based on the envelope leakage),
- total system (air handler) flow,
- fan power, and
- air temperature and barometric pressure (for air flow meter corrections).

These data allow the examination of the change in leakage and changes in house envelope air flows as the registers are closed. All the duct pressures are measured relative to outside the test chamber. For the air flow meters at each boot and the supply and return plenums the pressures are pressure differences across the flow elements.

In each test, the air handler was turned on with all the registers opened. The registers were closed one at a time. The measurements were made after waiting about two minutes for the system to be at steady operating conditions. The data were recoded using computer controlled data acquisition systems that allowed time averaging (for five seconds) of the measured data. Two combinations of register closing were tested: progressively closing registers starting at the farthest end of the system from the air handler, then repeating the tests starting at the nearest register to the air handler.

A total of eight different duct leakage configurations were evaluated using different combinations of plenum and boot leakage. These are summarized in Table 2. Note that the different leakage combinations do not simply add because the air handler flow and pressures across the leaks change for each leakage combination. For example, simple adding both supply and return plenum leaks indicates a total leakage of 10% + 11% = 21%, but the combined leakage total is only 18%. The combination of 11 register closing configurations (including all registers open), eight leakage configurations and two directions of register closing order led to a total of 176 experiments.

Table 2. Duct leakage configurations	
Total Duct Leakage % of air handler flow with all registers open	**Duct leakage setup**
0	No leakage
5	Leaks at all registers
10	Leaks at supply plenum
11	Leaks at return plenum
18	Leaks at supply & return plenum
14	Leaks at supply plenum & all registers
14	Leaks at return plenum & all registers
23	Leaks at supply & return plenum & all registers

Laboratory test results

The measured system pressures, air handler flow, air handler power consumption, and leakage air flows test results are given in detail in Appendix D. The test results were split into two cases based on the direction in which registers were systematically closed. The first case started with the register nearest to the air handler closed first (register 1 in Figure 4), followed by the next closest (register 2 in Figure 4) and so on, with the register furthest from the air handler closed last (register 10). Conversely, the second case started by closing the furthest register from the air handler (register 10 in Figure 4), then closing the next closest (register 9) and so on, with the register nearest the register closed last.

Duct Pressures

Closing far registers has less effect on register boot and plenum pressures than closing registers near the supply plenum. Closing registers near the plenum tends to increase pressures throughout the system, whereas closing far registers only affects the branch of the duct system being adjusted. For example, with four registers closed the average boot pressure is 3 to 4 times higher with near registers closed, leading to about double the system leakage. Figure 8 illustrates this point: with the far registers closed first, only the boots with closed registers (7, 8, 9 and 10) have significant pressure changes; but with the near registers closed first (registers 1, 2, 3, and 4 closed) all the boot pressures are increased. The magnitude of the directional effect increases as more registers are closed, until the point where all ten registers are closed. At that point there is a big change for the far registers closed first results, and the two directions have about the same pressure distribution throughout the duct system.

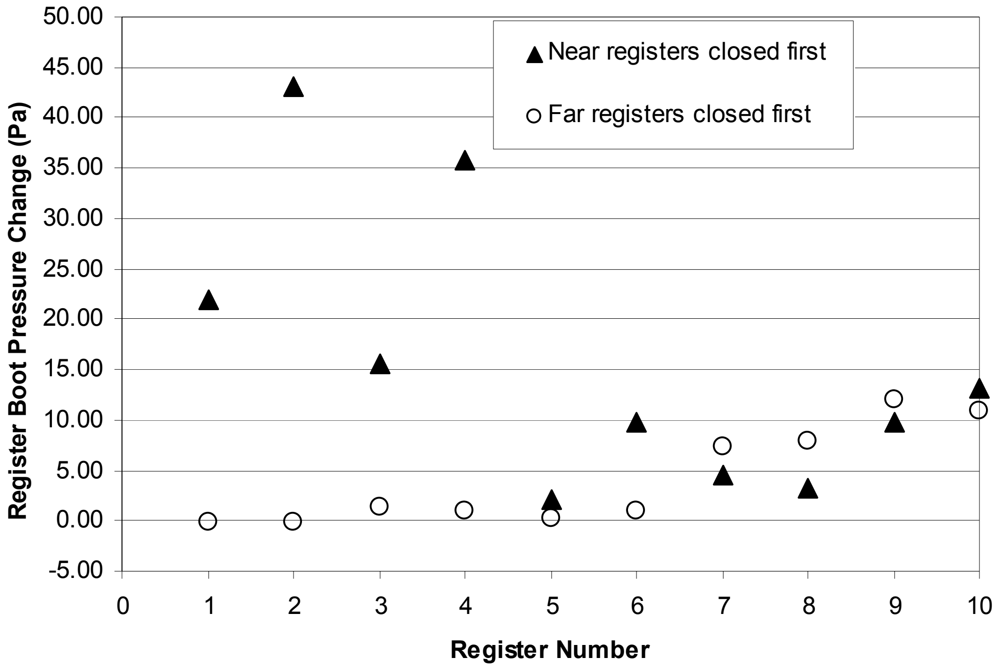

Figure 8. Individual register boot pressure changes with four registers closed for both closing directions with register boot, supply and return plenum leaks. Near registers closed first results have registers 1 through 4 closed and far registers closed first results have registers 7 through 10 closed.

Duct Leakage

For the supply leaks, closing registers increases duct system pressures and therefore duct leakage. For the same number of closed registers, closing the near registers first resulted in more duct leakage than closing far registers first due to the higher system pressures (see Figures 9 and 10). The eight different leakage combinations (as given in Table 2) have differing sensitivities to register closing. The supply boot leakage goes up by almost a factor of ten from 5% to 55% of air handler flow (24 L/s (50 cfm) to 240 L/s (500 cfm)) as the registers are closed. The supply plenum leakage increases by a factor of about 3.5, from 10% to 35% of air handler flow.

As a fraction of the coincident air handler flow (i.e. the air handler flow recoded with that specific number of registers closed and **not** the all registers open air handler flow) the return plenum leakage is essentially constant (±0.5% of air handler flow). This is because the return plenum static pressures depend on the flow resistance of the return that does not change as supply registers are closed. Therefore, the return leakage flow simply scales with the air handler flow and the fractional leakage does not change. These results imply that the system performance will change the least for systems with little low pressure boot leakage and with most of their leakage at the return plenum.

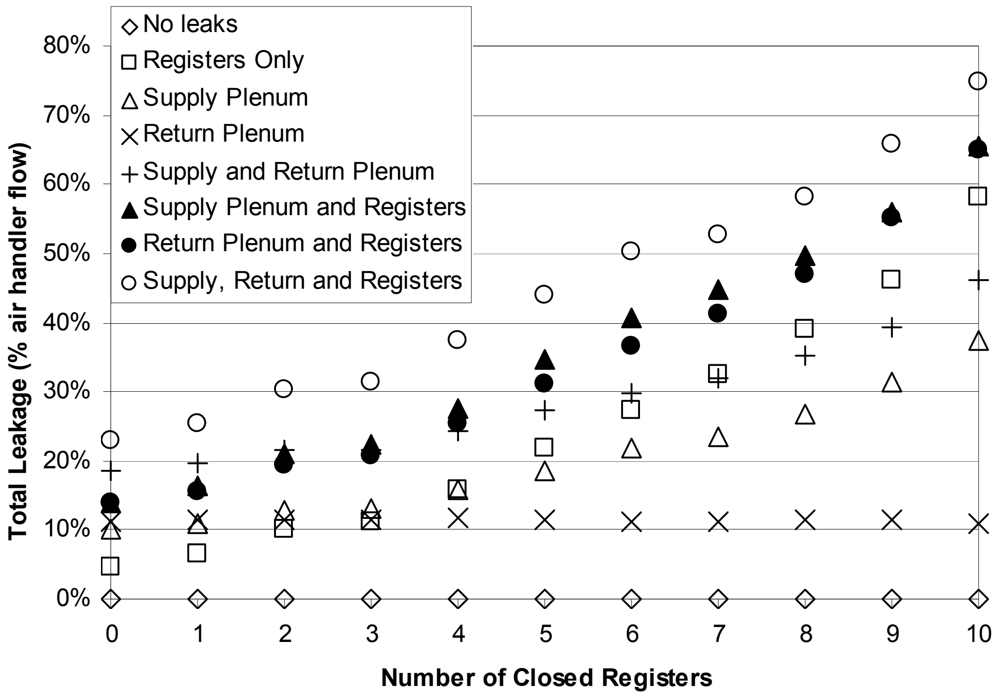

Figure 9. Duct system total air leakage as fraction of air handler Flow with near registers closed first.

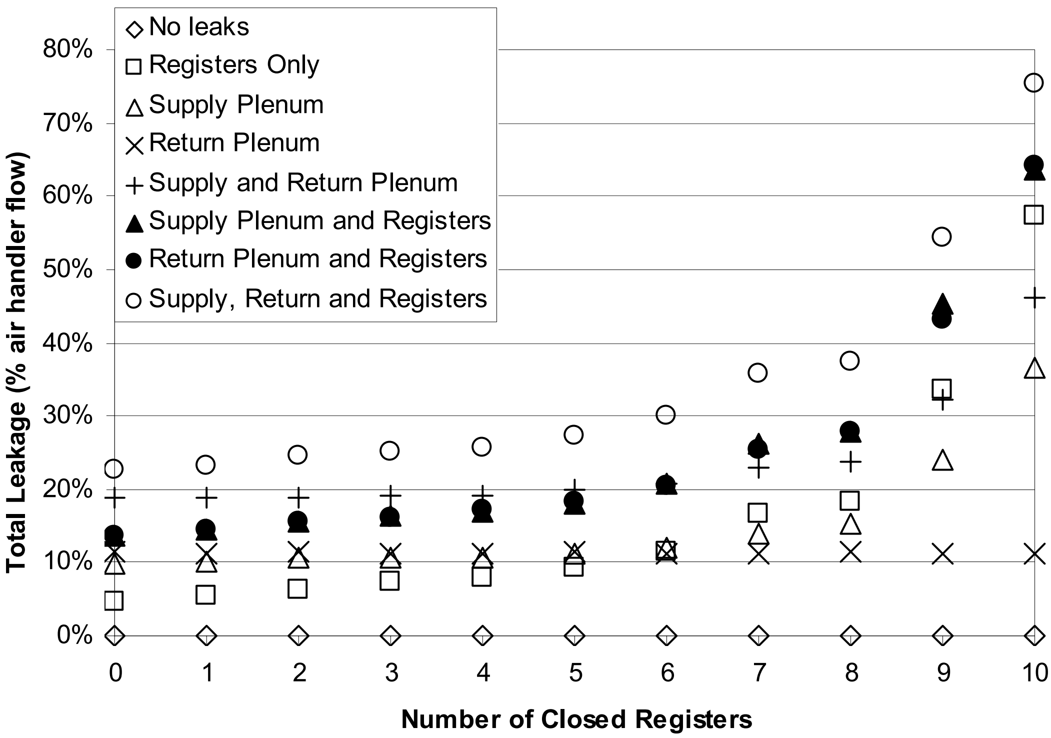

Figure 10. Duct system total air leakage as fraction of air handler Flow with far registers closed first.

Air Handler Flows

Reduced air handler flow leads to reduced heat exchanger efficiency, particularly for cooling systems. Therefore it is desirable to set a maximum acceptable reduction in air handler flow of about 20%. As expected, the no leaks system has the biggest changes in air handler flow as registers are closed and the leakiest system has the least change (due to the existence of alternative flow paths: the leaks). Also, with all registers open, the more leaky systems start with slightly higher (550 L/s (1160 cfm) compared to 530 L/s (1120 cfm)) air flows due to their lower flow resistance. With the near registers closed first (shown in Figure 11), the 20% reduction is reached when six registers are closed for the no leak system, but is never reached for the leakiest system (because the system air flow now flows almost exclusively through the leaks rather than through the registers). When the far registers are closed first (shown in Figure 12), the air flow reductions are more gradual and only closing the last couple of registers has any significant effect.

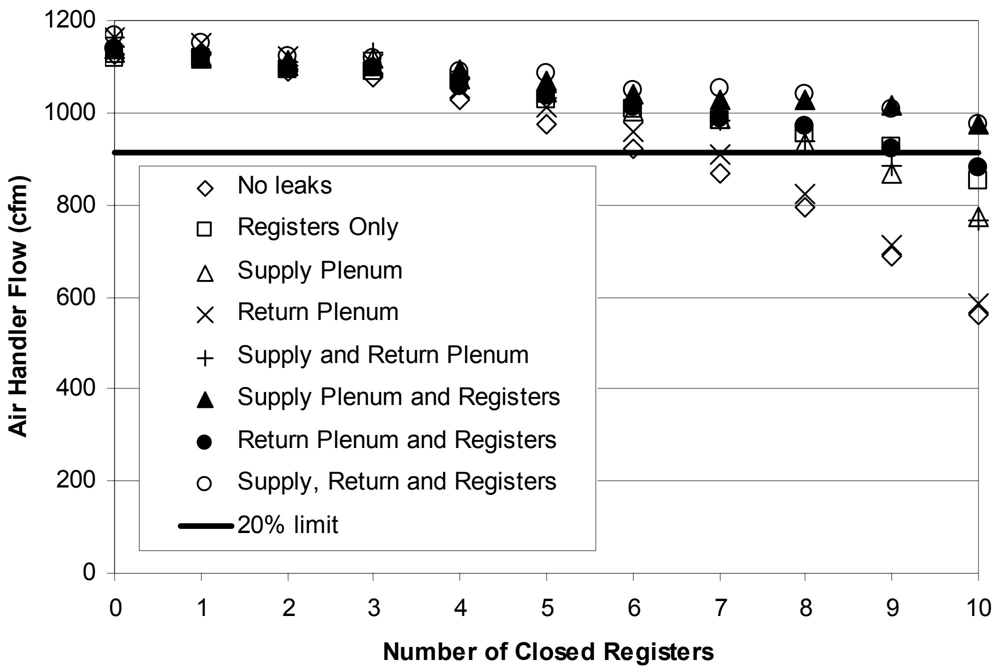

Figure 11. Changes in air handler flow as near registers are closed first.

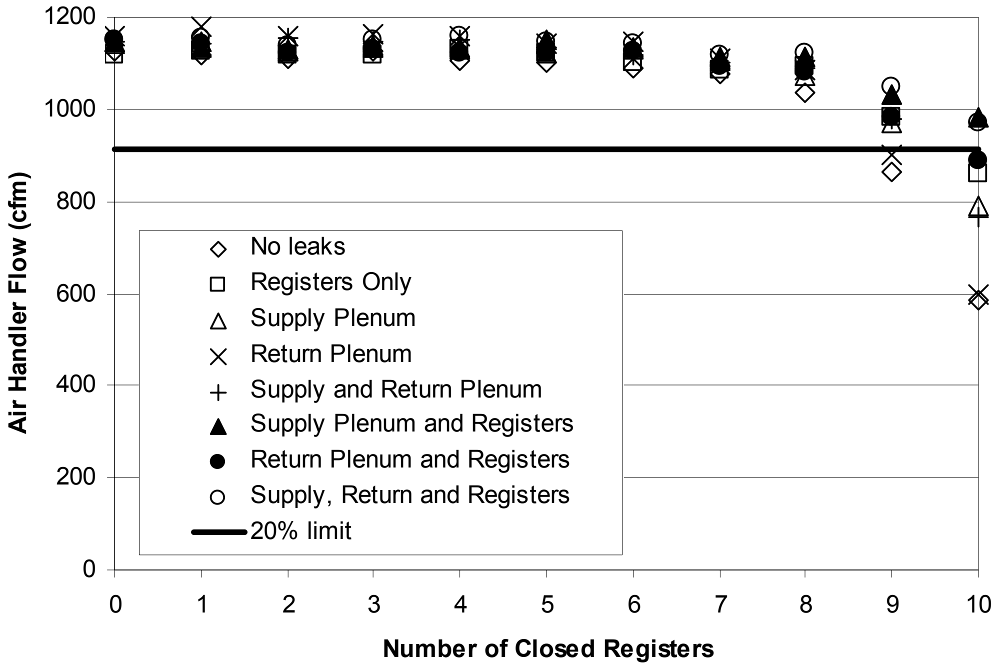

Figure 12. Changes in air handler flow as far registers are closed first.

Air Handler Power Consumption

Air handler power consumption depends on both the efficiency of the air handler under particular operating conditions and the power required to move the air in the system (given by the product of the volume of air handler flow and the static pressure difference across the air handler). The air handler power consumption shows less variation than the air flow because as the system air flow is reduced as the pressure difference across the air handler increases and therefore their product remains relatively constant. The air handler power consumption gradually drops from about 570 W to 460 W as the registers are closed as shown in Figures 13 and 14.

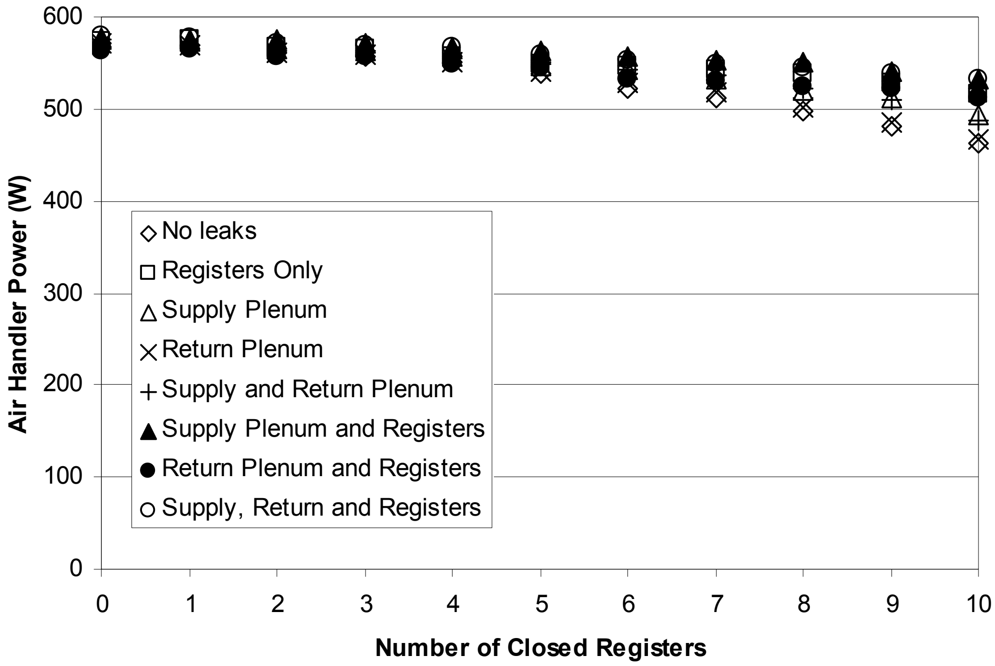

Figure 13. Changes in air handler power as near registers are closed first.

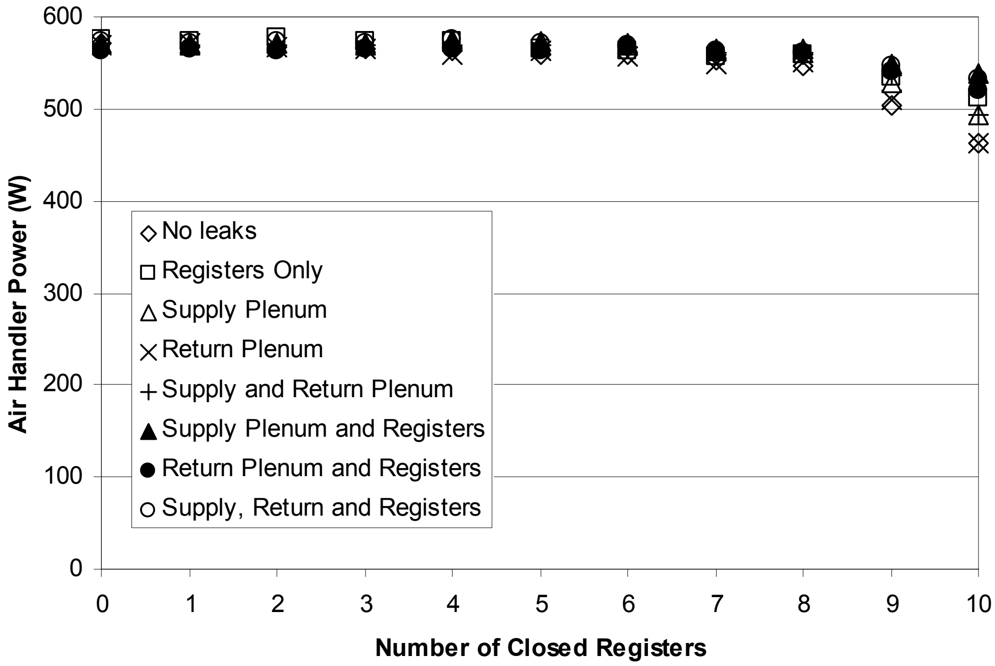

Figure 14. Changes in air handler power as far registers are closed first.

Envelope Pressures

The pressurization or depressurization of the house is an important issue because of potential combustion appliance backdrafting and deposition of moisture inside the house envelope. A house with a tighter envelope than used in these experiments would experience greater pressure changes and leaky home comparatively less.

Therefore the specific risks for an individual house require an assessment of the envelope leakage in addition to the guidance given here.

Significant envelope pressure changes can be caused by duct leakage: excess supply leaks lead to depressurization and excess return leaks lead to pressurization. Note that it is not the total leakage that is important, but the difference between supply and return leakage.

The greatest leakage imbalance was for the case with supply plenum and register boot leakage that resulted in depressurization. The depressurization of the envelope increased as more registers are closed and the leakage imbalance increased. When the near registers are closed first, the depressurization is less than 0.5 Pa until nine or ten registers were closed. It then increased sharply to almost 2 Pa of depressurization as the final two registers were closed. When the far registers are closed first, the same limit was achieved with all the registers closed, but at intermediate numbers of closed registers there was significantly more depressurization because the corresponding leakage flows are greater. The 0.5 Pa depressurization point was reached with only four registers nearest the air handler closed.

The other leakage configurations provided correspondingly less depressurization as the supply-return leakage imbalance was decreased. For example, for the return leak only case, the chamber was slightly pressurized (by only about 0.1 Pa) with near registers closed first and even less than this for the other direction.

ASHRAE 152 Estimates of Distribution System Efficiency

ASHRAE Standard 152 (ASHRAE 2003) was used to estimate the changes in distribution system efficiency corresponding to the duct leakage and air handler flow changes measured in the laboratory. Three California climates (Sacramento, Bakersfield and Los Angeles) were examined for heating and cooling, at design and seasonal conditions. Although the focus of this study was on heating system performance, the automated ASHRAE 152 calculation spreadsheet used for these calculations included the cooling efficiencies. These cooling results are presented for completeness and comparison purposes. These locations have relatively mild winter conditions are the likely candidates for applying register closing strategies. Extremely cold climates are unlikely to adopt register closing strategies due to concerns of condensation on the surfaces of the cold room or pipes freezing. The key duct system and house parameters used in the 152 calculations were:

- The house had two stories with a combined floor area of 155 m^2 (1700 ft^2).
- The duct system had a single return and all the ducts were in the attic.
- The ducts were all RSI 0.7 (R4) flex duct.
- The air conditioning cooling capacity was three tons.
- The furnace capacity was 29 kW (100kBtu/hr).

The laboratory measured duct leakage was used for each calculation. Other input data are summarized in Appendix E. All the calculated efficiencies are summarized in Appendix F.

These results can be used to decide how many registers can be closed before a minimum distribution system efficiency level cannot be met. Table 3 summarizes the results of this process for Sacramento (results for Bakersfield and Los Angeles are shown in Appendix G) at four levels of acceptable minimum efficiency: 90%, 80%, 70% and 60%. The grey cells in the tables indicate that the minimum efficiency specification cannot be met even with no registers closed. It should also be noted that these results are for seasonal average weather conditions. At more severe design conditions the restrictions would be even greater.

Table 3. Maximum number of registers that can be closed and still meet a minimum seasonal efficiency specification (Sacramento)

Minimum efficiency	90%				80%				70%				60%			
Seasonal Heating/Cooling	H		C		H		C		H		C		H		C	
Direction (n = near registers closed first, f = far registers closed first)	n	f	n	f	n	f	n	f	n	f	n	f	n	f	n	f
No leak	7	8			10	10	7	9	10	10	10	10	10	10	10	10
Leak at registers					3	6	1	2	4	8	3	6	6	8	5	8
Leak at supply plenum					1	5			5	8	3	7	8	9	6	8
Leak at return plenum	8	9			10	10	3	8	10	10	10	10	10	10	10	10
Leak at return & supply plenum					2	6			6	8	3	6	9	9	6	8
Leak at supply plenum and registers									2	6	0	2	4	8	3	6
Leak at return plenum and registers					3	6			5	8	3	6	7	8	4	8
Leak at registers, return & supply plenum									3	6			4	8	2	6

At high minimum efficiencies, only the heating no leakage and return plenum leakage cases allow any register closing. As the minimum efficiency level is dropped, more leakage scenarios allow register closing. The two leakage cases that are close to typical new construction (e.g., the 22% total leakage default in the Title 24 ACM) are: 1) leaks at supply plenum and registers, and 2) leaks at both plenums and registers. These cases severely restrict the number of occasions when registers can be closed even at only 70% efficiency. These distribution system efficiency calculations do not account for any decreasing building load that may offset the decrease in system efficiency. The more complex LBNL REGCAP simulation model was used to examine this effect in more detail.

REGCAP Simulations to Couple Reductions in Building Load With Distribution System Losses

The REGCAP model has been used in several previous studies by LBNL (Walker et al. 1998, 2001; Siegel et al. 2000). It combines a relatively simple building load model with a highly sophisticated thermal distribution and equipment model that focuses on duct losses to attic spaces. REGCAP performs minute-by-minute dynamic simulations to capture the effects of the cyclic performance of the distribution system and equipment. REGCAP uses an airflow network model that includes air flow through the duct leaks when the forced air system is not operating, and calculates changes in building air flows due to duct leakage imbalances that pressurize or depressurize the house.

For this study, the house was based on the standard Title 24 home that has been used previously (Sherman and Walker 2002, Walker et al. 2002). This is a 167 m^2 (1800 ft^2) two-story house with default Title 24 window locations and insulation levels. The duct system is in the attic and is made from R4 flex duct. The duct leakage levels were based on the results of the laboratory testing discussed above. The simulations were for heating conditions with an indoor setpoint of 68°F (20°C). Simulations were for a continuous 48 hours starting at midnight. The results presented here are based on the middle 24 hours, i.e., noon to noon, so that a complete night (when heating loads are greatest and the heating design conditions occur) is included.

Rationale for load reduction attributed to register closing

An adaptation to the existing REGCCAP model was required to allow the building load to change as registers are closed. It was assumed that a room with a closed register becomes a buffer space between conditioned parts of the house and the outside. The reduction in the effective envelope UA and envelope leakage area could then be calculated as each register was closed.

With ten registers in the house, it was assumed that 10% of the house floor area and envelope area was associated with each register. It was also assumed that each space conditioned by each register has an equal fraction of the house envelope UA associated with it. These assumptions ignored the complexities of an individual building but provided for a systematic analysis to be performed. When a register was closed, the total exterior area did not change but a buffer space was added to the remaining conditioned space. The thermal resistance of the buffer space was mostly from two additional air films (one on the inside of the outer wall and one on the face of the interior partition facing the buffer space), and from the interior partition itself. A reasonable thermal resistance for the buffer space was about RSI 0.88 (R5). Given that the insulated exterior wall had a thermal resistance of RSI 2.3 (R13), the change in thermal resistance was about 40% for that part of the building. With a total building UA of 150 W/K (285 Btu/h°F), each register was associated with 15 W/K (28.5 Btu/h°F). An increase in thermal resistance of 40% by closing one register reduced the UA value by 4 W/K (7.6 Btu/h°F) per register. Therefore, 4 W/K (7.6 Btu/h°F) was subtracted from the building envelope UA every time a register was closed. In addition, the effective volume of the house was reduced each time by 10%. In the model this reduced the effective thermal mass of the house.

REGCAP Input Data

Weather data

The weather files included the day of the year and hourly data for dry-bulb temperature, wind speed and direction, humidity ratio, and solar radiation. Three climate zones were simulated: CZ3 (Oakland/California coast), CZ12 (Sacramento/Central Valley) and CZ16 (Mount Shasta/Mountains). These three climates were used in order to exercise the concept of closing registers over a wide range. The weather files were based on those used for Title 24 calculations and use linear interpolation to determine minute-by-minute data from the hourly data. The weather day was chosen by determining the ASHRAE 1% design conditions (from ASHRAE Handbook of Fundamentals (2001)) for a representative city within the climate zone. Each day of weather data was examined to find the one with the greatest number of hours at or near these design conditions. This was called the design day (more details regarding weather data selection are covered by Walker et al. 2002). The 48 hours of total simulation time included the 12 hours before this design day and 12 hours after. This allowed enough time for any assumptions about initial temperature conditions to have a negligible effect.

Building data

For the building, the information required for the simulations included:

- Envelope data: house dimensions, thermal properties, and air leakage,
- Attic data: geometry (dimensions and roof pitch), air leakage, insulation, and roof materials, radiation properties of surfaces
- Duct data: location, dimensions, insulation and air leakage,
- Equipment data: manufacturers performance data, refrigerant charge and evaporator airflow.
- Altitude and latitude used for air density and solar calculations.

The characteristics of the house are summarized in Tables 4 through 6. The heating capacities were determined from the default in Title 24 (CEC (1998) Chapter 3.8). This default is 105 W/m^2 (34 Btu/h/ft^2) of floor area, which corresponds to about 17.5 kW (60 Btu/h) for a 167 m^2 (1800 ft^2) house. The duct leakage, air handler flow and power consumption data from our laboratory measurements are used as input to the REGCAP simulations. The duct leakage fractions for supply and return ducts are used directly. Because the air handler flow for the simulated house is less than for the laboratory tests (401 L/s (850 cfm) instead of (545 L/s (1150 cfm)), the fractional change in the laboratory measured air handler flow was applied to the simulated air handler flow. For example, if closing 6 registers reduced the laboratory air handler flow by 5% from (545 L/s (1150 cfm)) to 515 L/s (1095 cfm), then the simulated air handler flow was reduced by 5% from 400 L/s (850 cfm) to 380 L/s (810 cfm).

Table 4. House Description

General data	House is on a street in an urban environment (used for wind shelter), slab on grade	
	2 stories	
Dimensions	Volume	418 m^3 [15000 ft^3]
	Floor Area	167 m^2 [1800 ft^2]
Envelope Leakage, based on new construction with a Normalized Leakage (NL) of 0.4	C = 0.07 m^3/sPa^n [150 cfm/Pa^n], n = 0.65	
Leakage Distribution Data	R (fraction of leaks in floor an ceiling)=0.4 X (difference between floor and ceiling leaks)=0.2	
	33% of total leakage each in Wall 1 & 2 17% of leaks in Wall 3 & 4	
	No open Windows/Doors or ventilation fans operating	
Thermal data	House UA	150 W/K
	Ceiling insulation	R30
	Wall insulation	R13
	Latent Loads	None
	Internal Gains	600 W [2050 Btu/h]

Table 5. Description of Attic Characteristics

General data	Volume	76 m^3 [2812 ft^3]
	Area	84 m^2 [900 ft^2]
Roof	Asphalt shingle	
	Roof Ridge perpendicular to front of the house	
	Roof Pitch	26.5°
	Height of Roof Peak above grade	7.6 m [25 ft]
	Soffit Height above grade	5.8 m [19 ft]
Attic Leakage	C = 0.236 m^3/sPa^n [500 cfm/Pa^n], n = 0.51	
	No additional vents or ventilation fans	

Table 6. Base case duct features

General data	Located in the attic		
	Insulated plastic flex		
		Supply	Return
Dimensions	Diameter (mean)	0.25 m [10 in]	0.5 m [20 in]
	Length	38.7 m [127 ft]	5.1 m [16.8 ft]
Thermal data	Insulation thickness	0.05 m [2 in]	0.05 m [2 in]
	Thermal Resistance	RSI 0.7 [R 4]	RSI 0.7 [R 4]

Summary of REGCAP simulations

The simulations were selected based on the register closing test results discussed earlier. The number of closed registers was limited to six because it is unlikely that many people will want to have more than half of their house unconditioned and because the leakage and the ASHRAE 152 calculated efficiency results changed more rapidly as the second half of the registers were closed. In addition, for this number of closed registers, the results are not too extreme so that issues about air handler flow being too low and furnaces operating on the high limit switch all the time (or coil freeze-up if for cooling simulations) can be avoided.

Two leakage configurations were studied: 1) the lowest level tested in the laboratory with leaks at the register boots only, and 2) the highest level evaluated with leaks at both plenums and the boots. These represent nominal leakage of about 5% and 23% of air handler flow respectively. The laboratory results for register closing in both directions were used. Although leakage was proportionally less if far registers were closed first, this may not be feasible depending on the layout of the house and duct system where unoccupied rooms are not farthest from the air handler. The duct leakage coefficients (used to calculate air flows through the duct leaks when the air handler is off) were calculated by using the laboratory measured duct leakage air flow and an assumed reference pressure of 25 Pa. Tables 7 through 10 summarize the system parameters that were changed for each simulation.

Table 7. High leakage heating system parameters with registers closed in order moving toward the air handler: i.e., far registers closed first

	Air Handler flow L/s (cfm)	Duct Leakage Fraction		Air handler power, W	House UA, W/K (Btu/h°F)	House volume, m^3 (ft^3)	Duct Leakage Coefficient, C m^3/sPa^n (cfm/Pa^n)	
		Supply %	Return %				Supply	Return
No registers closed	401 (850)	13.7	9.0	500	150 (285)	418 (15000)	0.008 (17)	0.005 (11)
1 far reg closed	401 (850)	14.4	9.0	498	146 (277)	376 (13400)	-	-
2 far reg closed	396 (840)	15.6	9.0	500	142 (269)	334 (11900)	-	-
3 far reg closed	400 (848)	16.1	9.0	498	138 (262)	293 (10500)	-	-
4 far reg closed	404 (855)	16.8	9.0	502	134 (254)	251 (8950)	-	-
5 far reg closed	399 (845)	18.3	9.0	498	130 (247)	209 (7500)	-	-
6 far reg closed	397 (842)	20.9	9.0	495	126 (239)	167 (6000)	-	-

Table 8. High leakage heating system parameters with registers closed in order moving away from the air handler. i.e., near registers closed first

	Air Handler flow L/s (cfm)	Duct Leakage Fraction		Air handler power, W	House UA, W/K (Btu/h°F)	House volume, m^3 (ft^3)	Duct Leakage Coefficient, C m^3/sPa^n (cfm/Pa^n)	
		Supply %	Return %				Supply	Return
No registers closed	401 (850)	13.8	9.0	500	150 (285)	418 (15000)	0.008 (17)	0.005 (11)
1 near reg closed	396 (838)	16.3	9.0	498	146 (277)	376 (13400)	-	-
2 near reg closed	386 (817)	21.1	9.0	493	142 (269)	334 (11900)	-	-
3 near reg closed	384 (813)	22.2	9.0	491	138 (262)	293 (10500)	-	-
4 near reg closed	374 (792)	28.2	9.0	490	134 (254)	251 (8950)	-	-
5 near reg closed	372 (788)	35.0	9.0	483	130 (247)	209 (7500)	-	-
6 near reg closed	360 (762)	41.1	9.0	476	126 (239)	167 (6000)	-	-

Table 9: Low leakage heating system parameters with registers closed in order moving toward the air handler: i.e., far registers closed first

	Air Handler flow L/s (cfm)	Duct Leakage Fraction		Air handler power, W	House UA, W/K (Btu/h°F)	House volume, m^3 (ft^3)	Duct Leakage Coefficient, C m^3/sPa^n (cfm/Pa^n)	
		Supply %	Return %				Supply	Return
Standard Base	401 (850)	4.2	0	500	150 (285)	418 (15000)	0.0024 (5)	0
1 far reg closed	385 (815)	5	0	500	146 (277)	376 (13400)	-	-
2 far reg closed	389 (825)	5.9	0	500	142 (269)	334 (11900)	-	-
3 far reg closed	378 (800)	6.9	0	500	138 (262)	293 (10500)	-	-
4 far reg closed	381 (810)	7.5	0	500	134 (254)	251 (8950)	-	-
5 far reg closed	392 (830)	8.6	0	495	130 (247)	209 (7500)	-	-
6 Far reg closed	381 (810)	11.1	0	500	126 (239)	167 (6000)	-	-

Table 10: Low leakage heating system parameters with registers closed in order moving away from the air handler. i.e., near registers closed first

	Air Handler flow L/s (cfm)	Duct Leakage Fraction		Air handler power, W	House UA, W/K (Btu/h°F)	House volume, m^3 (ft^3)	Duct Leakage Coefficient, C m^3/sPa^n (cfm/Pa^n)	
		Supply %	Return %				Supply	Return
Standard Base	401 (850)	4.2	0	500	150 (285)	418 (15000)	0.0024 (5)	0
1 near reg closed	401 (850)	6.2	0	500	146 (277)	376 (13400)	-	-
2 near reg closed	396 (840)	10.1	0	490	142 (269)	334 (11900)	-	-
3 near reg closed	392 (830)	11.0	0	490	138 (262)	293 (10500)	-	-
4 near reg closed	385 (815)	15.3	0	480	134 (254)	251 (8950)	-	-
5 near reg closed	371 (785)	20.6	0	475	130 (247)	209 (7500)	-	-
6 near reg closed	359 (760)	27.1	0	475	126 (239)	167 (6000)	-	-

Results of REGCAP simulations

The following results are presented as 24-hour averages of gas and electricity consumption. Appendix G contains all the gas consumption and air handler fan electricity consumption results from REGCAP for all the register closing, duct leakage and climate variations. Table 11 summarizes the results from all the climate zones for both gas consumption and air handler electricity use, and shows how the more severe climates have a greater building load and therefore have more gas and electricity use. Figure 15 illustrates the changes in gas consumption as registers are closed for CZ 16.

In every case the closing of registers led to increased energy consumption, even for the low leakage configuration. This trend occurs for all three climate zones: it was not possible to save energy by closing registers; and closing more registers led to increased energy usage. The electricity used by the air handler shows the same changes as the gas consumption.

Table 11. Summary of 24 Hour Averaged REGCAP Register Closing Simulation Results

	Average Gas Power Consumption, kW (kBtu/h)	Fractional change as registers are closed, %		
	Number of Closed Registers			
	None	1	2	3
CZ3, Low Leakage	5.1 (13.4)	3	9	21
CZ3, High Leakage	6.1 (20.7)	1	5	16
CZ12, Low Leakage	6.9 (23.5)	3	17	39
CZ12, High Leakage	10.0 (34.1)	0	2	8
CZ16, Low Leakage	9.3 (31.8)	6	15	19
CZ16, High Leakage	11.5 (39.3)	1	3	5
	Average Air Handler Power, W	Fractional change as registers are closed, %		
	Number of Closed Registers			
	None	1	2	3
CZ3, Low Leakage	145	3	9	21
CZ3, High Leakage	172	1	5	15
CZ12, Low Leakage	196	3	17	39
CZ12, High Leakage	284	0	2	7
CZ16, Low Leakage	264	5	15	21
CZ16, High Leakage	319	1	3	8

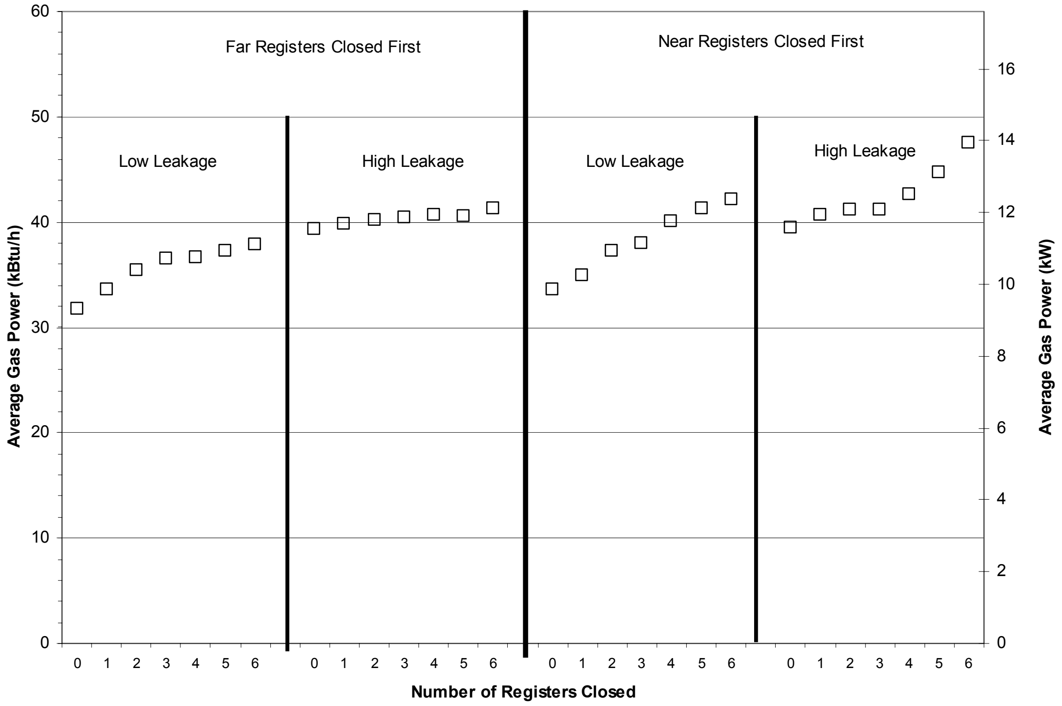

Figure 15. Increase in gas use (averaged over 24 hours for a design day) as registers are closed for Climate Zone 16.

Conclusions

The closing of registers led to an increase in energy use for the typical California house and duct system used in this study. The reduction in building load due to not conditioning the entire house was more than offset by increased duct system losses mostly due to increased duct leakage.

The register closing technique has less impact on energy use if registers furthest from the air handler are closed first because this tends to only affect the pressures and air leakage for the closed off branch. Closing registers nearer the air handler tends to increase the pressures and air leakage for the whole system.

Closing too many registers (more than 60%) is not recommended because the added flow resistance severely restricts the air flow though the system to the point where furnaces may operate on the high-limit switch and cooling systems may suffer from frozen coils.

References

ASHRAE 2001. ASHRAE Handbook of Fundamentals. ASHRAE, Atlanta, GA.

ASHRAE 2003. ASHRAE Standard 152. *Method Of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems*. ASHRAE. Atlanta, GA.

CEC. 1998. Low-rise residential Alternative Calculation Method Approval Manual for 1998 Energy Efficiency Standards for Low-Rise Residential Buildings, California Energy Commission, Sacramento, California.

Sherman, M.H. and Walker, I.S. 2002. "Residential HVAC and Distribution Research Implementation". CIEE/PG&E Final Report. LBNL 47214.

Siegel, J., Walker, I. and Sherman, M. 2000. "Delivering Tons to the Register: Energy Efficient Design and Operation of Residential Cooling Systems". Proc. ACEEE Summer Study 2000. Vol. 1, pp. 295-306. American Council for an Energy Efficient Economy, Washington, D.C. LBNL 45315.

Walker, I.S., Siegel, J.A., Degenetais, G. 2001. "Simulation of Residential HVAC System Performance". Proc. ESIM2001 Conference, pp. 43-50. CANMET Energy Technology Centre/Natural Resources Canada, Ottawa, Ontario, Canada. LBNL 47622.

Walker, I.S., Brown, K., Siegel, J. and Sherman, M.H. 1998. "Saving Tons at the Register", Proc. ACEEE 1998 Summer Study. Vol. 1, pp. 367-384. American Council for an Energy Efficient Economy, Washington, D.C. LBNL 41957.

Walker, I.S., Degenetais, G. and Siegel, J.A., 2002. "Simulations of Sizing and Comfort Improvements for Residential Forced air heating and Cooling Systems." LBNL 47309.

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Appendix A. Test Chamber Construction

Figure A1. Photographs of test chamber construction showing registers located in the floor

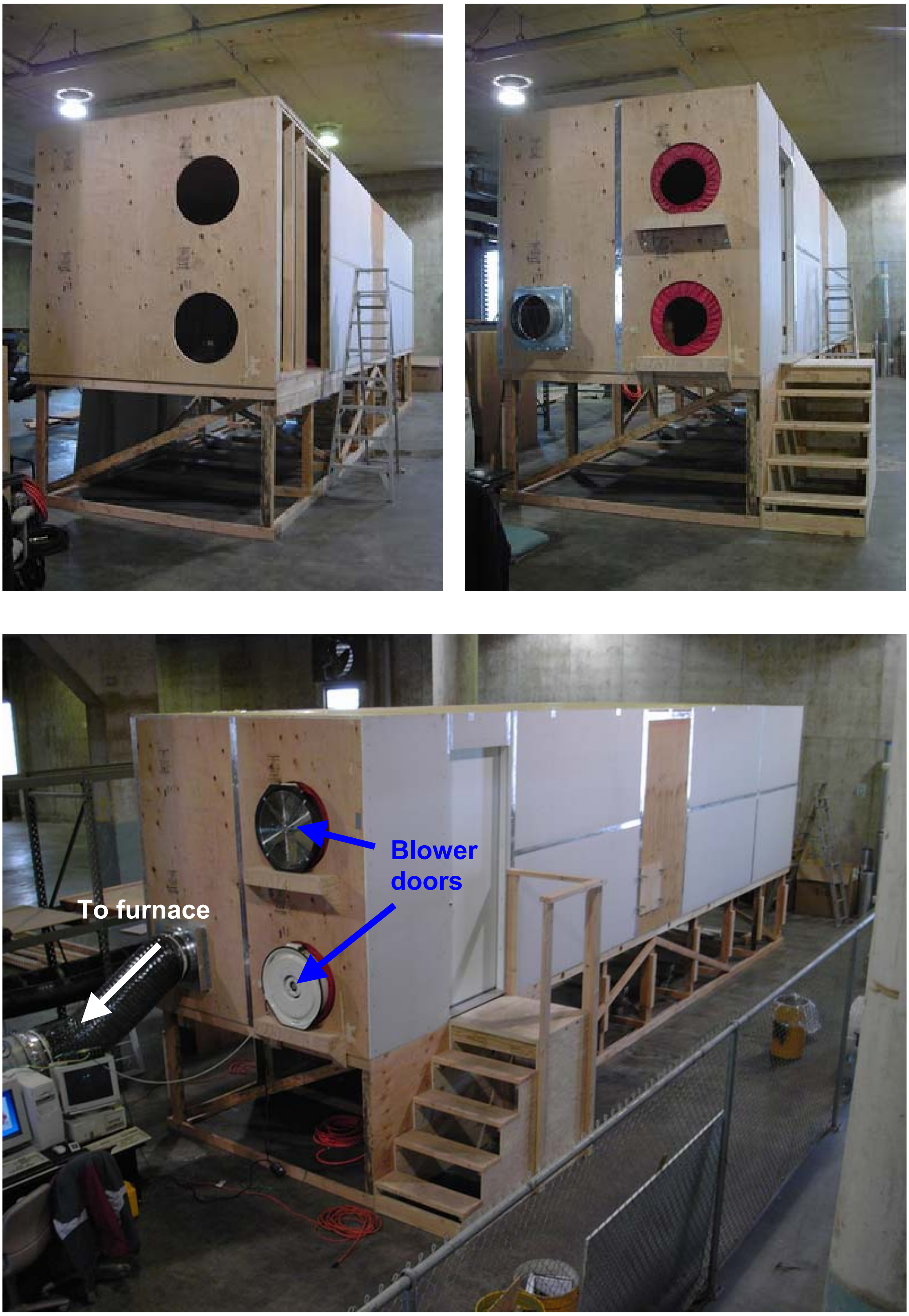


Figure A2. Photographs of the exterior of the test chamber showing the crawlspace (where the supply ducts are located), blower doors for leakage testing and the connection to the furnace (supply ducts not installed).

Table A1. Summary of Duct and Chamber background leakage

	C (cfm/Pa^n)	n	Q25 (cfm)
Chamber + ducts, Blower Door not sealed, registers closed	10.08	0.560	90
Chamber + ducts, Blower Door sealed, registers closed	3.26	0.686	30
Chamber + air handler (no ducts), Blower Door sealed.	4.44	0.645	35
Chamber, Blower Door sealed (pre added holes)	3.80	0.648	31
Chamber, Blower Door not sealed (pre added holes)	12.35	0.552	73

Figure A3. Calibration of boot leaks showing (clockwise from top left): complete calibration apparatus, variable speed blower and hand held manometer, high precision flow nozzle and end view of prototype boot leak filled with straws

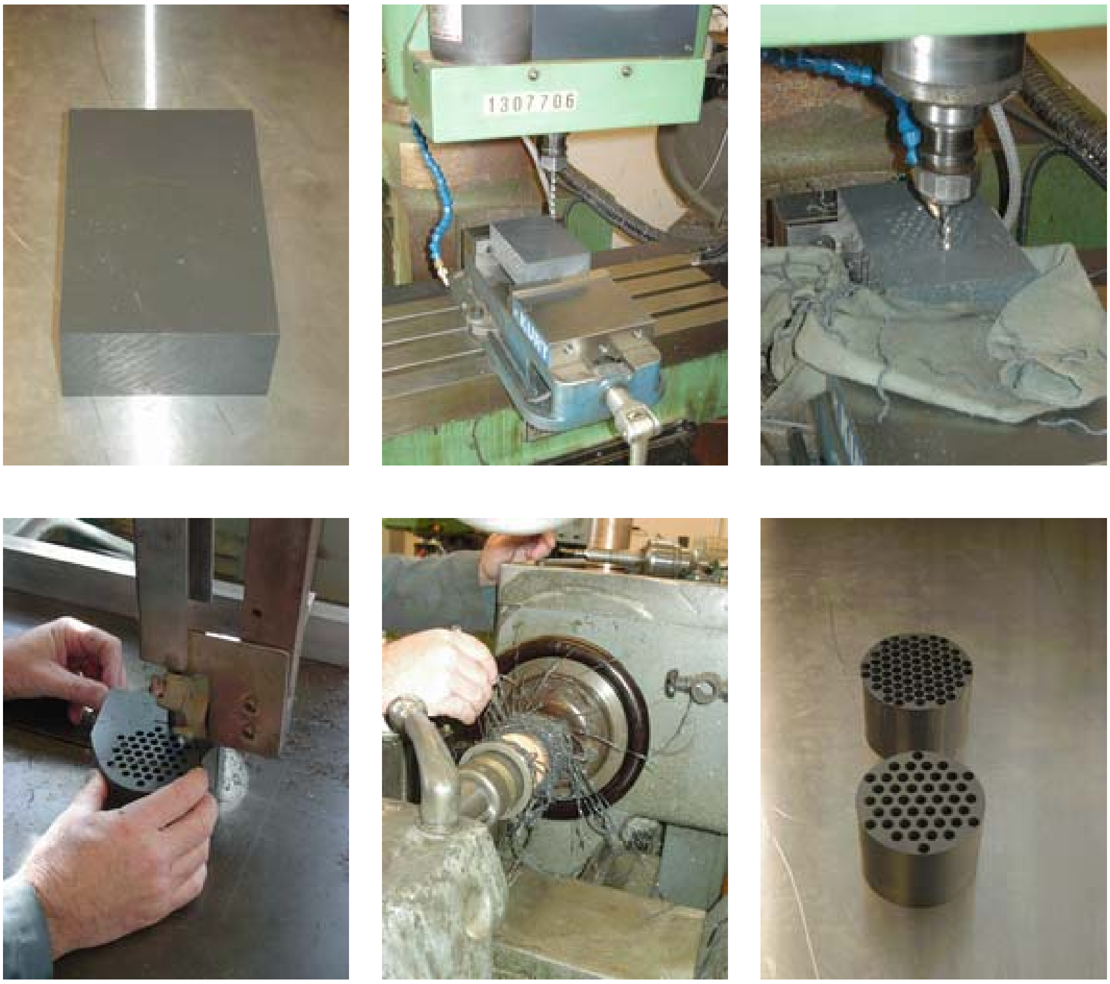


Figure A4. Construction of controlled pressure exponent boot leaks machined from solid PVC blocks.

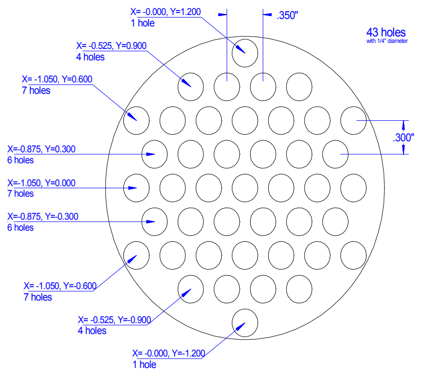
Boot Leak Calibrations

PVC (43 holes) in 3" PVC

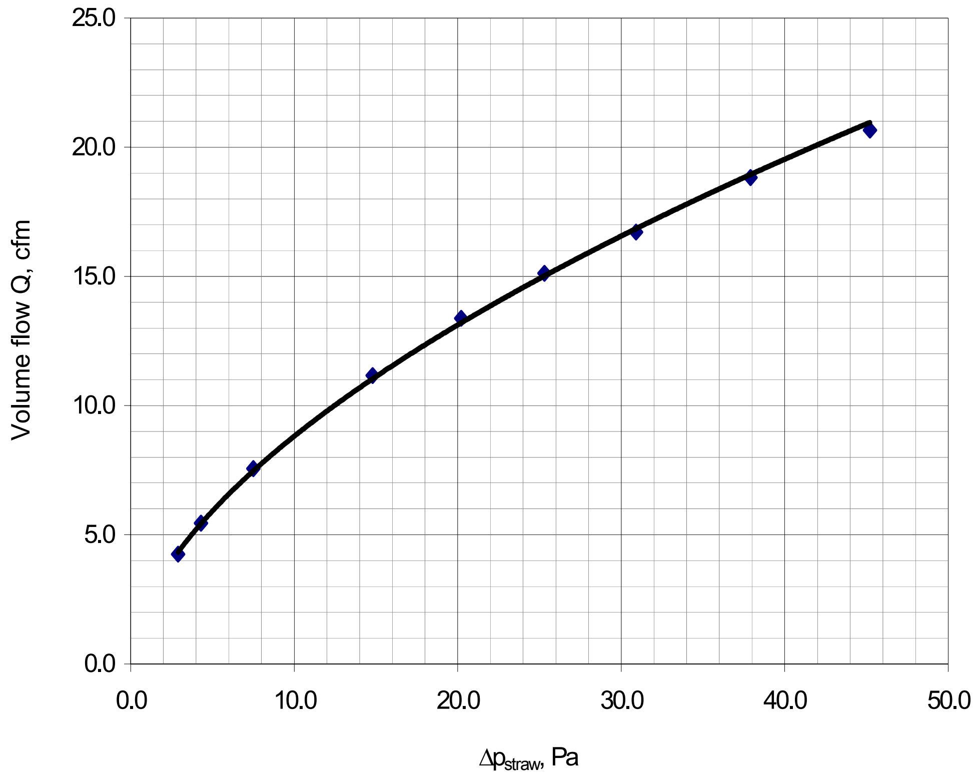
Date: 11/18/02			
nozzle: # 513			
K(513) = 0.4765			
Δp_{straw}	Δp_{nozzle}	Volume flow Q	
Pa	Pa	cfm	l/s
2.9	79.3	4.2	2.00
4.3	131	5.5	2.57
7.5	252	7.6	3.57
14.8	549	11.2	5.27
20.2	788	13.4	6.31
25.3	1006	15.1	7.13
30.9	1231	16.7	7.89
37.9	1561	18.8	8.89
45.2	1881	20.7	9.75

$$Q = 2.350 \cdot \Delta P^{0.574}$$

Coefficient:	2.350 +/- 0.0744	(95%)
Exponent:	0.574 +/- 0.0112	(95%)



Number of straws/holes	43	-
Length of straws/holes	2	in.
OD straws/holes	0.25	in.
cross-sectional area	2.11	in²
wall thickness straws	-	in.
circumference straws	-	in²
ID pipe	2.70	in.
cross-sectional area pipe	5.73	in²
spaces between straws	3.61	in²
ratio	**36.9**	**%**
free cross-sectional area	**63.1**	**%**



PVC (55 holes) in 3" PVC

Date: 11/18/02

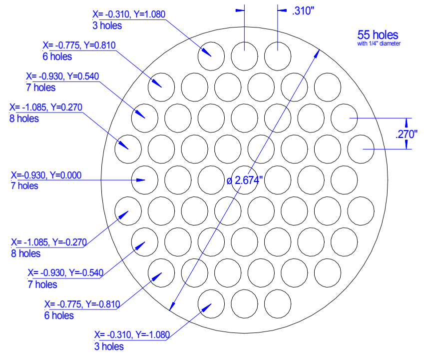
nozzle: # 513

K(513) = 0.4765

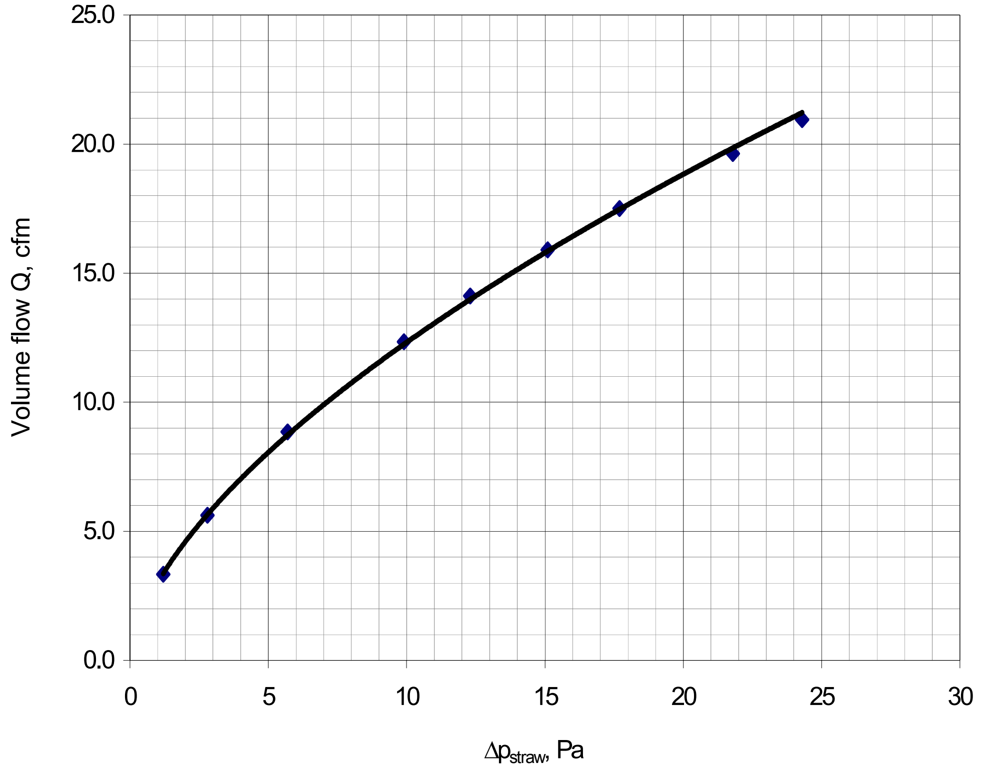
Δp_{straw} Pa	Δp_{nozzle} Pa	Volume flow Q cfm	Volume flow Q l/s
1.2	49	3.3	1.57
2.8	139	5.6	2.65
5.7	345	8.9	4.18
9.9	671	12.3	5.83
12.3	878	14.1	6.66
15.1	1114	15.9	7.51
17.7	1350	17.5	8.26
21.8	1698	19.6	9.27
24.3	1931	20.9	9.88

$$Q = 3.007 \cdot \Delta P^{0.612}$$

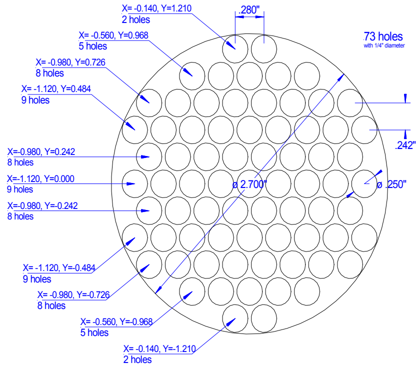
Coefficient:	3.007 +/- 0.0605	(95%)
Exponent:	0.612 +/- 0.0085	(95%)



Number of straws/holes	55	-
Length of straws/holes	2	in.
OD straws/holes	0.25	in.
cross-sectional area	2.70	in²
wall thickness straws	-	in.
circumference straws	-	in²
ID pipe	2.70	in.
cross-sectional area pipe	5.73	in²
spaces between straws	3.03	in²
ratio	**47.2**	**%**
free cross-sectional area	**52.8**	**%**



PVC (73 holes) in 3" PVC



Date: 11/18/02

nozzle: # 513

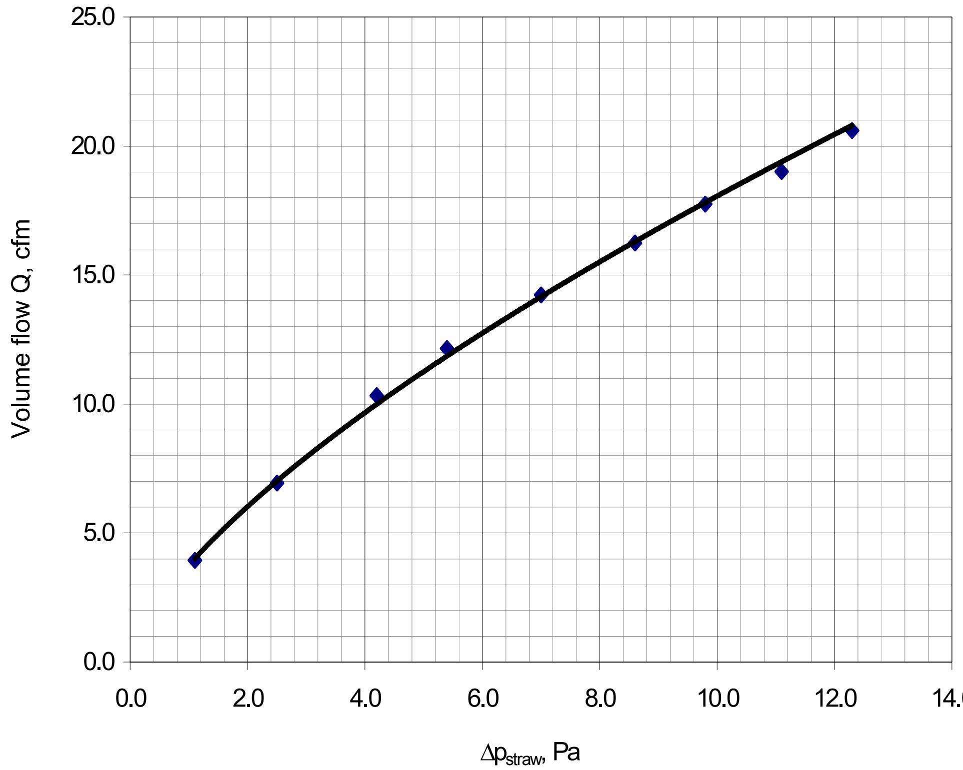
K(513) = 0.4765

Δp_{straw}	Δp_{nozzle}	Volume flow Q	
Pa	Pa	cfm	l/s
1.1	68.6	3.9	1.86
2.5	212	6.9	3.27
4.2	470	10.3	4.88
5.4	650	12.1	5.73
7.0	891	14.2	6.71
8.6	1162	16.2	7.67
9.8	1387	17.7	8.38
11.1	1592	19.0	8.97
12.3	1870	20.6	9.73

Number of straws/holes	73	-
Length of straws/holes	2	in.
OD straws/holes	0.25	in.
cross-sectional area	3.58	in²
wall thickness straws	-	in.
circumference straws	-	in²
ID pipe	2.70	in.
cross-sectional area pipe	5.73	in²
spaces between straws	2.14	in²
ratio	**62.6**	**%**
free cross-sectional area	**37.4**	**%**

$$Q = 3.755 \cdot \Delta P^{0.682}$$

Coefficient:	3.755 +/- 0.1386	(95%)
Exponent:	0.682 +/- 0.0201	(95%)



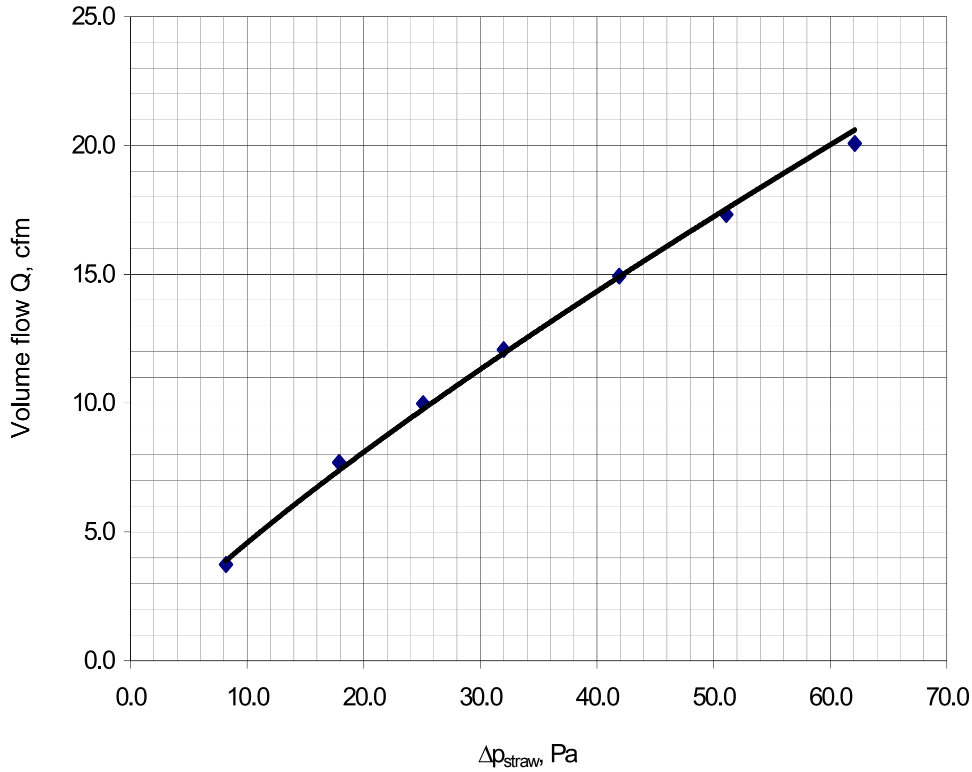
Small straws in 2" PVC

Date: 10/10/02			
nozzle: # 513			
K(513) = 0.4765			
Δp_{straw}	Δp_{nozzle}	**Volume flow Q**	
Pa	Pa	cfm	l/s
8.2	61.6	3.7	1.77
17.9	261	7.7	3.63
25.1	439	10.0	4.71
32.0	643	12.1	5.70
41.9	981	14.9	7.04
51.1	1320	17.3	8.17
62.1	1775	20.1	9.48

Number of straws/holes	200	-
Length of straws/holes	5.5	in.
OD straws/holes	0.13	in.
cross-sectional area	-	in²
wall thickness straws	0.010	in.
circumference straws	-	in²
ID pipe	-	in.
cross-sectional area pipe	-	in²
spaces between straws	-	in²
ratio	**-**	**%**
free cross-sectional area	**-**	**%**

$$Q = 0.686 \cdot \Delta P^{0.824}$$

Coefficient:	0.686 +/- 0.0994	(95%)
Exponent:	0.824 +/- 0.0458	(95%)



1/4" straws in 2" PVC

Date: 10/11/02

nozzle: # 513

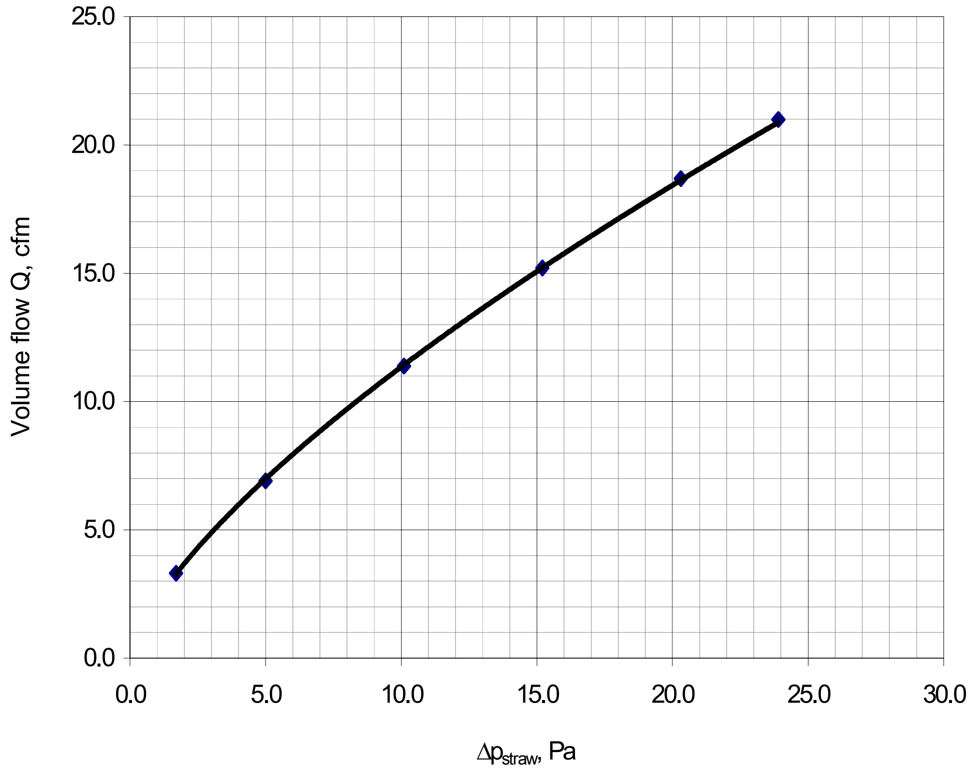
K(513) = 0.4765

Δp_{straw} Pa	Δp_{nozzle} Pa	Volume flow Q cfm	Volume flow Q l/s
1.7	48.4	3.3	1.56
5.0	210	6.9	3.26
10.1	571	11.4	5.37
15.2	1018	15.2	7.18
20.3	1537	18.7	8.82
23.9	1940	21.0	9.91

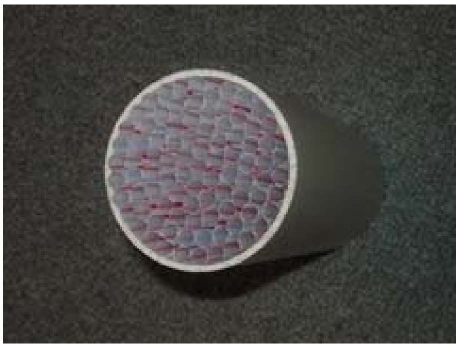
$$Q = 2.268 \cdot \Delta P^{0.699}$$

Coefficient:	2.268 +/- 0.0553	(95%)
Exponent:	0.699 +/- 0.0102	(95%)

Number of straws/holes	-	-
Length of straws/holes	5.5	in.
OD straws/holes	0.13	in.
cross-sectional area	-	in²
wall thickness straws	0.010	in.
circumference straws	-	in²
ID pipe	-	in.
cross-sectional area pipe	-	in²
spaces between straws	-	in²
ratio	**-**	**%**
free cross-sectional area	**-**	**%**



1/4" straws in 3" PVC

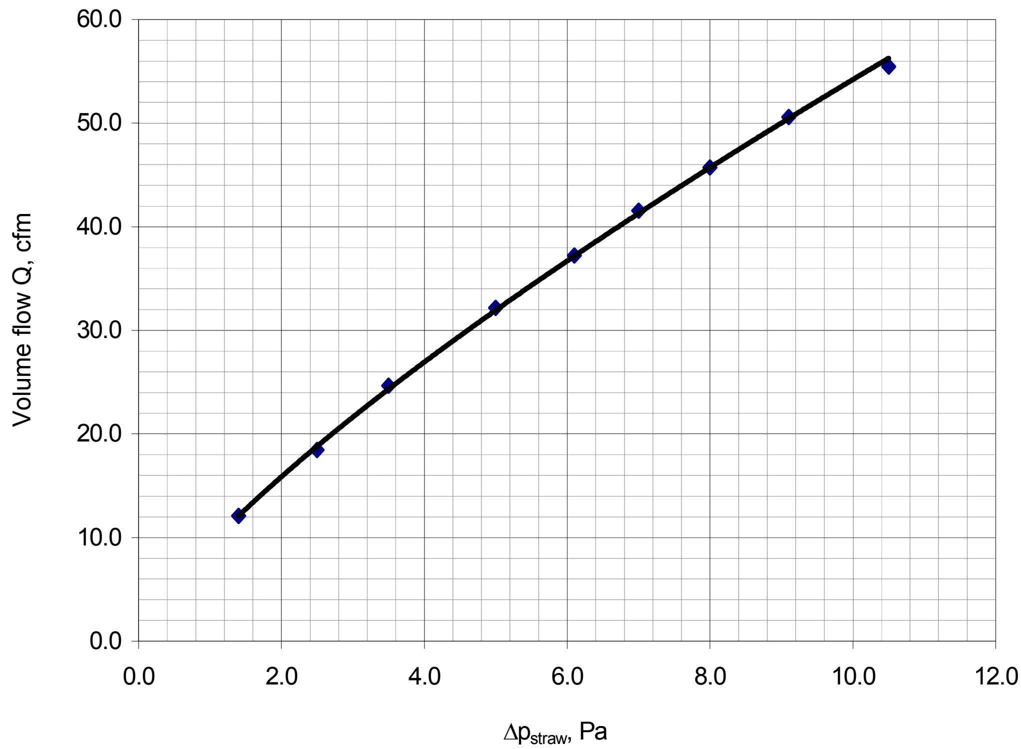


Date:	10/11/02		
nozzle:	*# 485*		
K(485) =	*1.4462*		
Δp_{straw}	Δp_{nozzle}	Volume flow Q	
Pa	Pa	cfm	l/s
1.4	70	12.1	5.71
2.5	163	18.5	8.71
3.5	291	24.7	11.64
5.0	495	32.2	15.19
6.1	662	37.2	17.56
7.0	825	41.5	19.61
8.0	999	45.7	21.58
9.1	1224	50.6	23.88
10.5	1470	55.4	26.17

$$Q = 3.080 \cdot \Delta P^{0.763}$$

Coefficient:	3.080 +/- 0.0741	(95%)
Exponent:	0.763 +/- 0.0141	(95%)

Number of straws/holes	-	-
Length of straws/holes	0.5	in.
OD straws/holes	0.25	in.
cross-sectional area	-	in²
wall thickness straws	0.010	in.
circumference straws	-	in²
ID pipe	-	in.
cross-sectional area pipe	-	in²
spaces between straws	-	in²
ratio	**-**	**%**
free cross-sectional area	**-**	**%**



Rubber tubes in 3" PVC

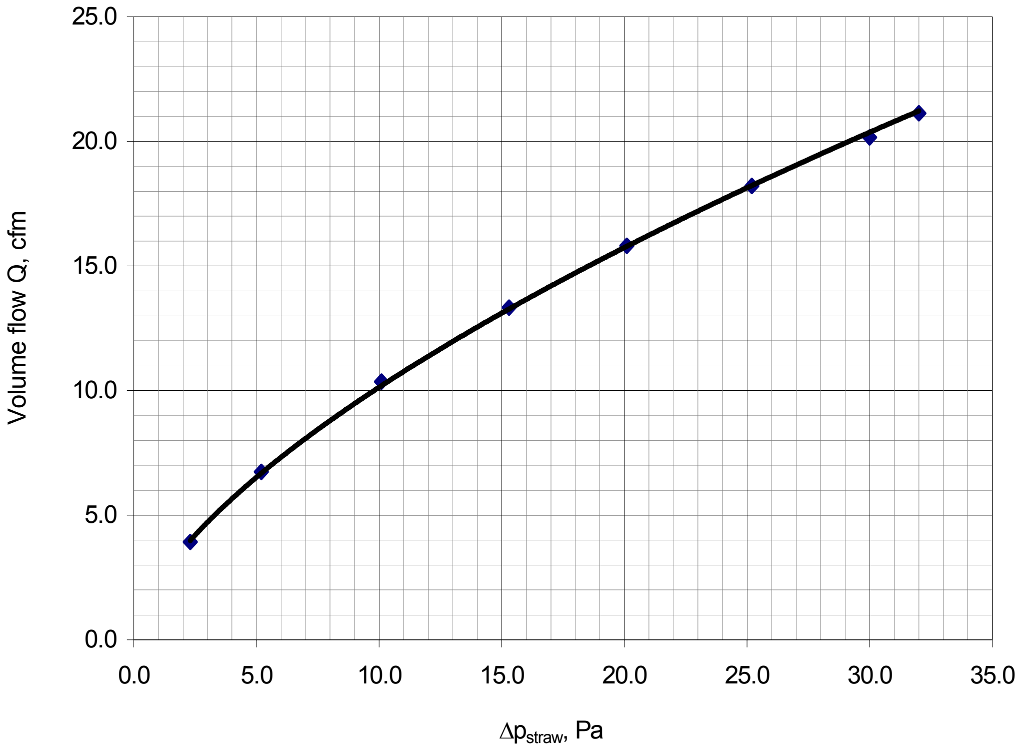
Date: 10/17/02
nozzle: # 513
K(513) = 0.4765

Δp_{straw}	Δp_{nozzle}	Volume flow Q	
Pa	Pa	cfm	l/s
2.3	68	3.9	1.85
5.2	200	6.7	3.18
10.1	472	10.4	4.89
15.3	783	13.3	6.29
20.1	1101	15.8	7.46
25.2	1461	18.2	8.60
30.0	1789	20.2	9.51
32.0	1965	21.1	9.97

Number of straws/holes	40	-
Length of straws/holes	2	in.
OD straws/holes	0.38	in.
cross-sectional area	4.42	in²
wall thickness straws/tubes	0.060	in.
circumference straws/tubes	2.60	in²
ID pipe	2.70	in.
cross-sectional area pipe	5.73	in²
spaces between straws/tubes	1.31	in²
ratio	**29.6**	**%**
free cross-sectional area	**54.6**	**%**

$$Q = 2.345 \cdot \Delta P^{0.635}$$

Coefficient:	2.345 +/- 0.0634	(95%)
Exponent:	0.635 +/- 0.0101	(95%)



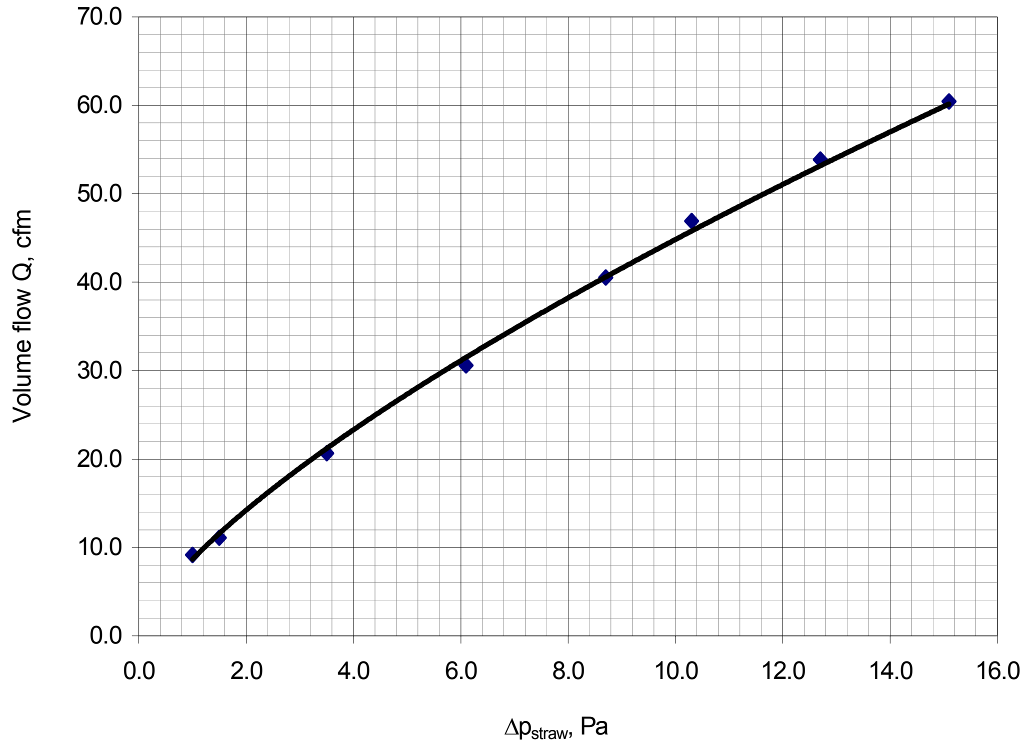
Honeycomb in 3" PVC

Date:	10/17/02		
nozzle:	*# 485*		
K(485) =	*1.4462*		
Δp_{straw}	Δp_{nozzle}	**Volume flow Q**	
Pa	Pa	cfm	l/s
1.0	40	9.1	4.32
1.5	59	11.1	5.24
3.5	204	20.7	9.75
6.1	447	30.6	14.43
8.7	786	40.5	19.14
10.3	1053	46.9	22.15
12.7	1387	53.9	25.42
15.1	1746	60.4	28.52

$$Q = 2.855 \cdot \Delta P^{0.714}$$

Coefficient: 2.855 +/- 0.1646 (95%)
Exponent: 0.714 +/- 0.0312 (95%)

Number of straws/holes	-	-
Length of straws/holes	2	in.
OD straws/holes	-	in.
cross-sectional area	-	in²
wall thickness straws/tubes	-	in.
circumference straws/tubes	-	in²
ID pipe	-	in.
cross-sectional area pipe	-	in²
spaces between straws/tubes	-	in²
ratio	**-**	**%**
free cross-sectional area	**-**	**%**



Appendix B. Envelope leakage estimate

Several studies have been summarized by the California Energy Commission in the state energy code:

http://www.energy.ca.gov/title24/residential_manual/res_manual_chapter4.PDF (section 4.1.7)

that have defaults of 0.7 cfm/ft^2 of floor area for a typical house. For the 1200 cfm **(**2039 m^3/h**)** system under test, the corresponding floor area is 1714 ft^2 (159 m^2). The house volume, for a ceiling height of 8.5 ft, is 14,500 ft^3 **(**≅ 413 m^3**)**.

Using the rough approximation of NL=1 being equivalent to 17.5 ACH (Air Changes per Hour) at 50 Pa envelope pressure difference, then using the value close to the California average (From Sherman and Dickerhoff, LBNL 35700) for envelope leakage of NL=0.73. This resulting a required envelope leakage of about 3100 cfm50, or 2200 cfm25.

$$Q = 15.34\sqrt{\Delta P} \qquad \textbf{(B1)}$$

Appendix C. Flowmeter Calibrations

For the measurement of the airflow through the return duct, a 40.6 cm (16 inch) nozzle was used as part of the return duct and mounted between the chamber and the return plenum. The relationship between the airflow, pressure difference (ΔP in Pa) across this nozzle and air density (ρ in kg/m^3) is:

$$Q_{return\_duct}(cfm) = 165.06\sqrt{\frac{2\Delta P}{\rho}} \quad \textbf{(C1)}$$

The calibration for the boot leaks (ΔP in Pa) is:

$$\mathbf{Q\ (cfm) = 3.007\ \Delta P^{0.612}} \quad \textbf{(C2)}$$

For the six-inch nozzle the relationship between the airflow and the pressure difference is:

$$Q = 18.21\sqrt{\frac{2\times\Delta P}{\rho}} \quad \textbf{(C3)}$$

For the return leak the 4-inch orifice has the following relationship between the airflow and the pressure difference:

$$Q = 15.34\sqrt{\Delta P} \quad \textbf{(C4)}$$

Appendix D. Laboratory test results

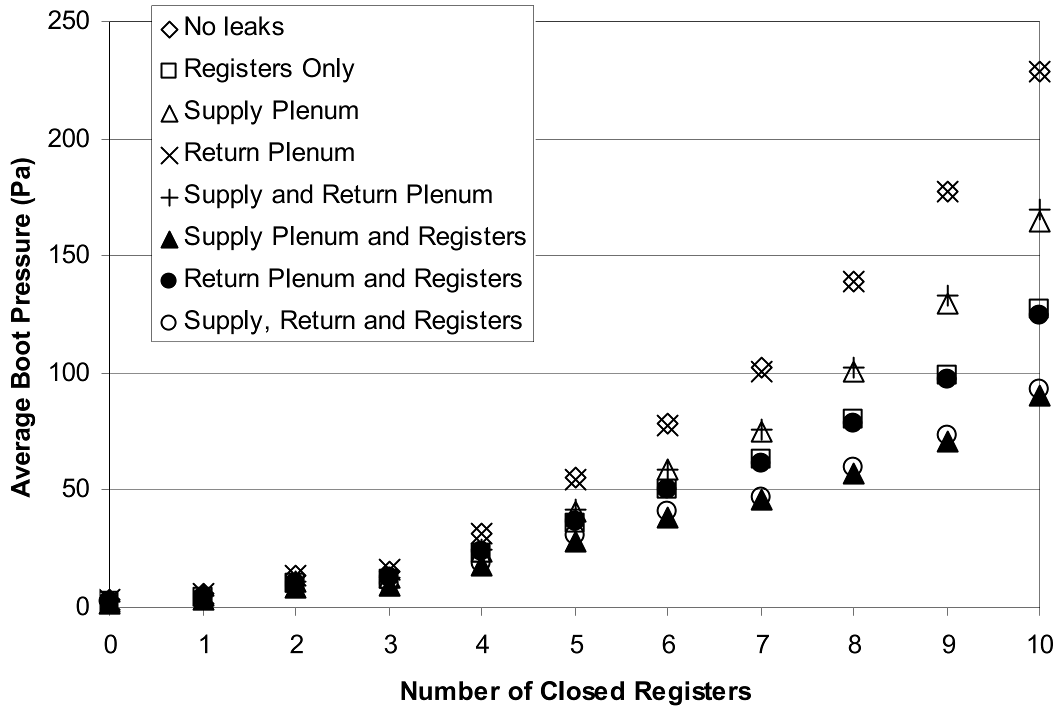


Figure D1. Average boot pressures - near registers closed first

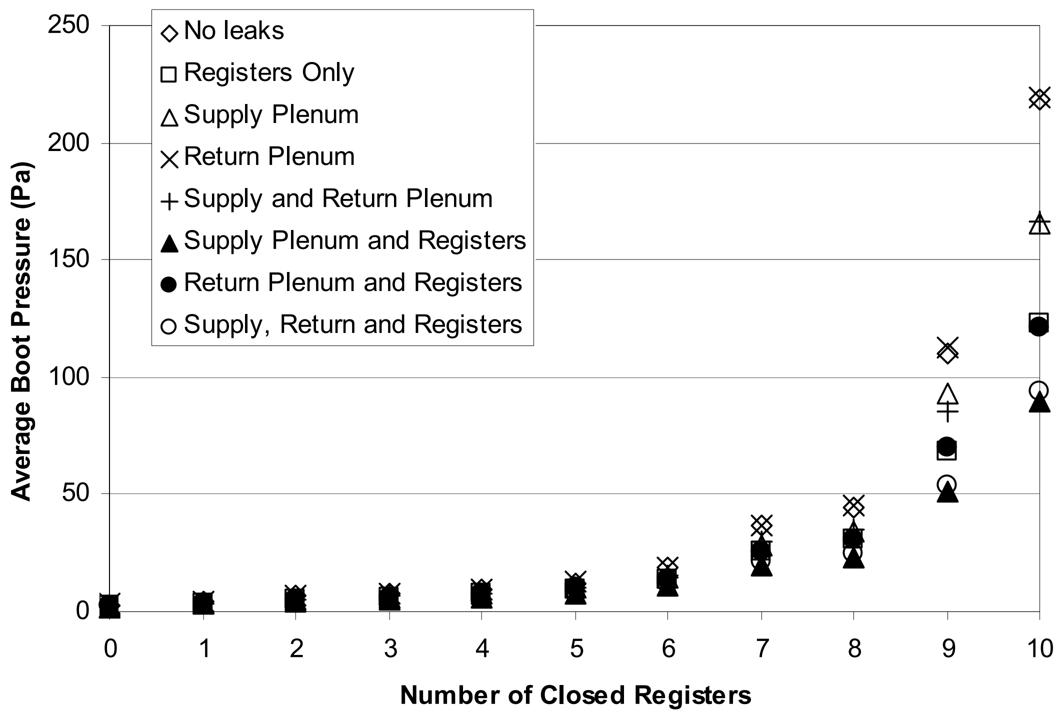


Figure D2. Average boot pressure - Far registers closed first

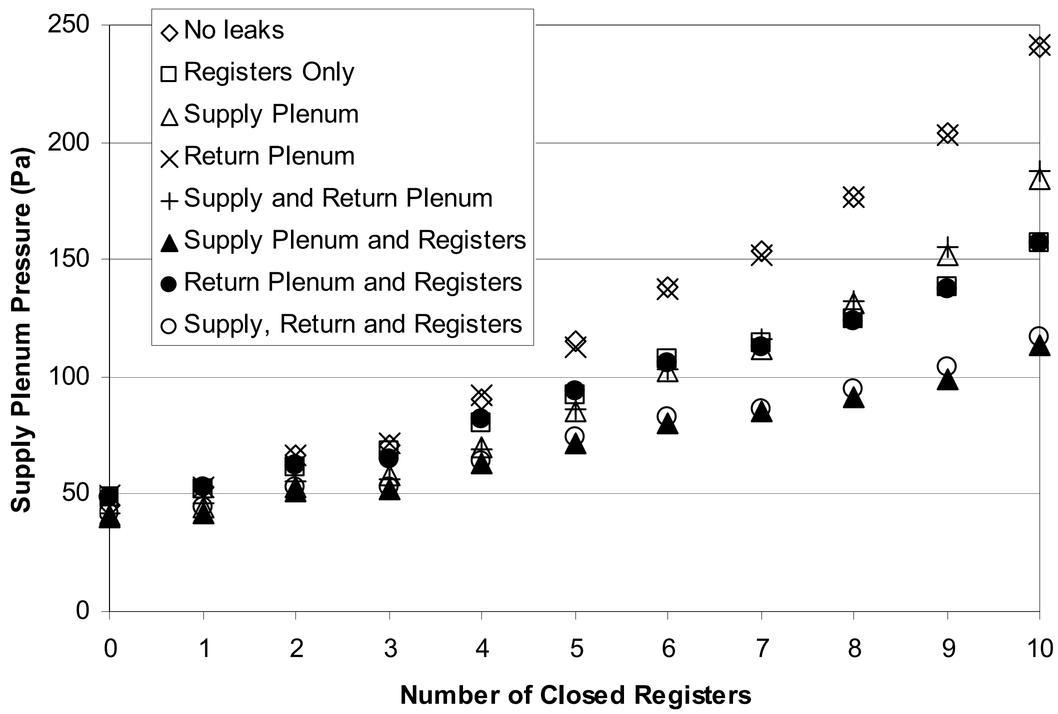


Figure D3. Supply plenum pressure - Near registers closed first

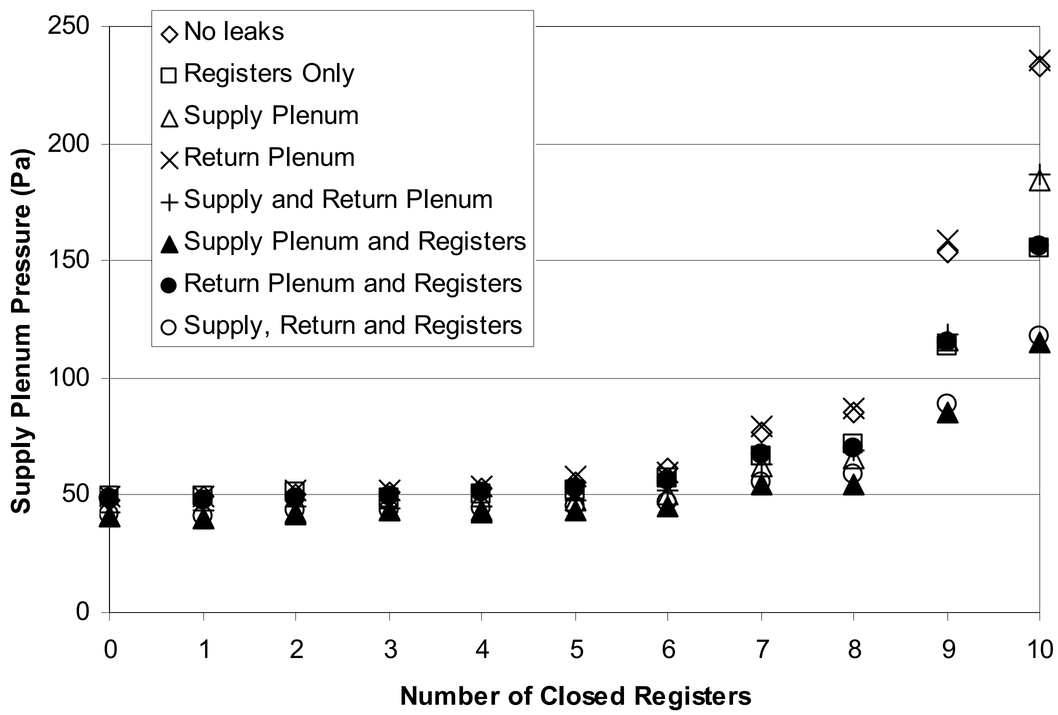


Figure D4. Supply plenum pressure - Far registers closed first

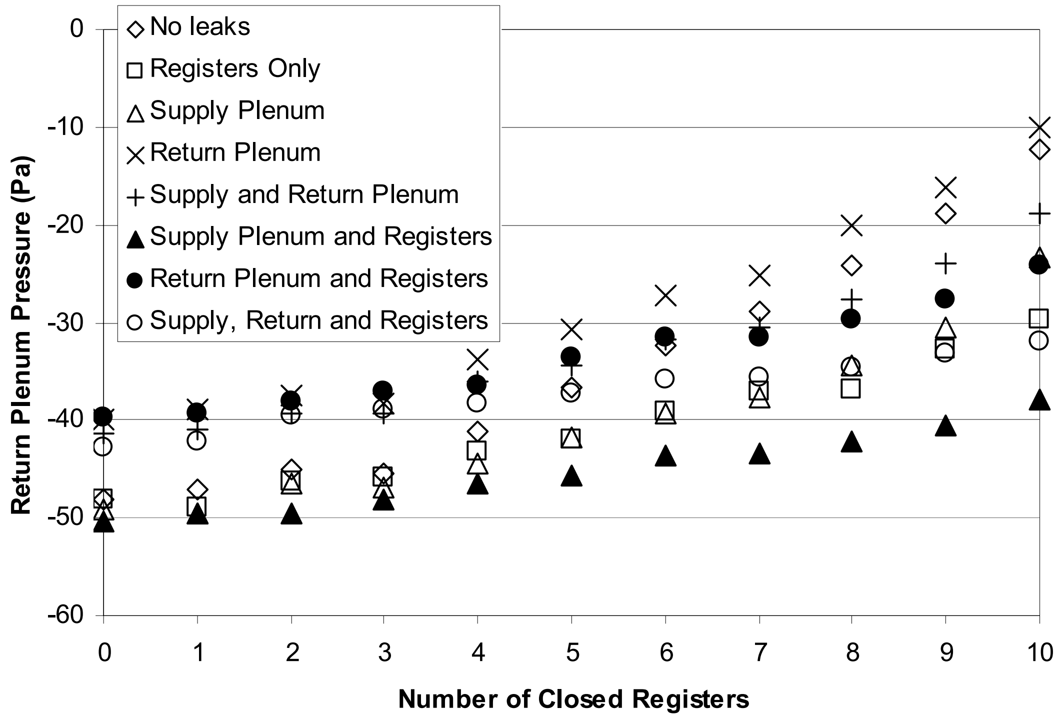


Figure D5. Return plenum pressure - Near registers closed first

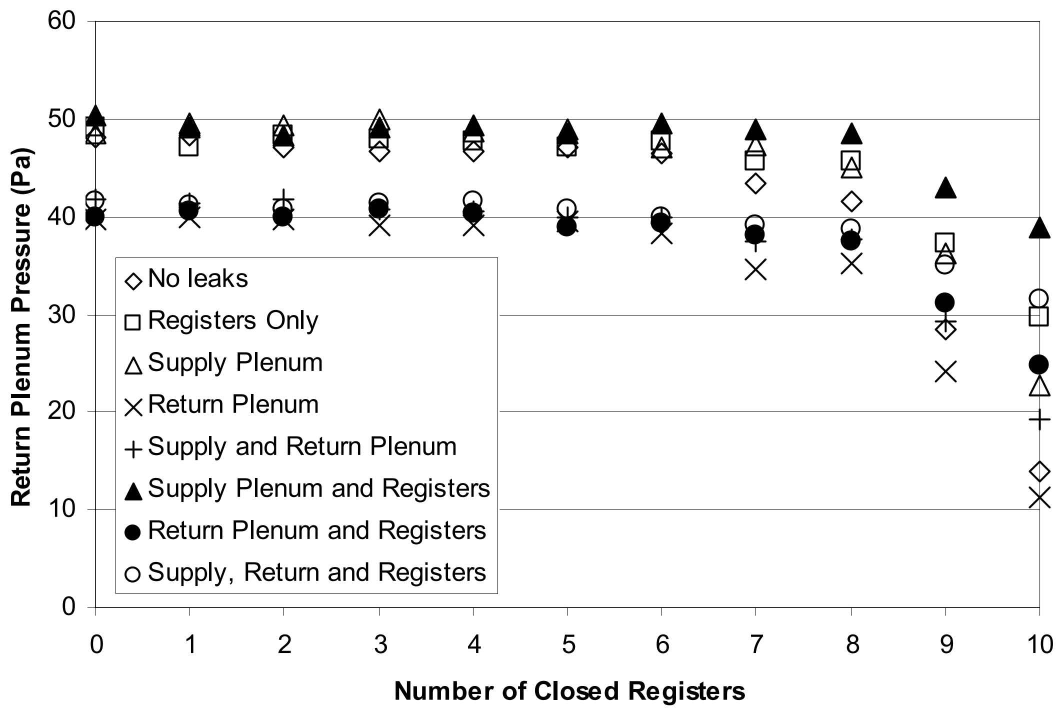


Figure D6. Return plenum pressure - Far registers closed first

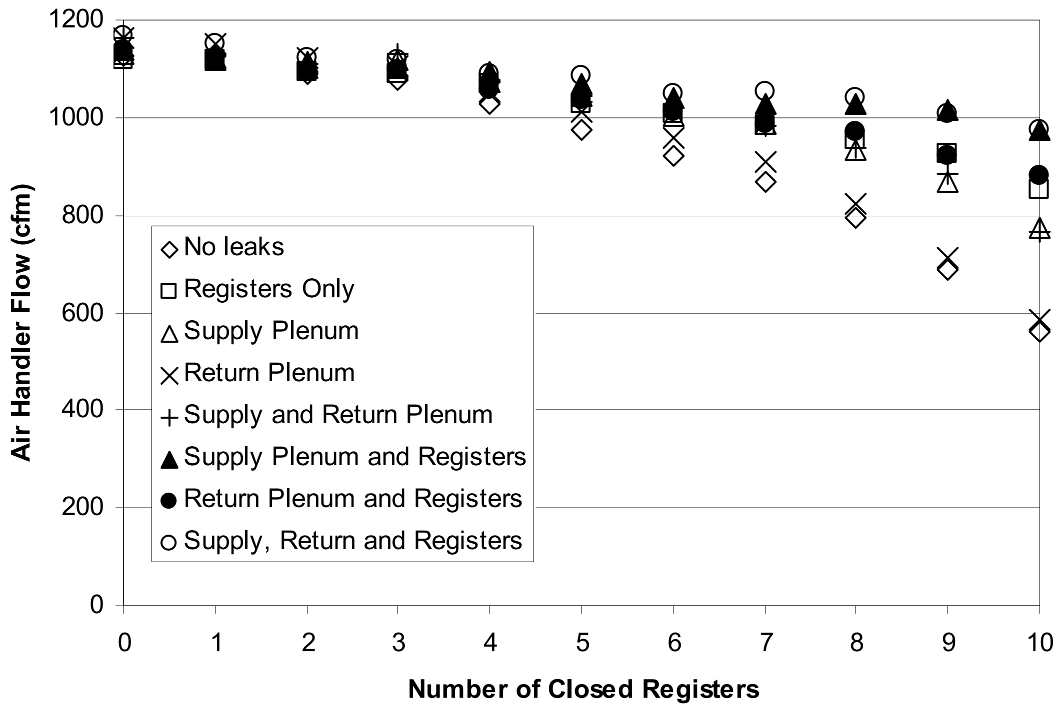


Figure D7. Air handler flow changes - Near registers closed first

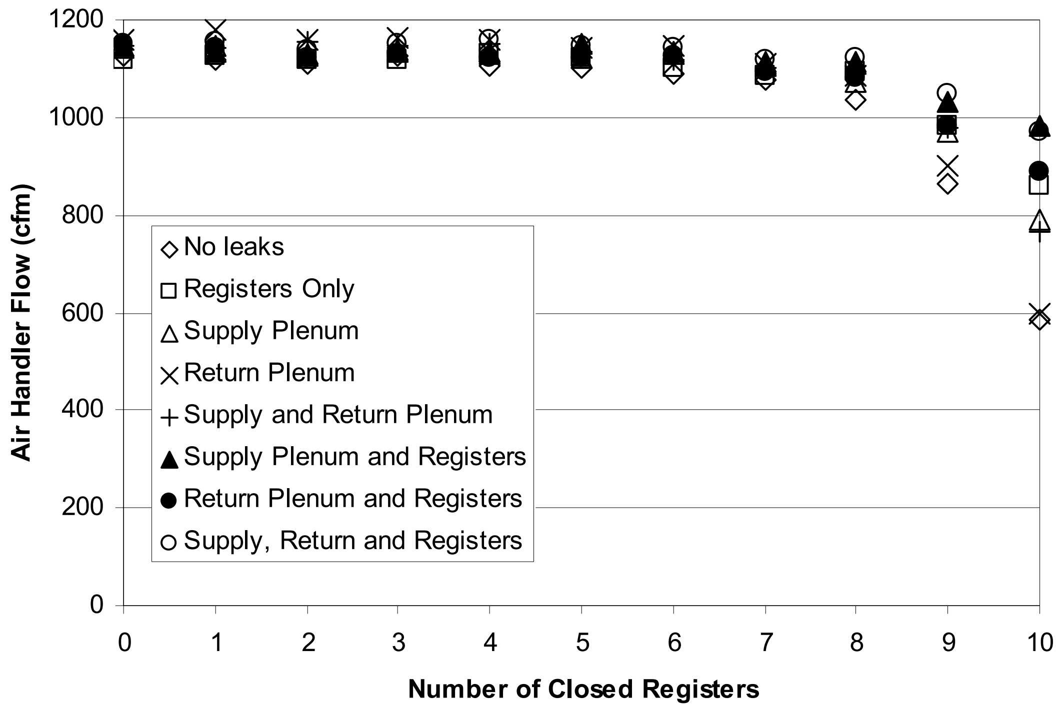


Figure D8. Air handler flow changes - Far registers closed first

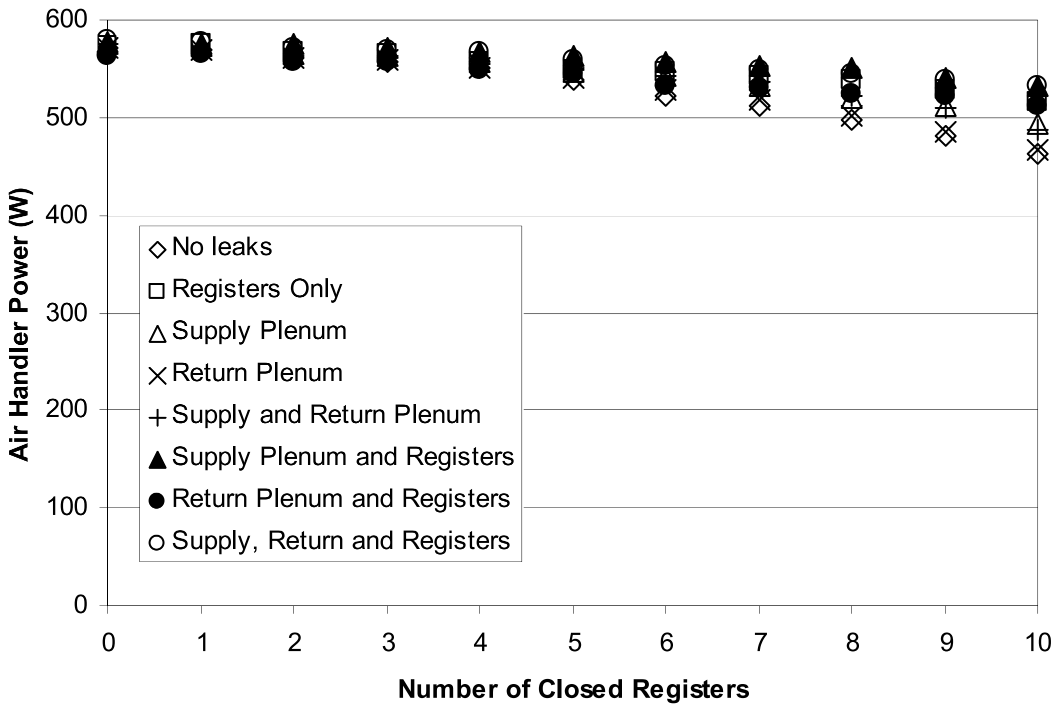


Figure D9. Air handler power consumption - Near registers closed first

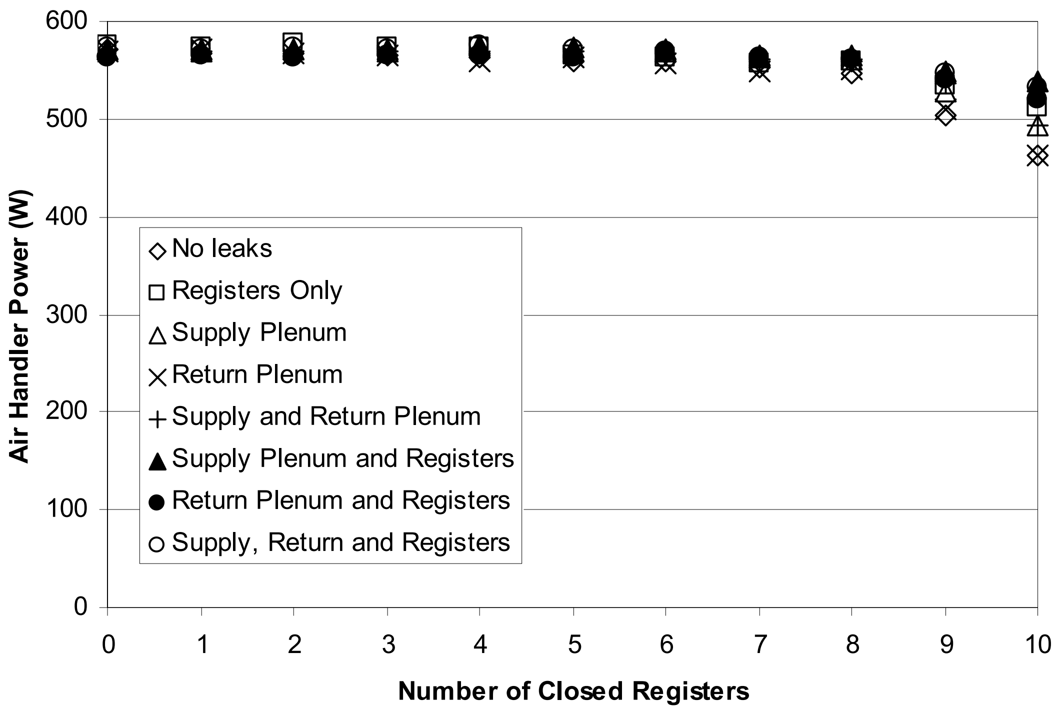


Figure D10. Air handler power consumption - Far registers closed first

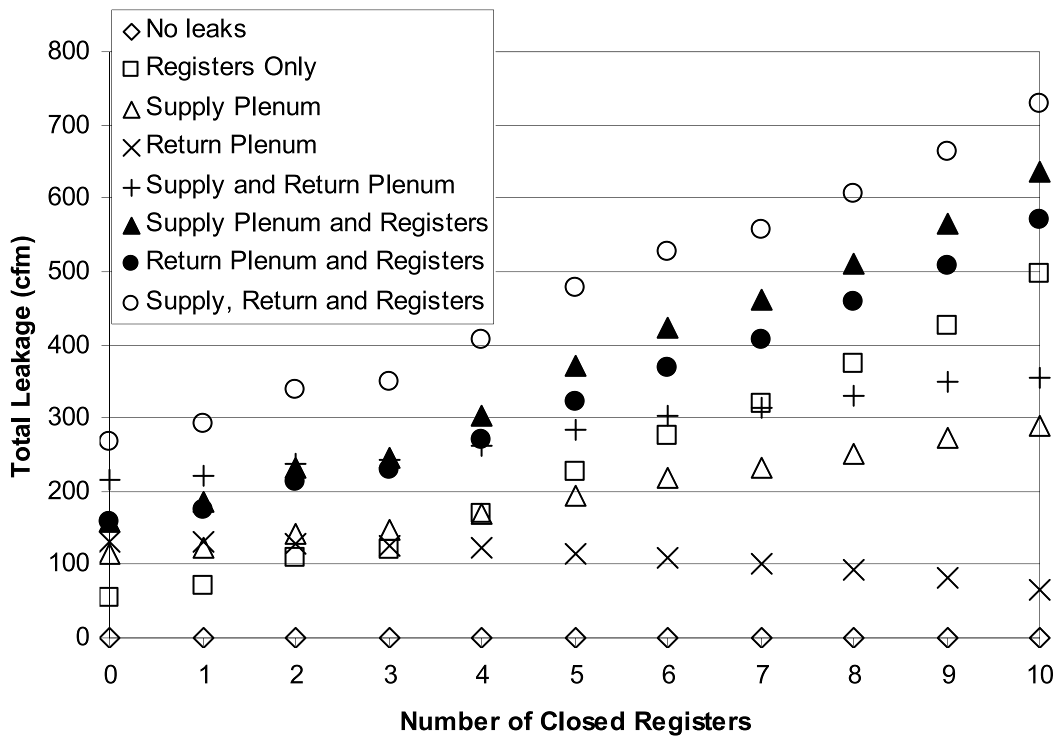


Figure D11. Total duct leakage - Near registers closed first

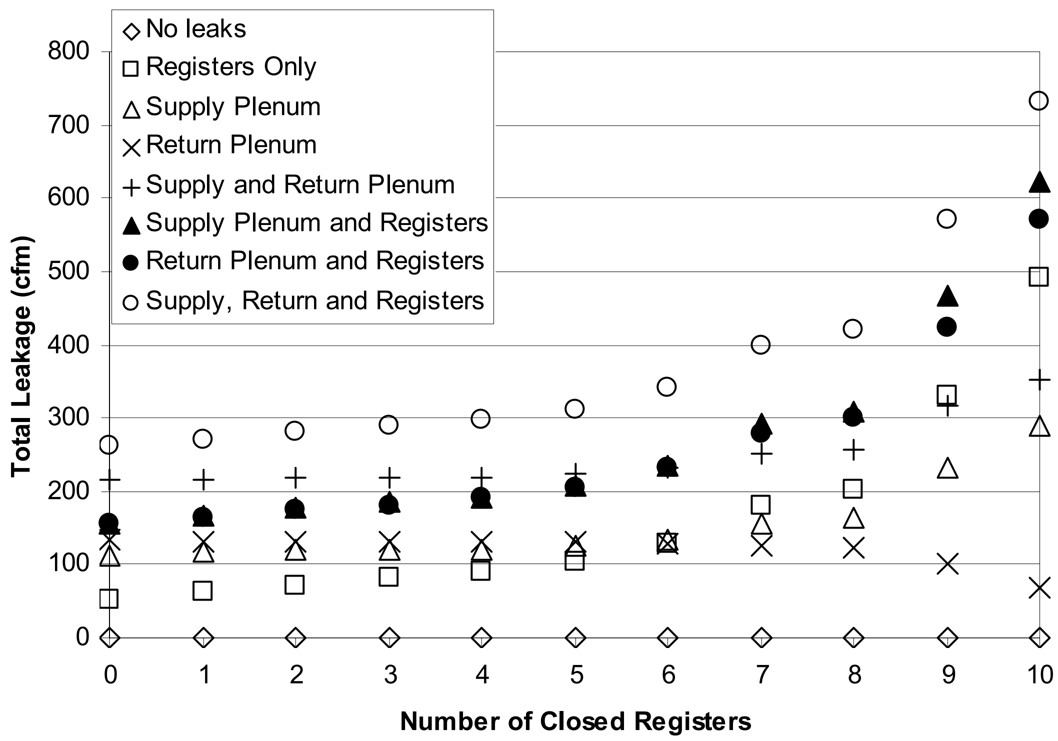


Figure D12. Total duct leakage - Far registers closed first

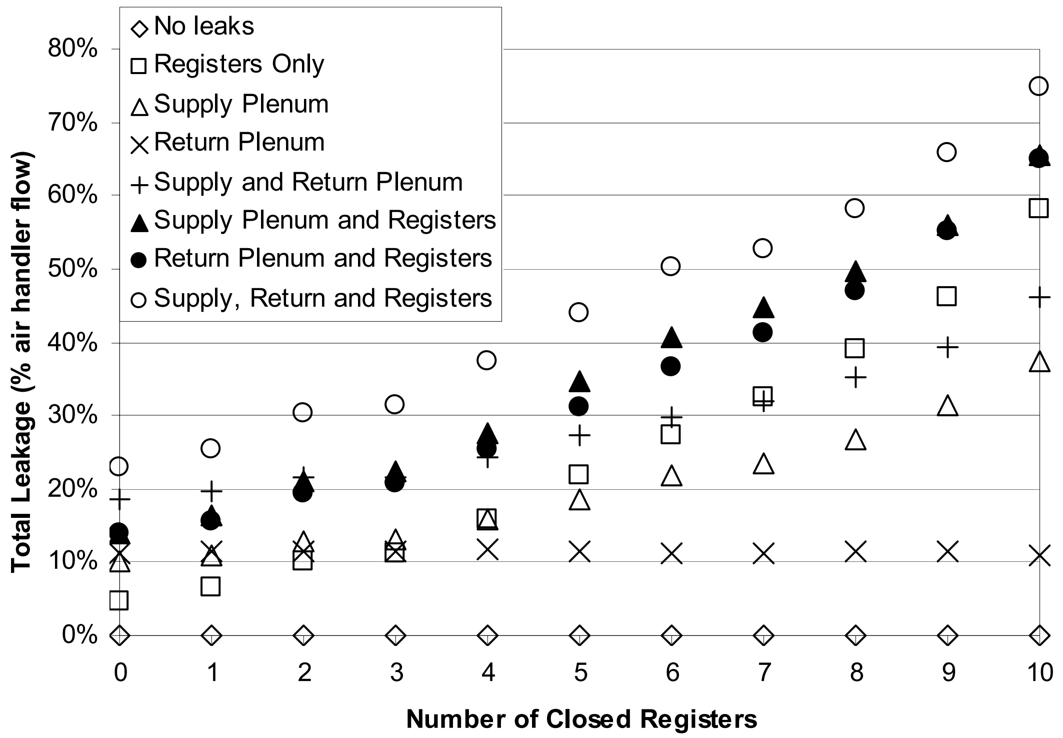


Figure D13. Total duct leakage as fraction of air handler flow - Near registers closed first

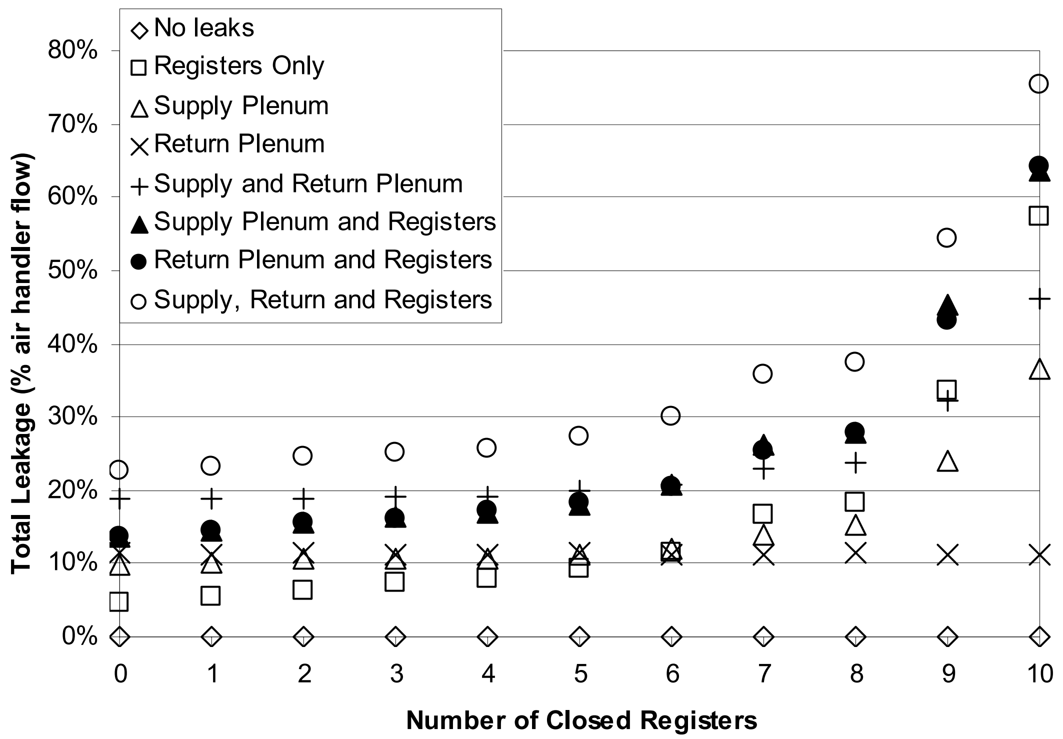


Figure D14. Total duct leakage as fraction of air handler flow - Far registers closed first

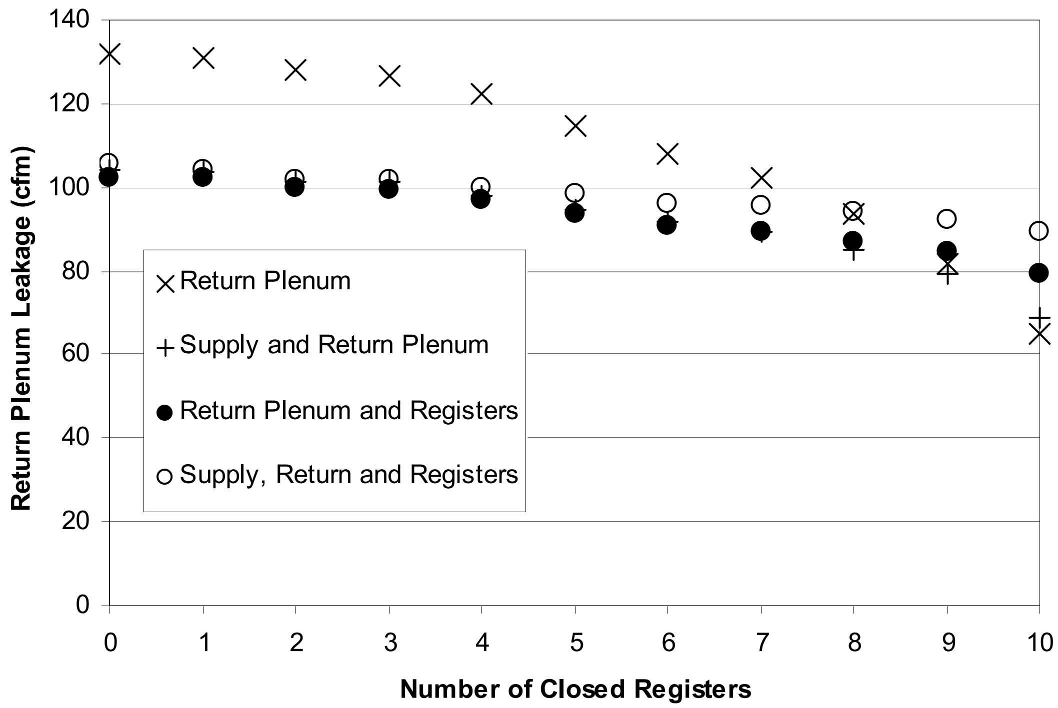


Figure D15. Return plenum leakage - Near registers closed first

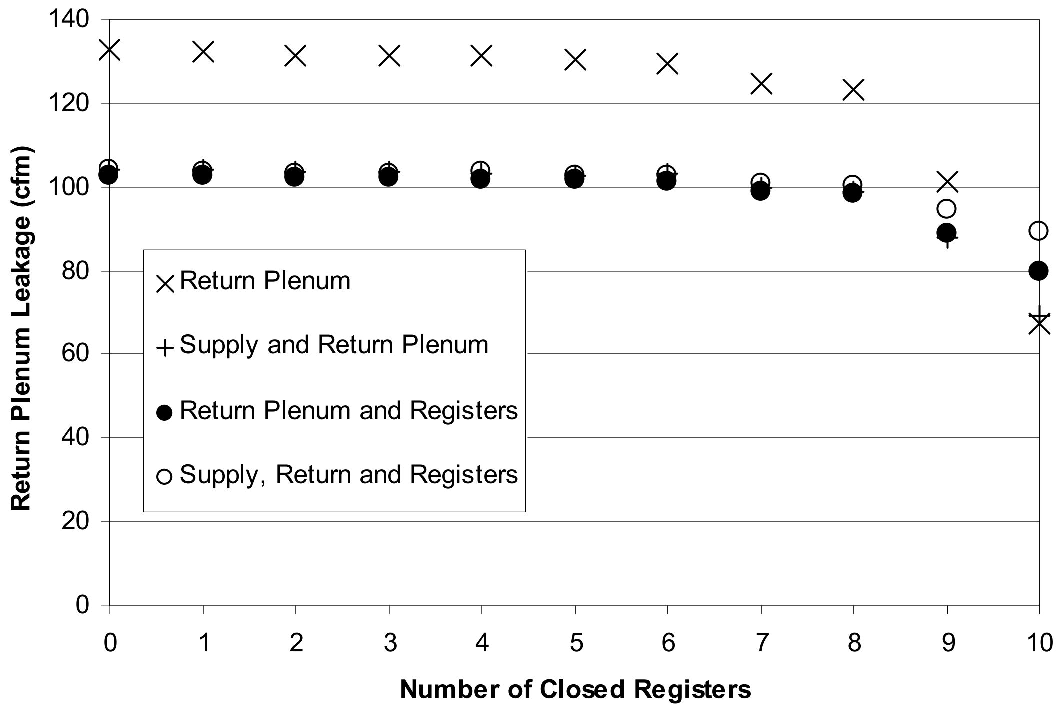


Figure D16. Return plenum leakage - Far registers closed first

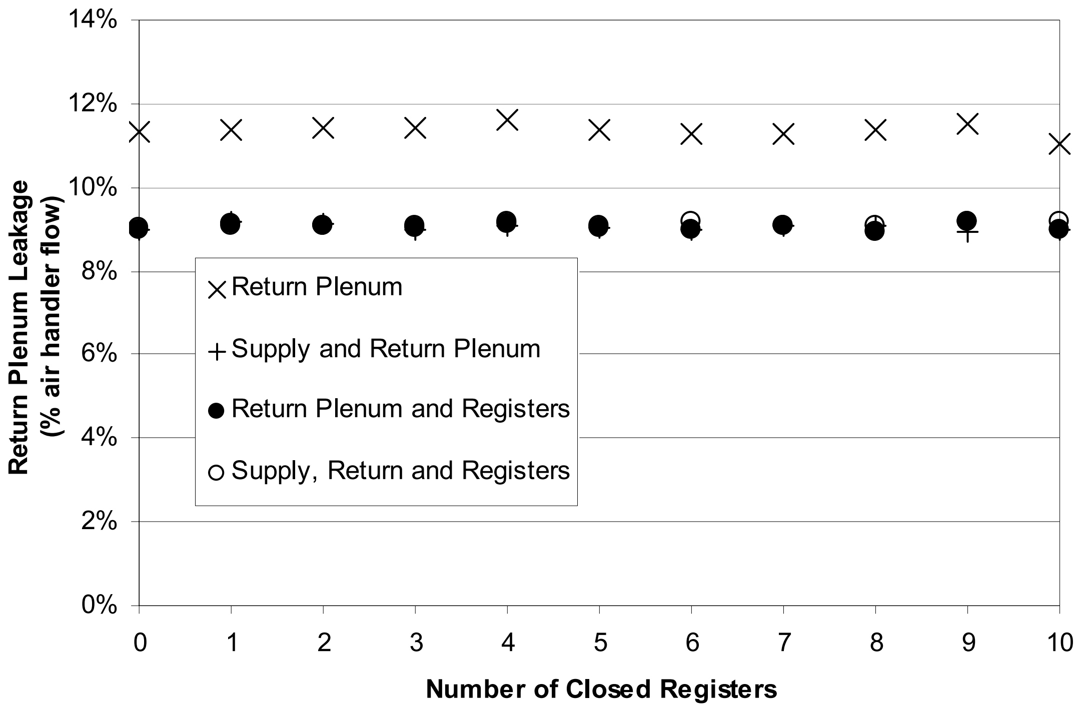


Figure D17. Return plenum leakage as a fraction of air handler flow - Near registers closed first

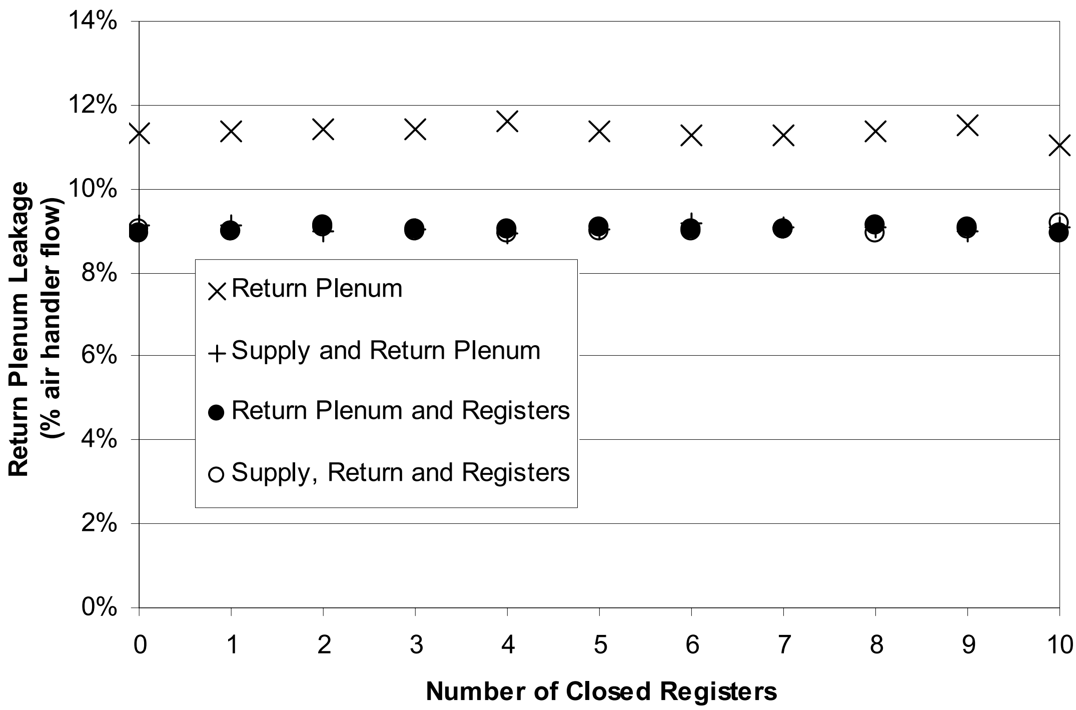


Figure D18. Return plenum leakage as a fraction of air handler flow - Far registers closed first

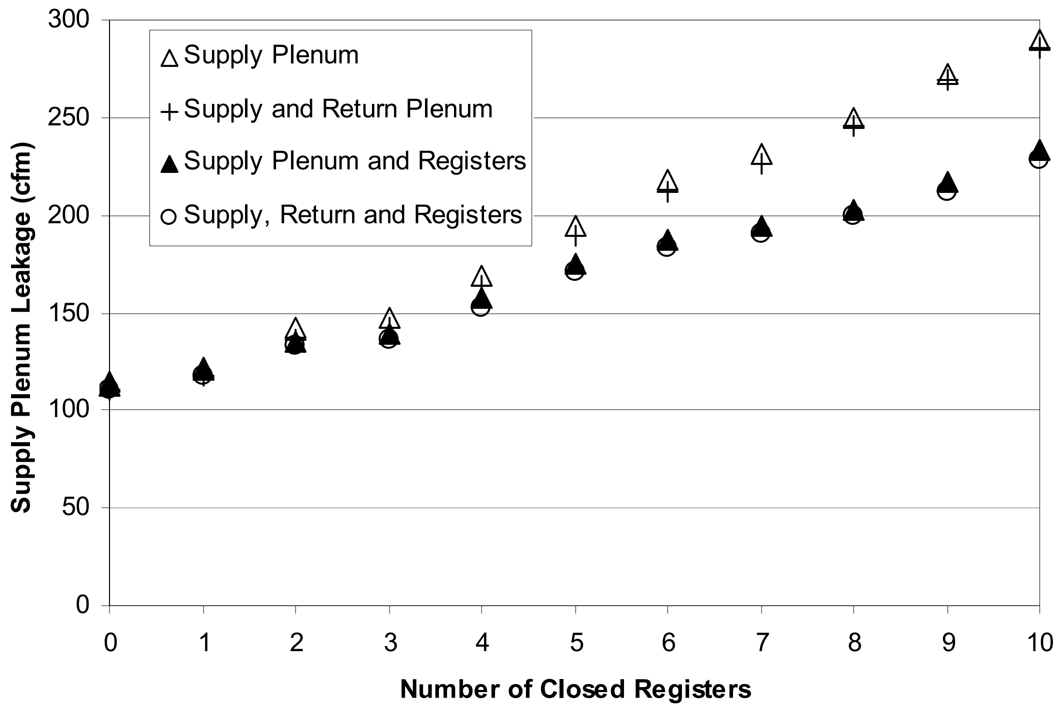


Figure D19. Supply plenum leakage - Near registers closed first

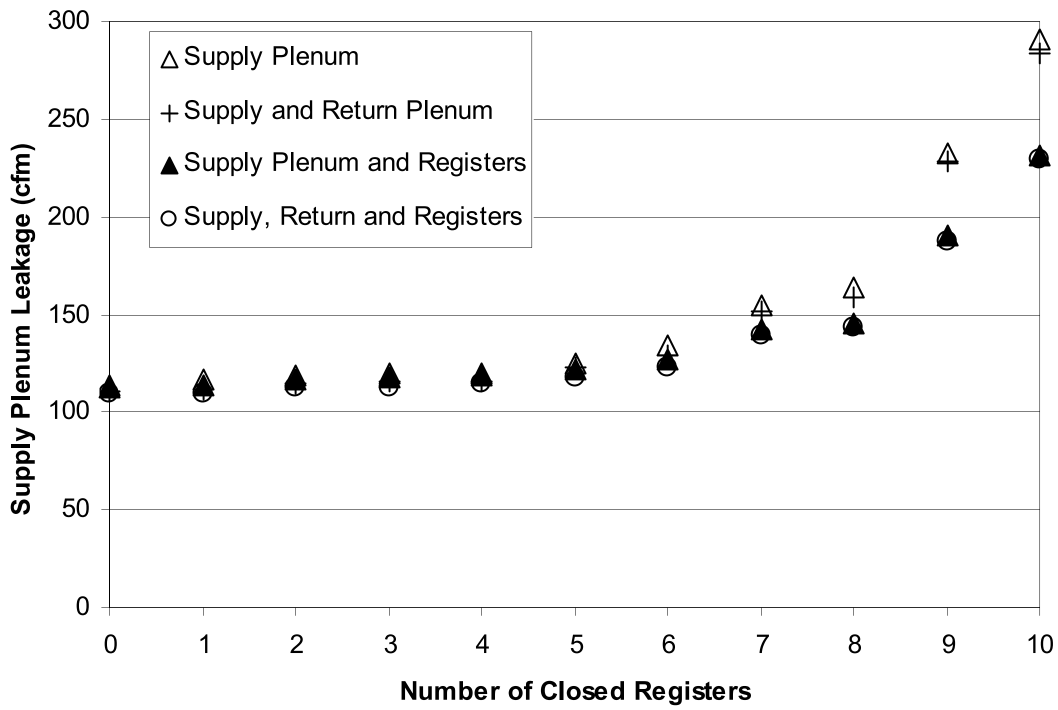


Figure D20. Supply plenum leakage - Far registers closed first

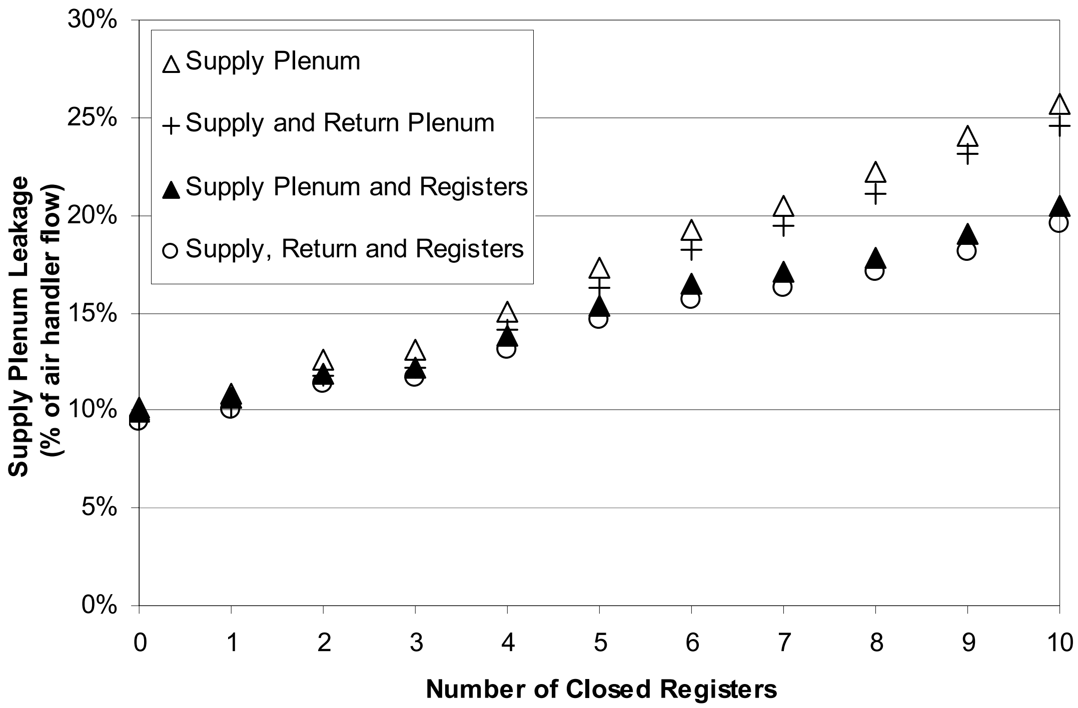


Figure D21. Supply plenum leakage as a fraction of air handler flow - Near registers closed first

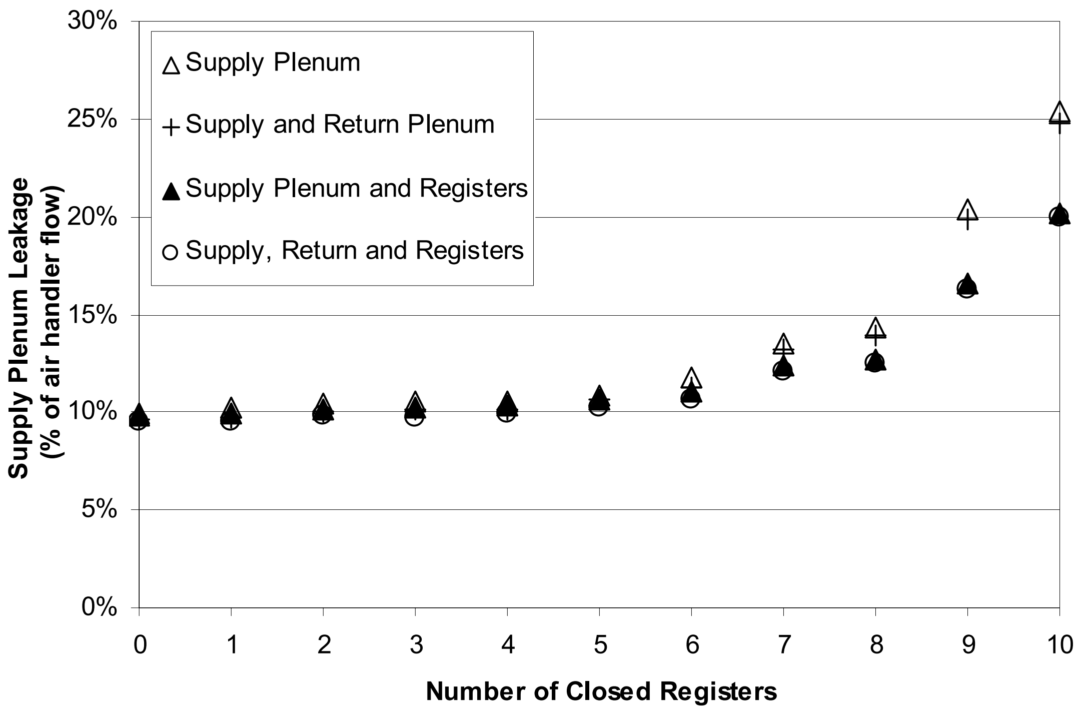


Figure D22. Supply plenum leakage as a fraction of air handler flow - Far registers closed first

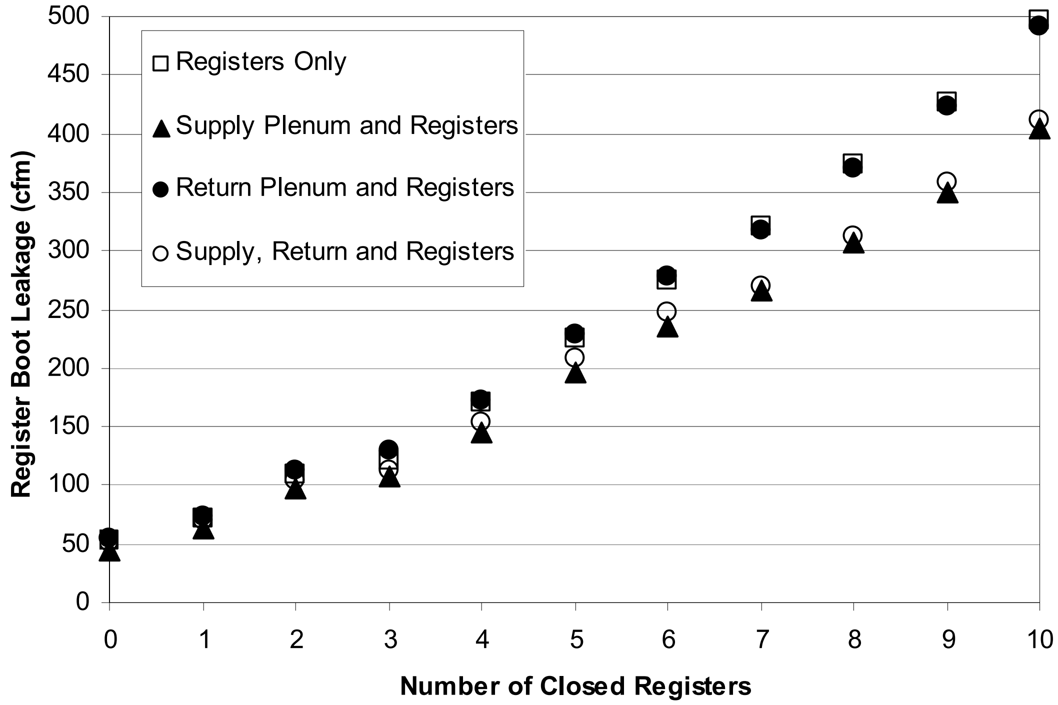


Figure D23. Register boot only leakage - Near registers closed first

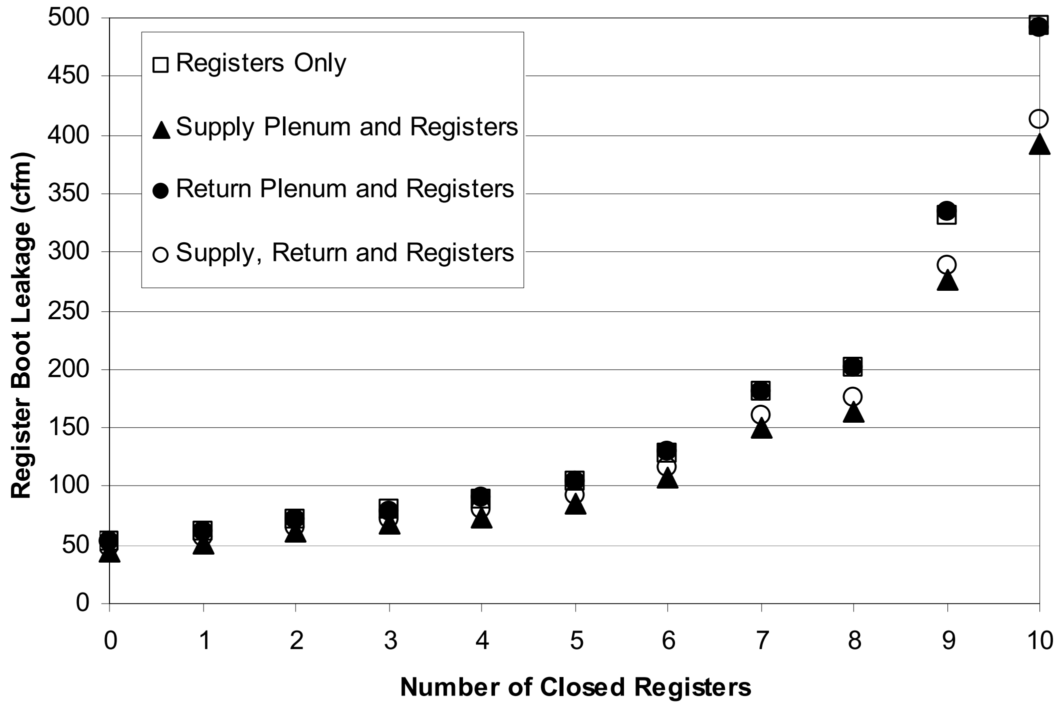


Figure D24. Register boot only leakage - Far registers closed first

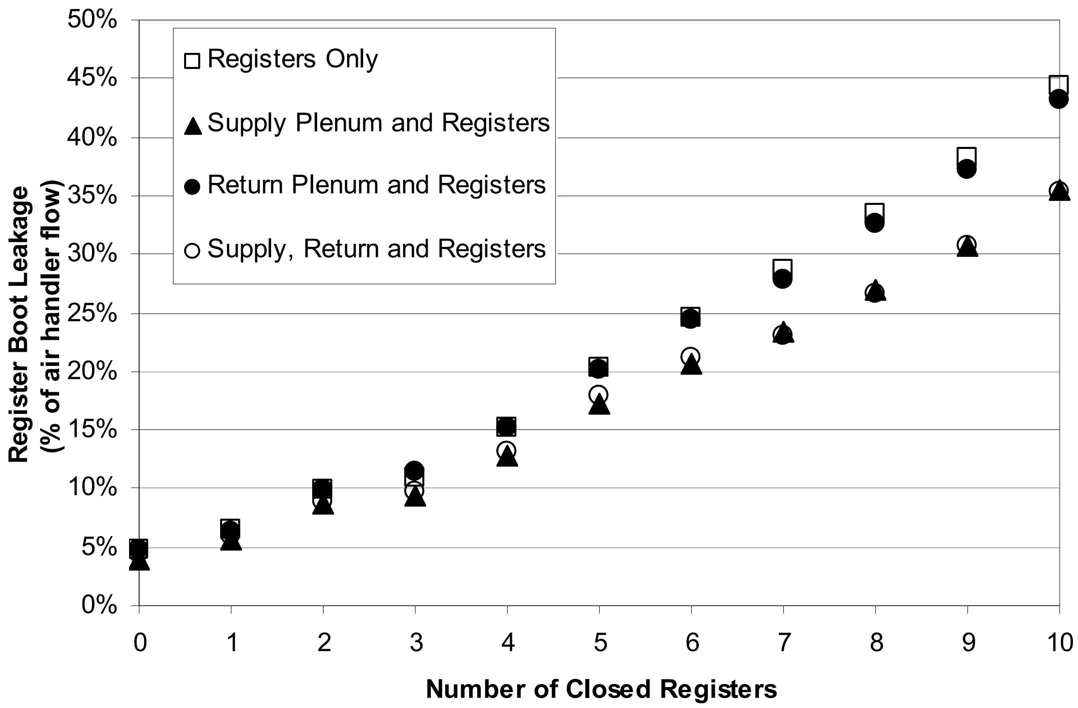


Figure D25. Register boot only leakage as a fraction of air handler flow - Near registers closed first

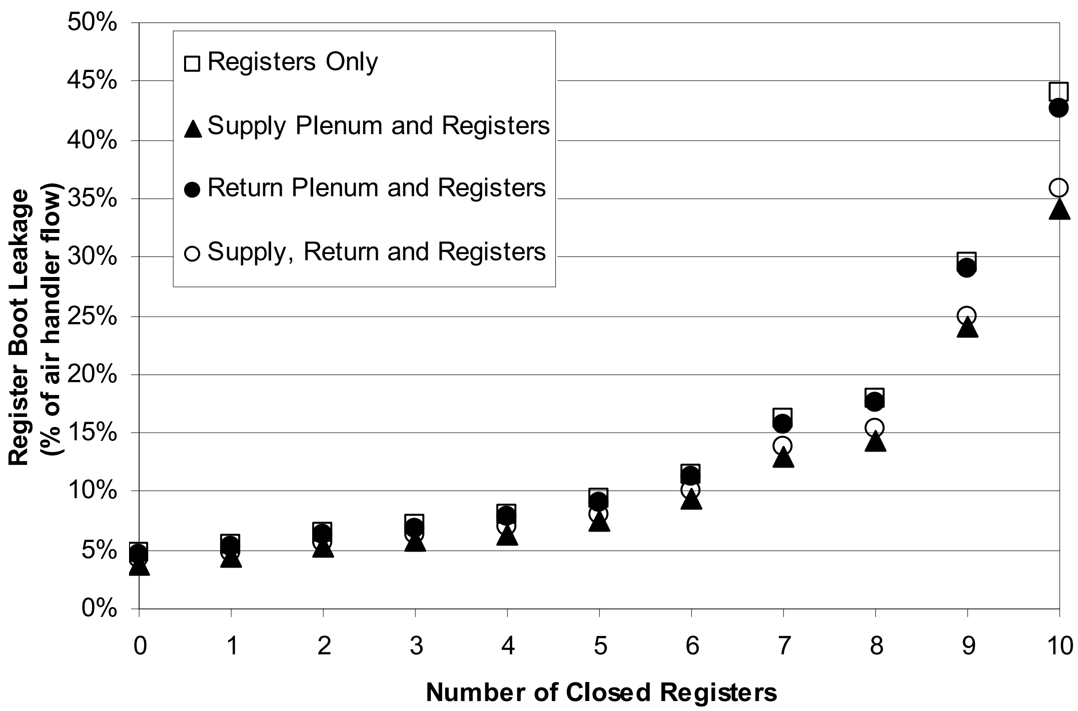


Figure D26. Register boot only leakage as a fraction of air handler flow - Far registers closed first

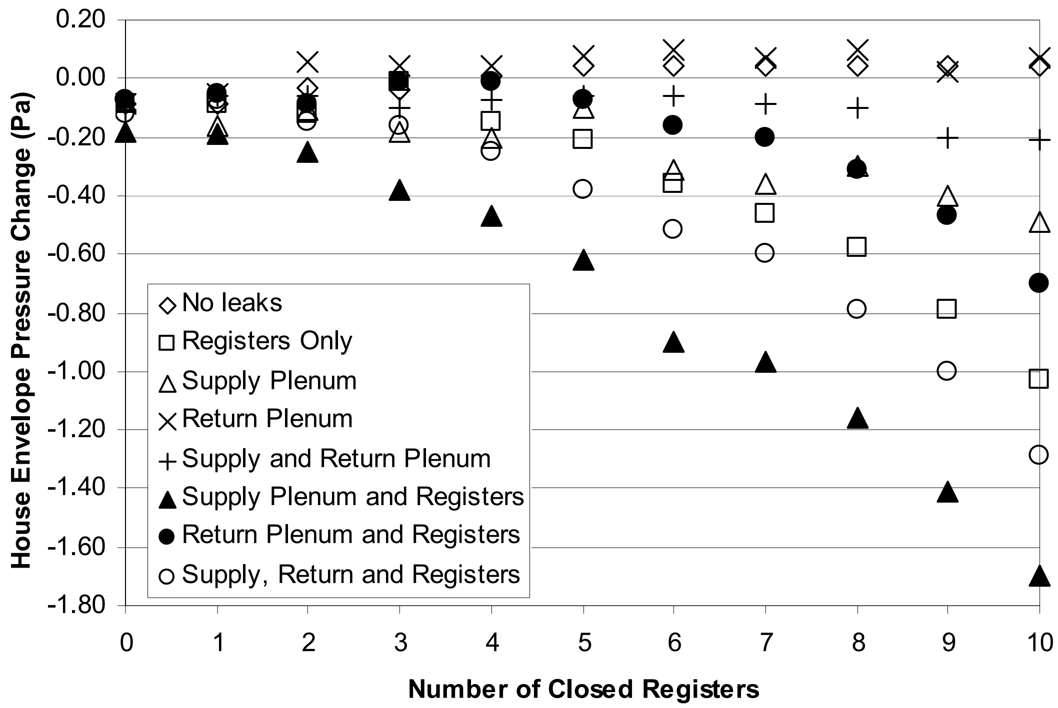


Figure D27. Envelope pressure changes - Near registers closed first

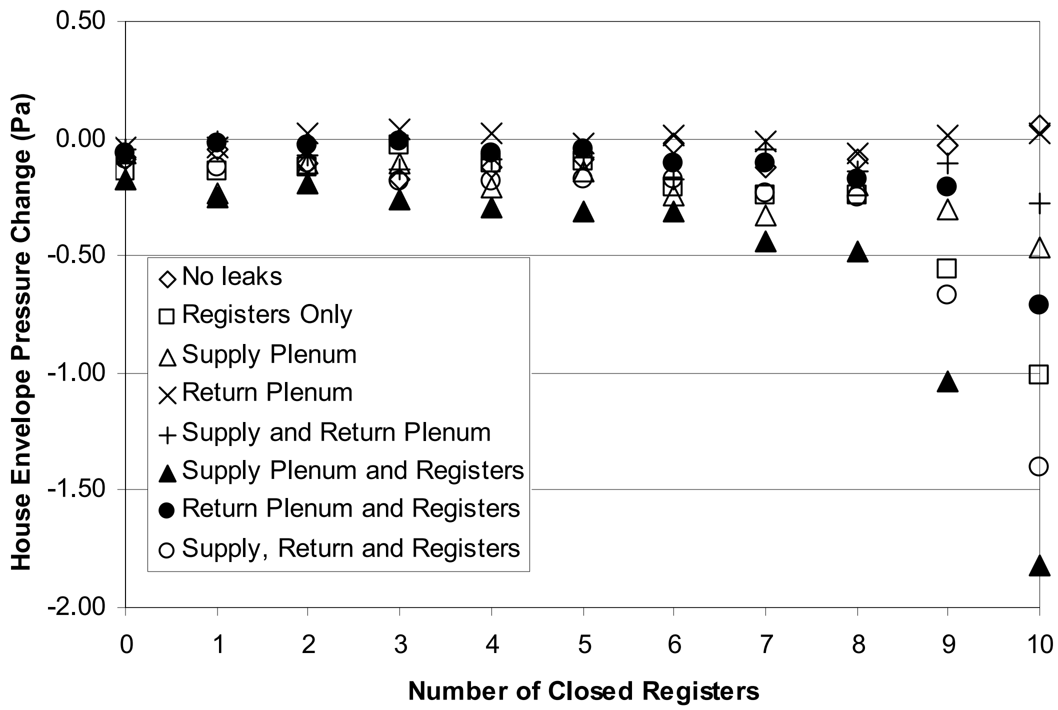


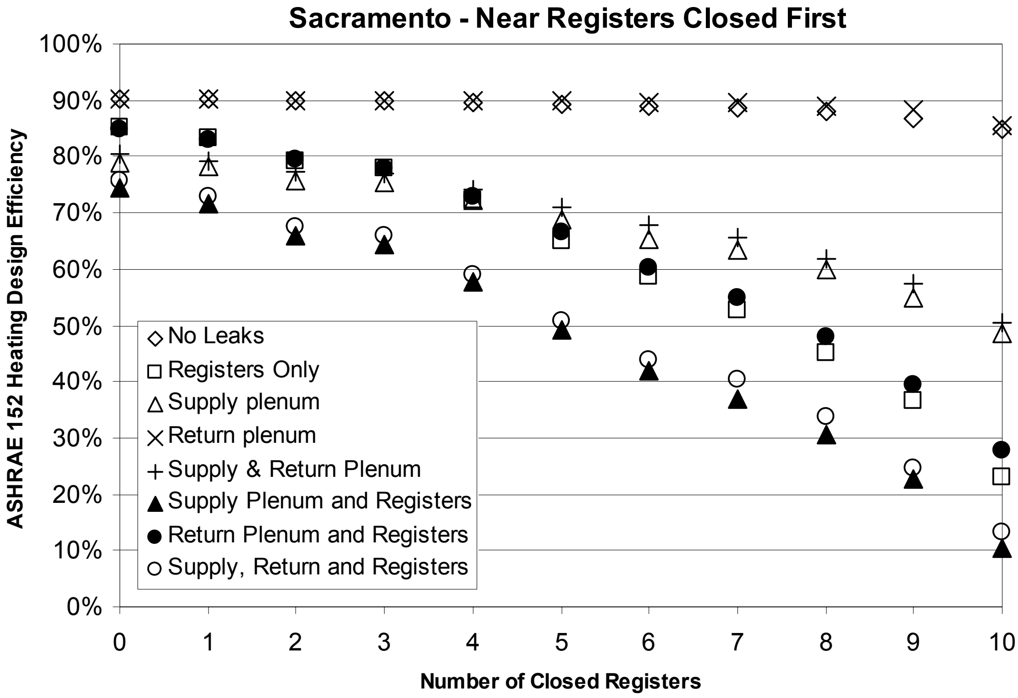
Figure D28. Envelope pressure changes - Far registers closed first

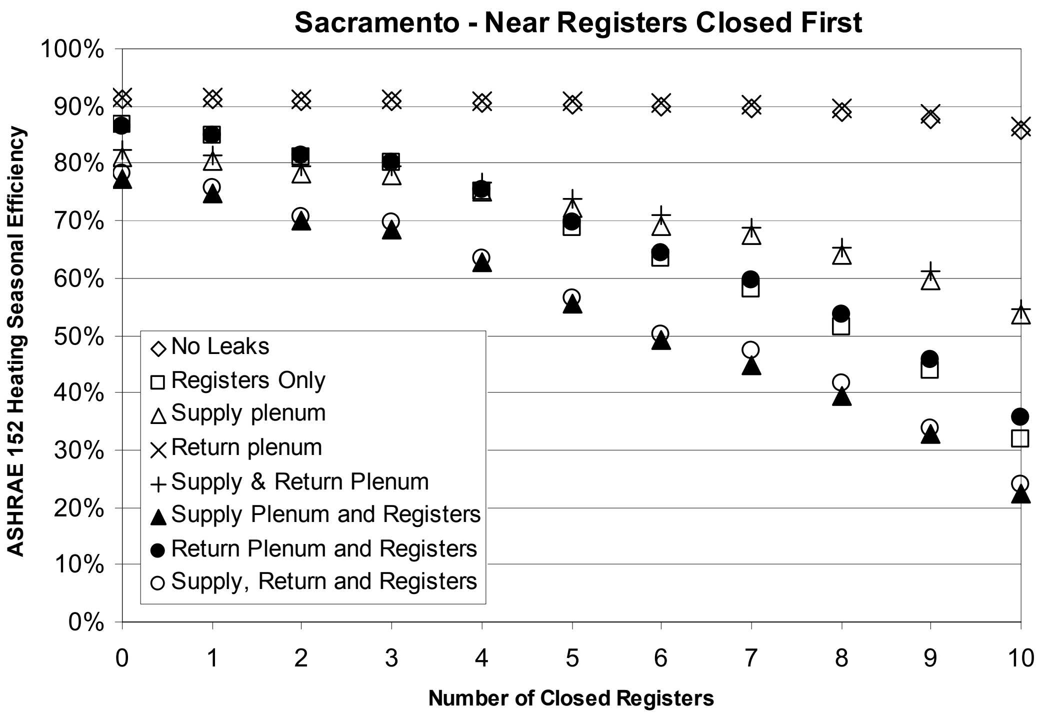
ASHRAE Standard 152 Input Data

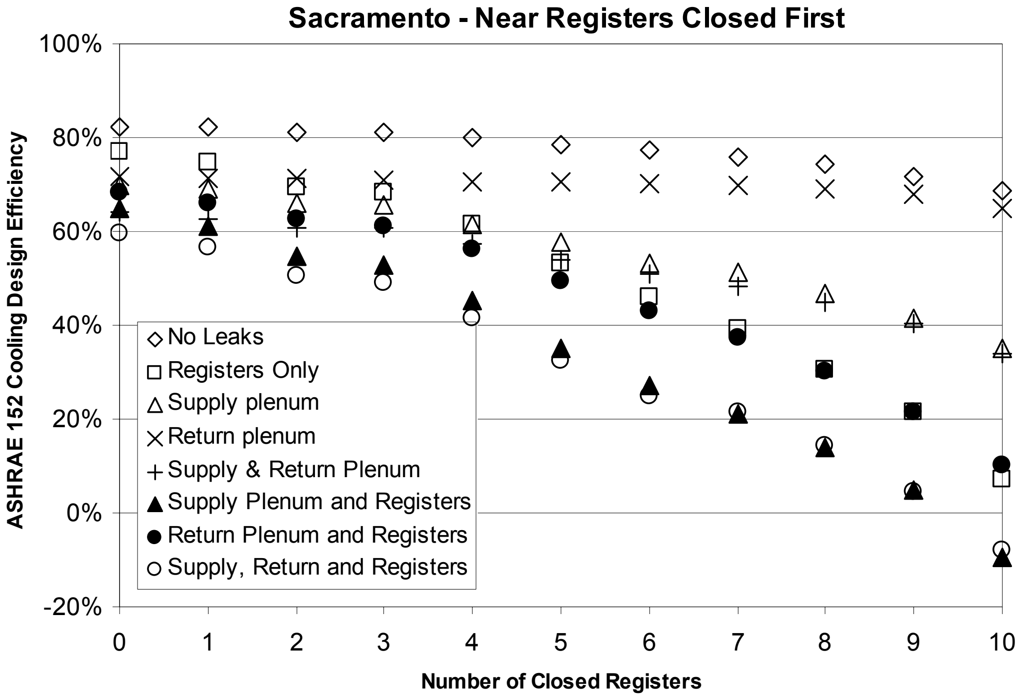
Draft ASHRAE standard 152 duct efficiency calculations							
Jan-03							
INPUT PARAMETERS			CALCULATED PARAMETERS				
	Value used in calculation	**Notes**					
Conditioned floor area, (ft^2)	1761						
Number of Stories	2						
Number of return Registers	6		Ground Temperature for basements, and slabs	65.0			
House Volume, (ft^3)	14440.2	**has a default of 8.2*Floor Area**					
Supply Duct Surface Area, (ft^2)	356.6025	**has default equation**	Fraction of supply duct outside conditioned space	1.0			
Return Duct Surface Area, (ft^2)	330.1875	**has default equation**	Fraction of return duct outside conditioned space	1.0			
Fraction of supply duct in attic	1		Design Supply Duct Zone temperature, Heating, (F)	43.0	Design Temp. diff for supply, dTs, heating	25.0	
Fraction of supply duct in garage	0		Seasonal Supply Duct Zone temperature, Heating, (F)	55.0	Seasonal Temp. diff for supply, dTs, heating	13.0	
Fraction of supply duct in unvented & uninsulated crawlspace	0		Design Return Duct Zone temperature, Heating, (F)	43.0	Design Temp. diff for return, dTr, heating	25.0	
Fraction of supply duct in unvented crawlspace with insulated building floor and crawlspace walls	0		Seasonal Return Duct Zone temperature, Heating, (F+D26)	55.0	Seasonal Temp. diff for return, dTr, heating	13.0	
Fraction of supply duct in unvented crawlspace with insulated building floor	0		Design Supply Duct Zone temperature, Cooling, (C)	119.0	Design Temp. diff for supply, dTs, cooling	-41.0	
Fraction of supply duct in Vented & uninsulated crawlspace	0		Seasonal Supply Duct Zone temperature, Cooling, (C)	99.0	Seasonal Temp. diff for supply, dTs, cooling	-21.0	
Fraction of supply duct in Vented crawlspace with insulated building floor and crawlspace walls	0		Design Return Duct Zone temperature, Cooling, (C)	119.0	Design Temp. diff for return, dTr, cooling	-41.0	119.0
Fraction of supply duct in Vented crawlspace with insulated building floor	0		Seasonal Return Duct Zone temperature, Cooling, (C)	99.0	Seasonal Temp. diff for return, dTr, cooling	-21.0	99.0
Fraction of supply duct in uninsulated basement	0		Design Supply Duct Zone Enthalpy, Cooling, (Btu/lbF)	38			
Fraction of supply duct in basement with insulated walls	0		Seasonal Supply Duct Zone Enthalpy, Cooling, (Btu/lbF)	33			
Fraction of supply duct in basement with insulated ceiling	0		Design Return Duct Zone Enthalpy, Cooling, (Btu/lbF)	37.6			38
Fraction of supply duct under slab	0		Seasonal Return Duct Zone Enthalpy, Cooling, (Btu/lbF)	33.3			33
Fraction of supply duct in exterior walls	0		Fcycloss	0.02			
Fraction of return duct in attic	1						
Fraction of return duct in garage	0		Infiltration, Fan off, cfm	84.2345			
Fraction of return duct in unvented & uninsulated crawlspace	0		HIGH SPEED:				
Fraction of return duct in unvented crawlspace with insulated building floor and crawlspace walls	0		Heating as	0.9			
Fraction of return duct in unvented crawlspace with insulated building floor	0		Heating, ar	0.9			
Fraction of return duct in Vented & uninsulated crawlspace	0		Cooling as	0.9			
Fraction of return duct in Vented crawlspace with insulated building floor and crawlspace walls	0		Cooling ar	0.9			
Fraction of return duct in Vented crawlspace with insulated building floor	0		Temperature change across heat exchanger, dTe, heating	61.73			
Fraction of return duct in uninsulated basement	0		Temperature change across heat exchanger, dTe, cooling	-27.78			
Fraction of return duct in basement with insulated walls	0		Heating, Bs	0.95			
Fraction of return duct in basement with insulated ceiling	0		Heating, Br	0.95			

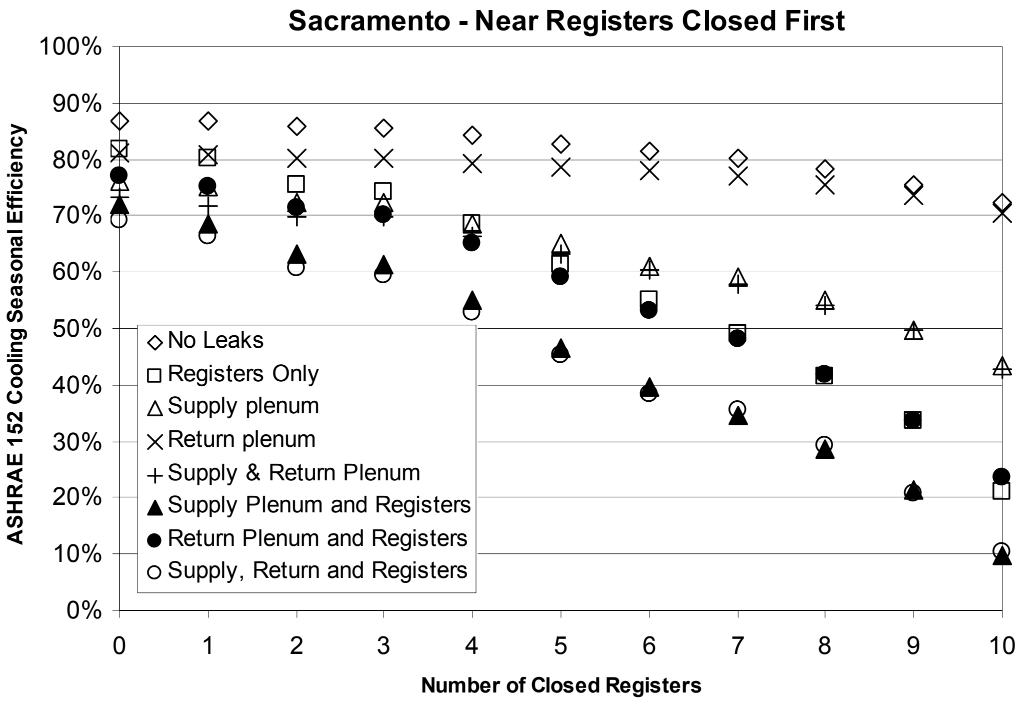
Return Duct R value(hft^2F/Btu)	4.2		Imbalance Flow, Cooling, (cfm)	0			
Heating Design temperature from Table 6.3a (F)	33		Net building infiltration, heating, (cfm)	86.1227			
Cooling Design temperature from Table 6.3a (F)	97		Net building infiltration, cooling, (cfm)	86.1227			
Heating Seasonal temperature from Table 6.3a (F)	48		Load Factor, heating, design	0.999			
Cooling Seasonal temperature from Table 6.3a (F)	86		Load Factor, heating, seasonal	1.000			
Design Humidity ratio	0.0081		Load Factor, cooling, design	0.998			
Design Indoor Humidity ratio	0.0072						
Seasonal Humidity Ratio	0.0086		Load Factor, cooling, seasonal	0.999			
Seasonal Indoor Humidity ratio	0.0074		Equipment factor, heating, design	1			
Design Enthalpy	32		Equipment factor, heating, seasonal	1			
Design Indoor Enthalpy	27		Equipment Factor, Cooling, design	1.00035	Manufacturers rated fan flow	1198.8	
Seasonal Enthalpy	30		Equipment Factor, cooling, seasonal	1.00035			
Seasonal Indoor Enthalpy	27						
Is there solar gain reduction in the attic? [Y/N]	N						
Equipment Heating Capacity, Btu/hour	100000	Enter single speed equipment capacity here. For two speed equipment, enter higher capacity here					
Equipment Cooling Capacity, Btu/hour (this should be entered as a negative number)	-36000	Enter single speed equipment capacity here. For two speed equipment, enter higher capacity here					
Equipment Heating Capacity, Btu/hour, LOW	0	For two speed equipment, enter lower capacity here					
Equipment Cooling Capacity, Btu/hour (this should be entered as a negative number), LOW	0	For two speed equipment, enter lower capacity here					
Heating Fan Flow, (cfm)	1500	For two speed equipment, enter higher flow here					
Cooling Fan Flow, (cfm)	1200	For two speed equipment, enter higher flow here					
Heating Supply duct leakage (cfm)	150	For two speed equipment, enter higher flow here					
Heating Return duct leakage (cfm)	150	For two speed equipment, enter higher flow here					
Cooling Supply duct leakage (cfm)	120	For two speed equipment, enter higher flow here					
Cooling Return duct leakage (cfm)	120	For two speed equipment, enter higher flow here					
Heating Fan Flow, (cfm), ACCA Manual D calculation or measured value, LOW SPEED	0	For two speed equipment, enter lower flow here					
Cooling Fan Flow, (cfm), ACCA Manual D calculation or measured value, LOW SPEED	0	For two speed equipment, enter lower flow here					
Heating Supply duct leakage (cfm), LOW SPEED	0	For two speed equipment, enter lower flow here					
Heating Return duct leakage (cfm), LOW SPEED	0	For two speed equipment, enter lower flow here					
Cooling Supply duct leakage (cfm), LOW SPEED	0	For two speed equipment, enter lower flow here					
Cooling Return duct leakage (cfm), LOW SPEED	0	For two speed equipment, enter lower flow here					
For Duct Thermal Mass Correction, Enter F for flex duct or duct board, M for sheet metal	F						
Enter 1 for single speed equipment, 2 for multispeed equipment	1		Uncorrected DE				
For Vented Attic, Enter V for vented, U for unvented	V						
For cooling systems, Enter T for TXV control, O for other control	O		0.79				

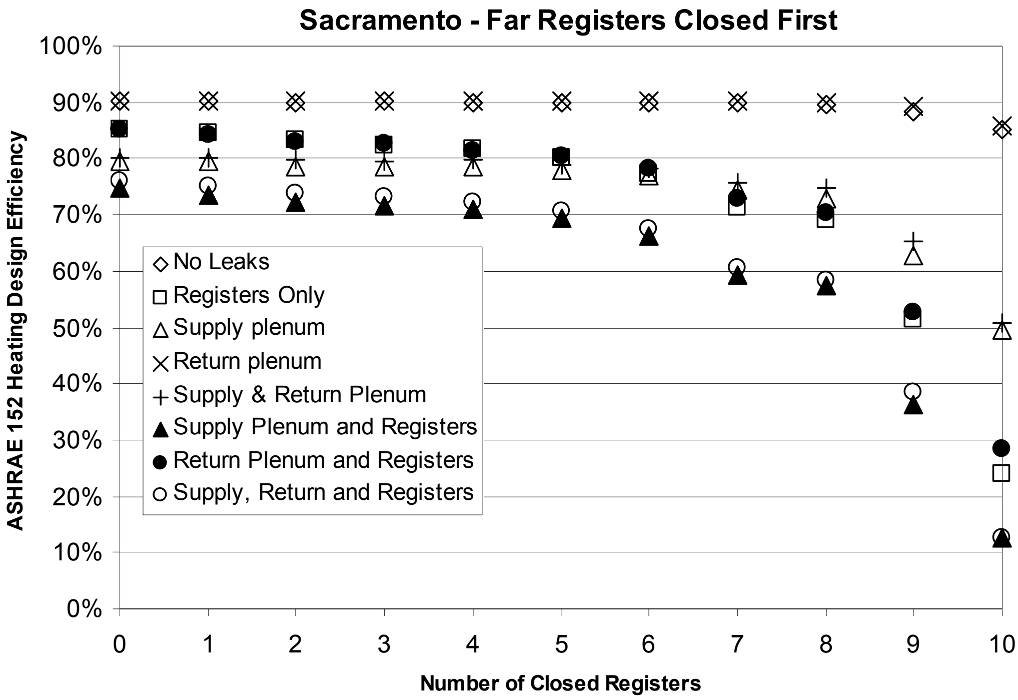
Appendix E. ASHRAE 152 Calculated Distribution System Efficiencies

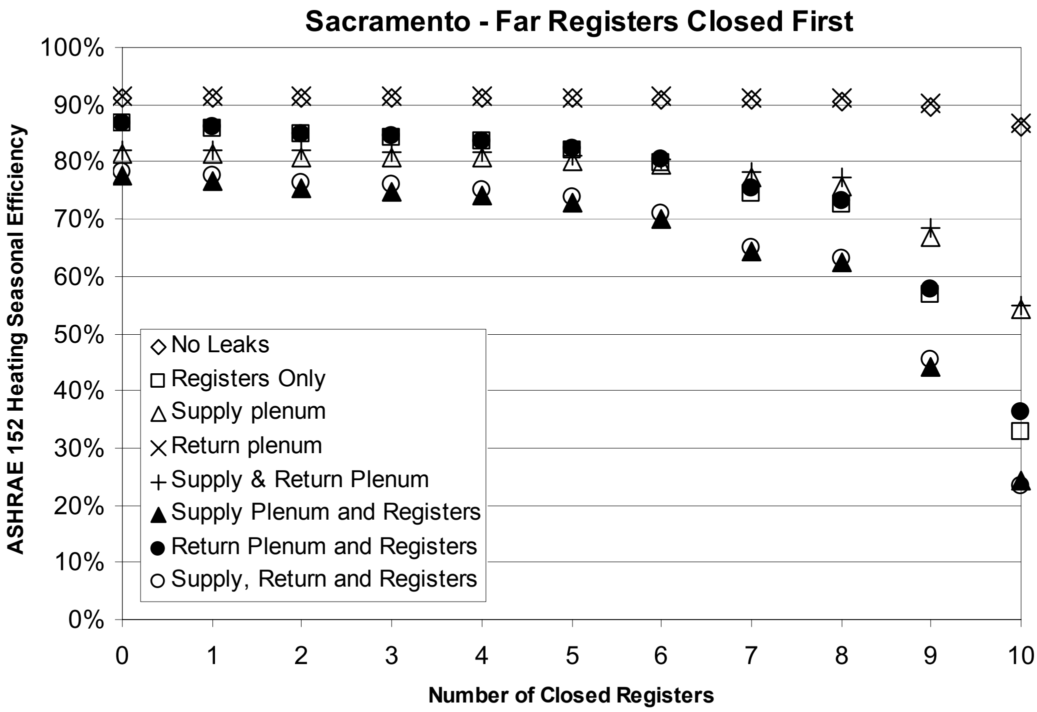


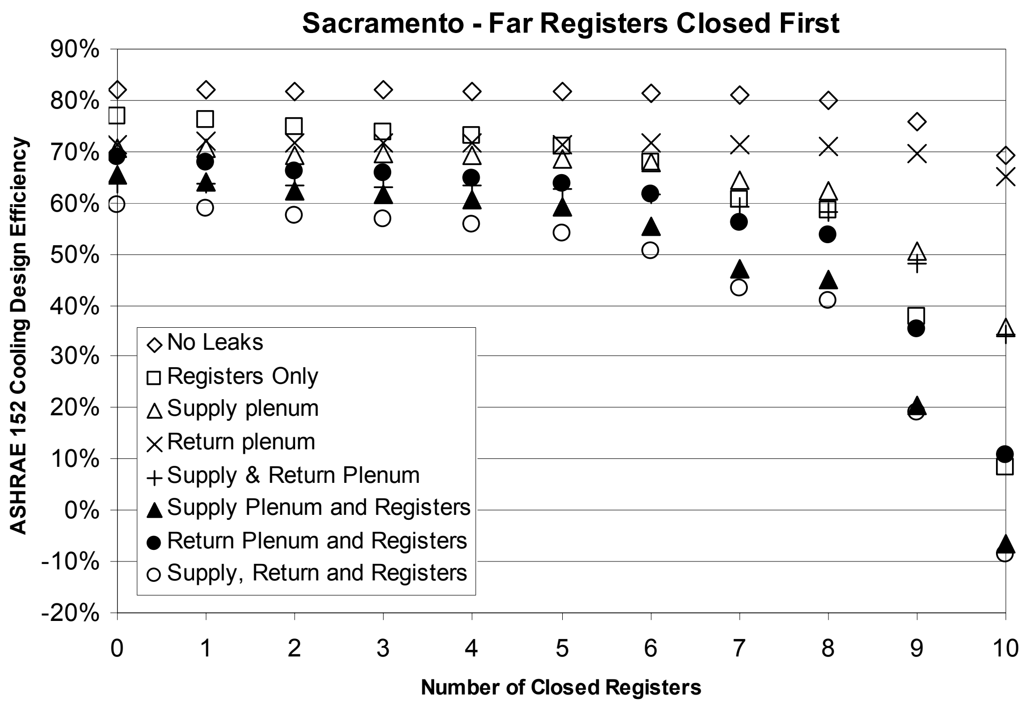


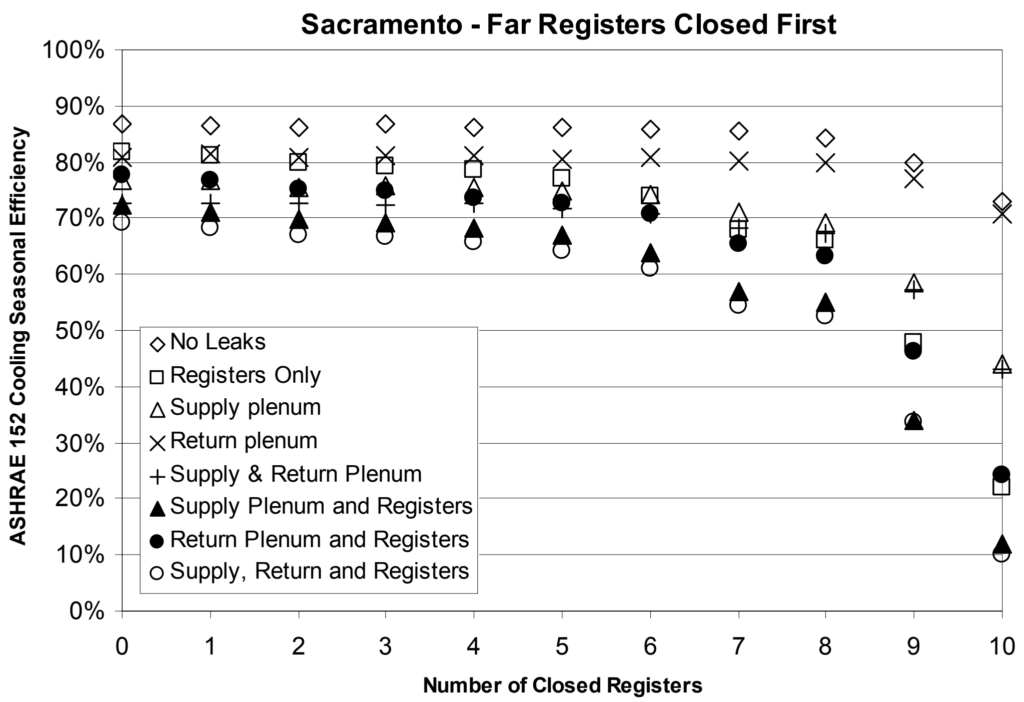

Sacramento - Near Registers Closed First
ASHRAE 152 Cooling Design Efficiency
100%
80%
60%
40%
20%
0%
-20%
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

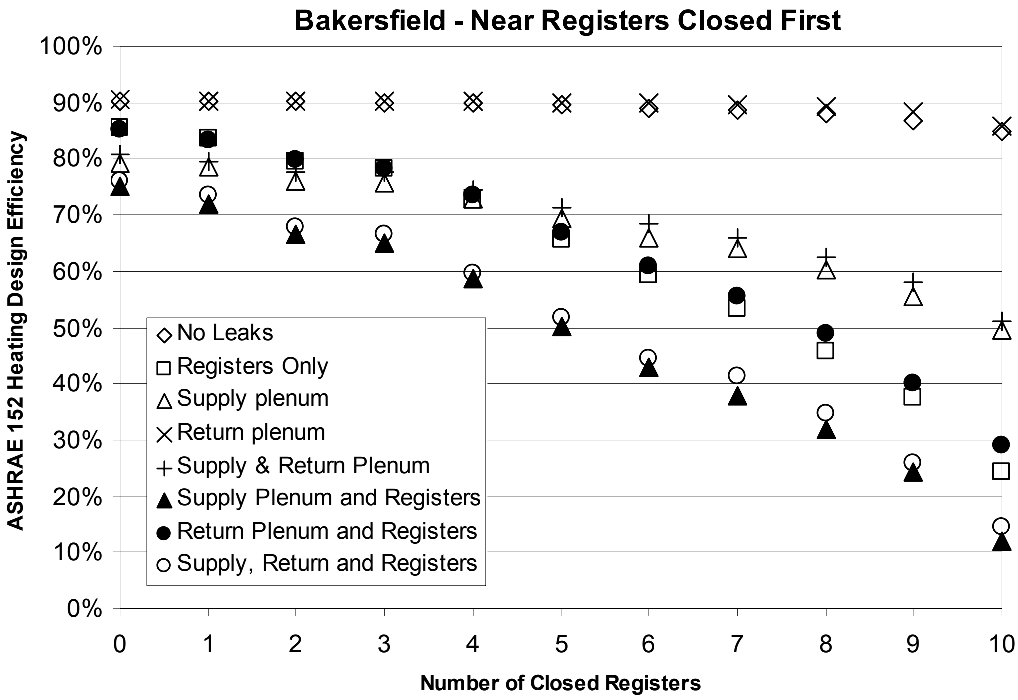

Sacramento - Near Registers Closed First
ASHRAE 152 Cooling Seasonal Efficiency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

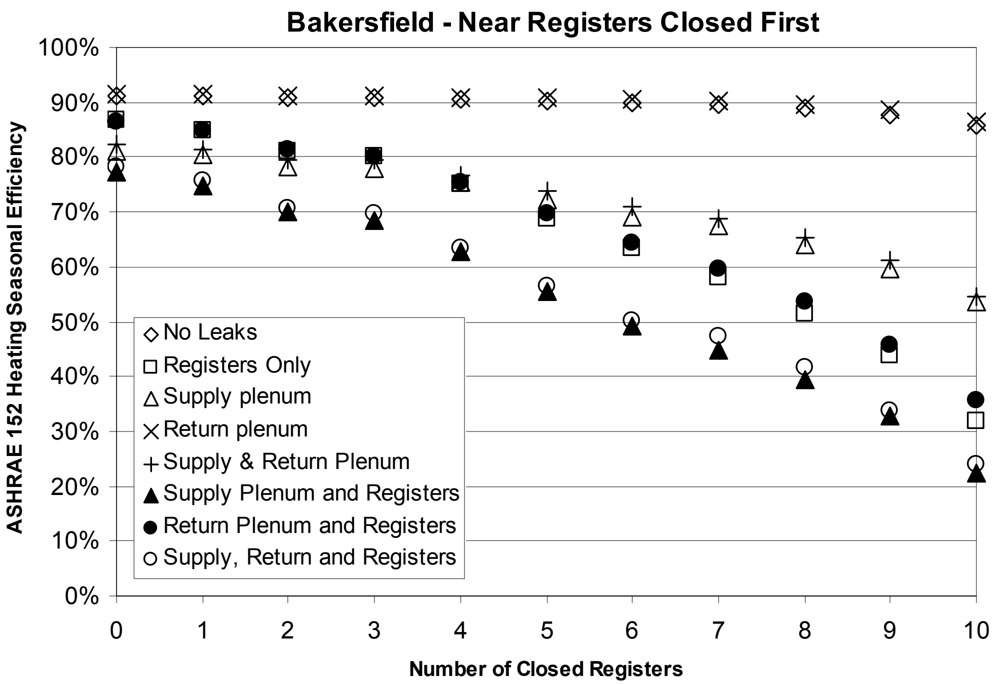

Sacramento - Far Registers Closed First
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
ASHRAE 152 Heating Design Efficiency
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

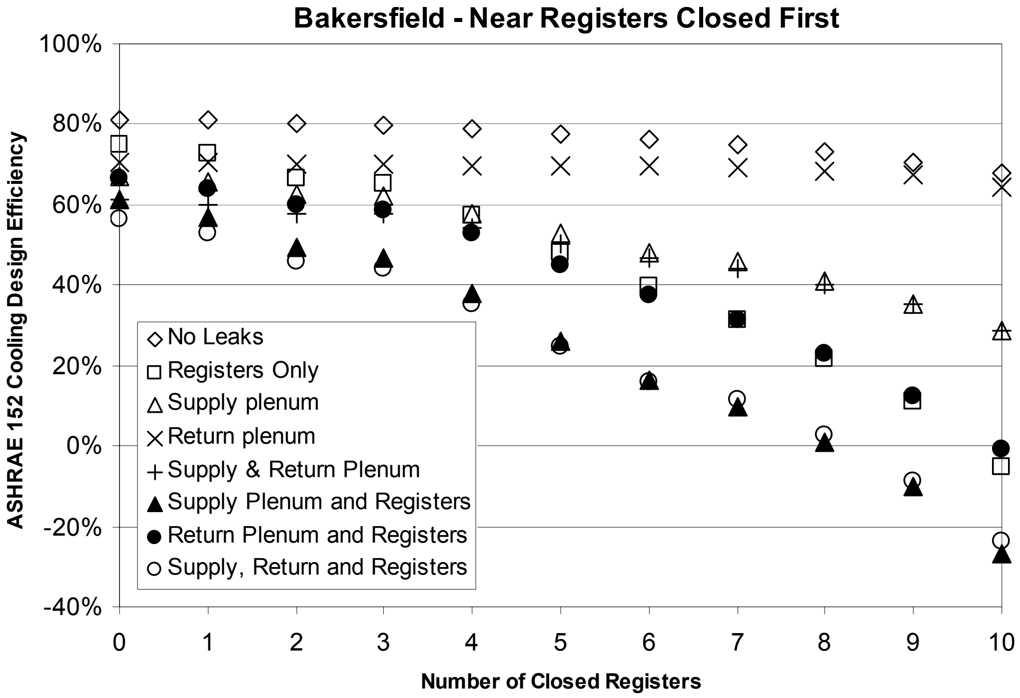

Sacramento - Far Registers Closed First
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
ASHRAE 152 Heating Seasonal Efficiency
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers


Sacramento - Far Registers Closed First
ASHRAE 152 Cooling Design Efficiency
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-10%
-20%
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

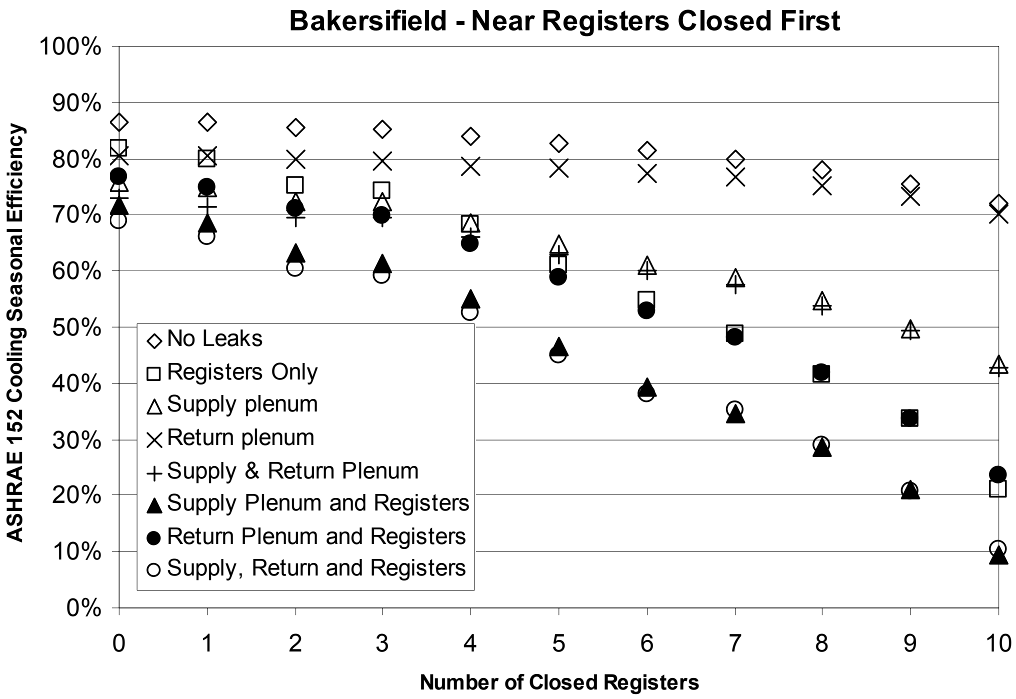

Sacramento - Far Registers Closed First
ASHRAE 152 Cooling Seasonal Efficiency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers


Bakersfield - Near Registers Closed First
ASHRAE 152 Heating Design Efficiency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

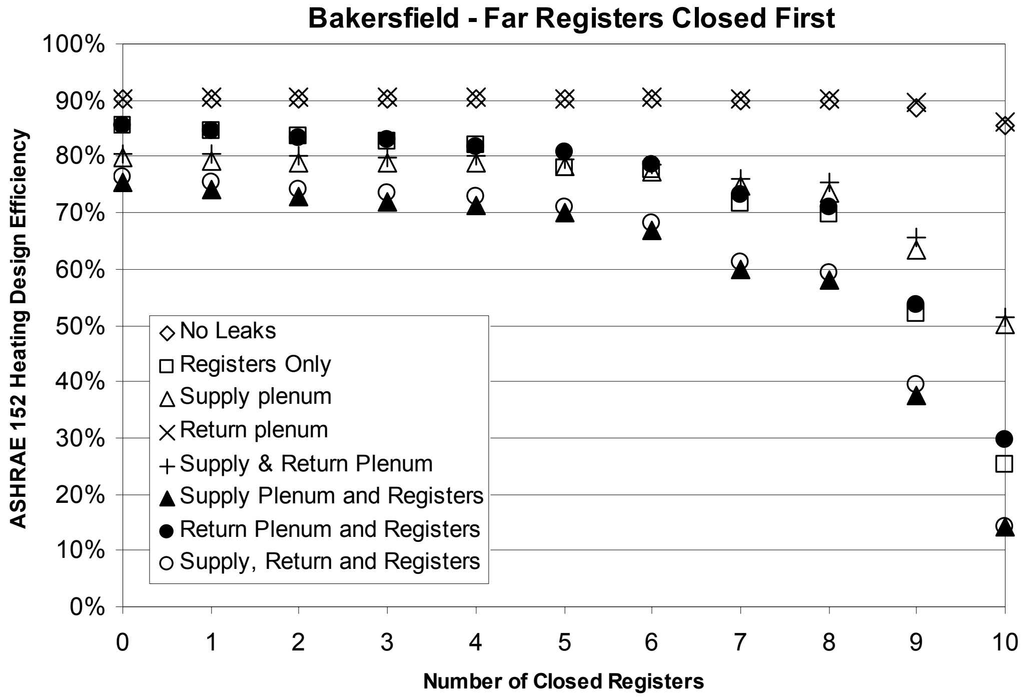

Bakersfield - Near Registers Closed First
ASHRAE 152 Heating Seasonal Efficiency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

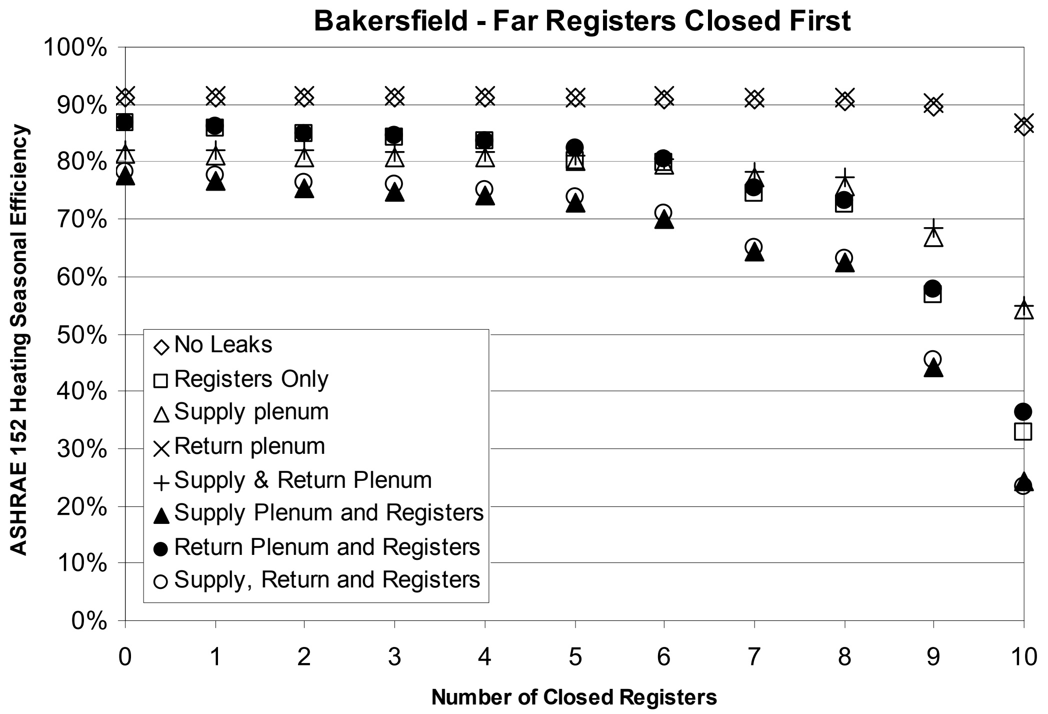


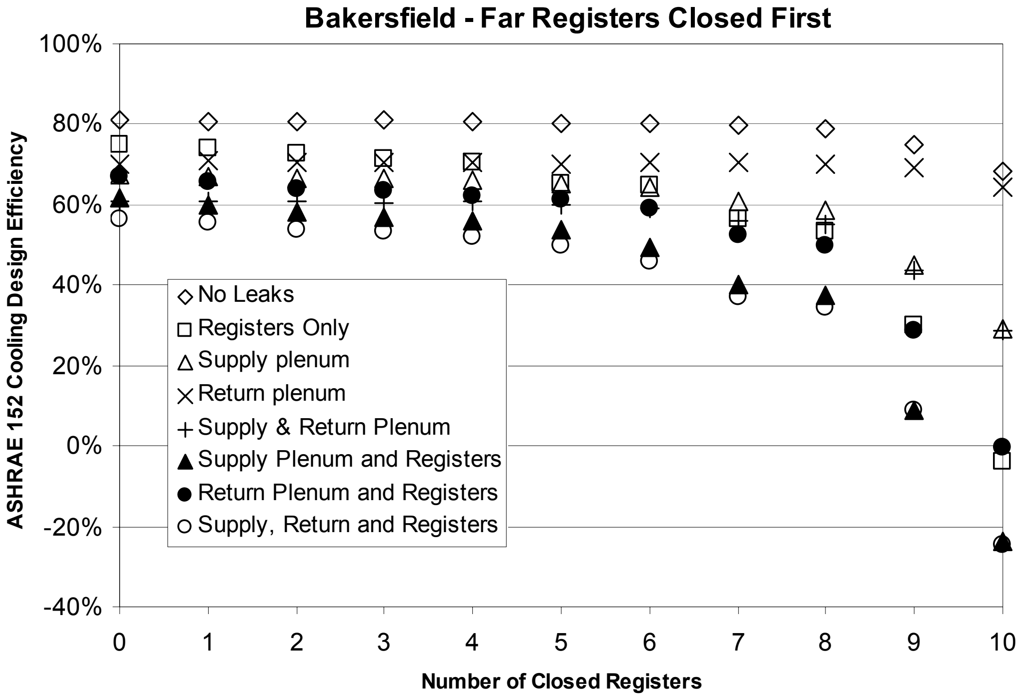
Bakersfield - Near Registers Closed First
100%
80%
60%
40%
20%
0%
-20%
-40%
ASHRAE 152 Cooling Design Efficiency
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

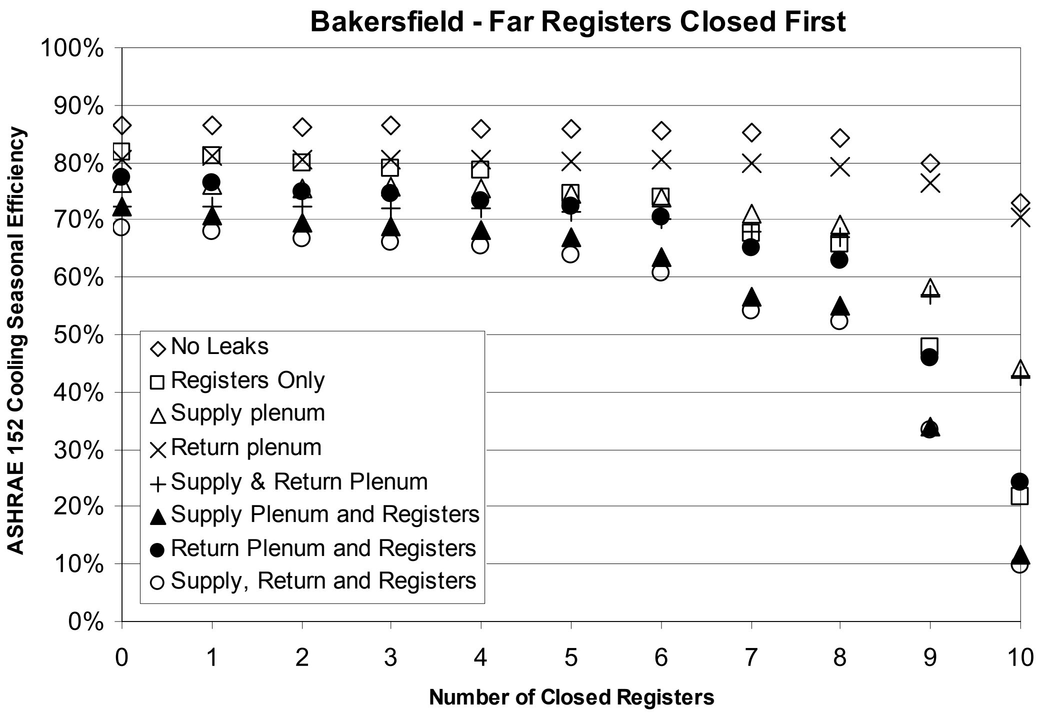


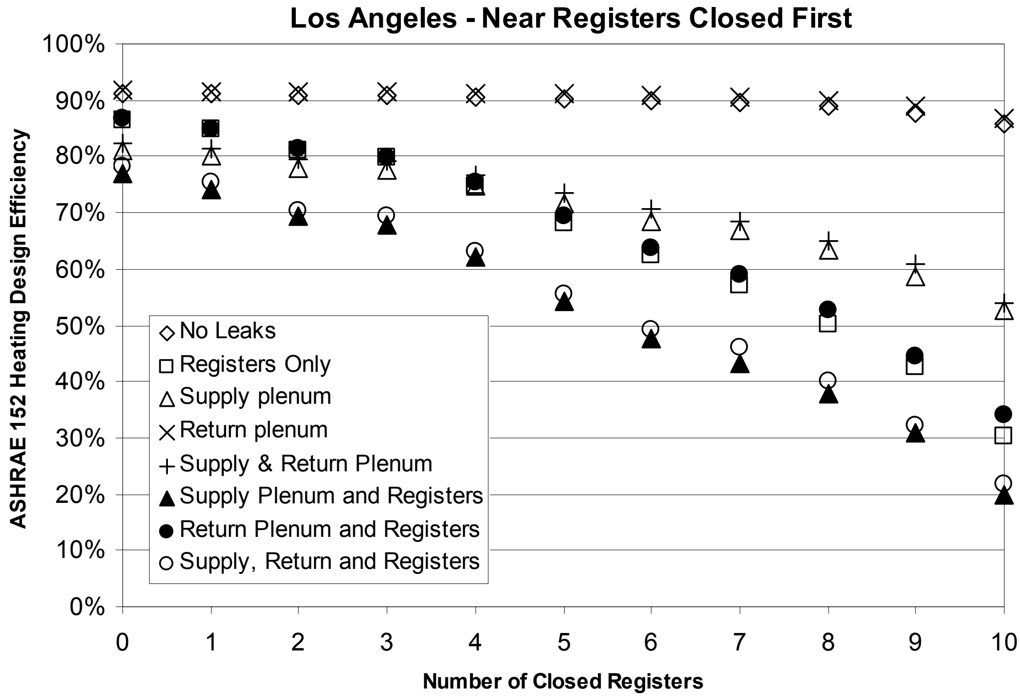
Bakersifield - Near Registers Closed First
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
ASHRAE 152 Cooling Seasonal Efficiency
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

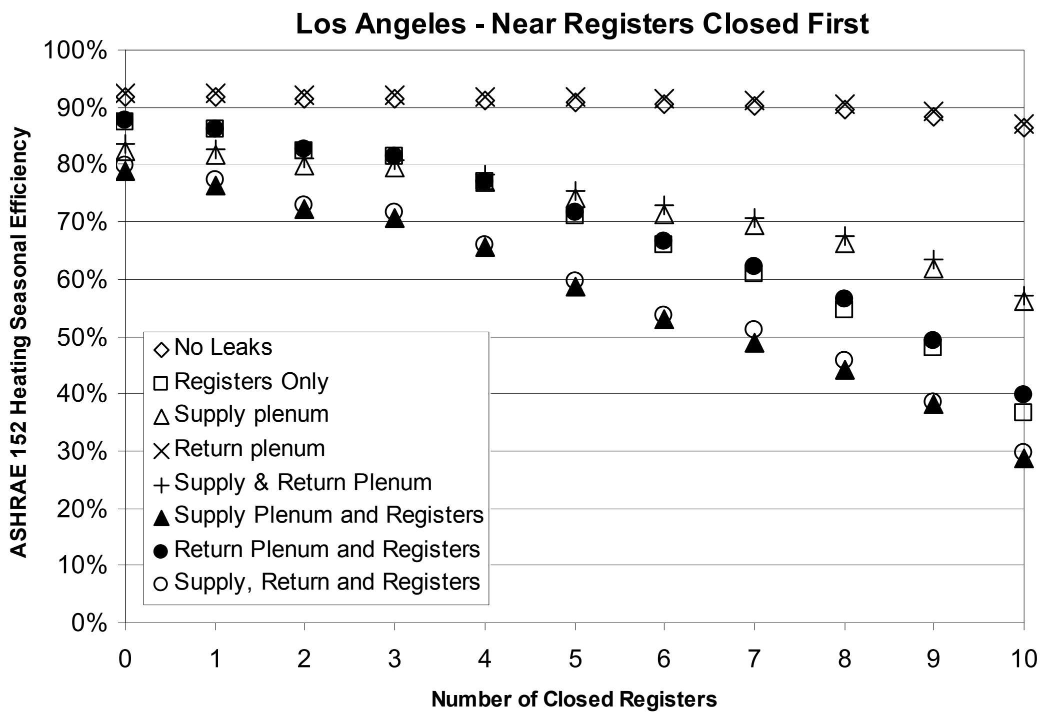

Bakersfield - Far Registers Closed First
ASHRAE 152 Heating Design Efficiency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

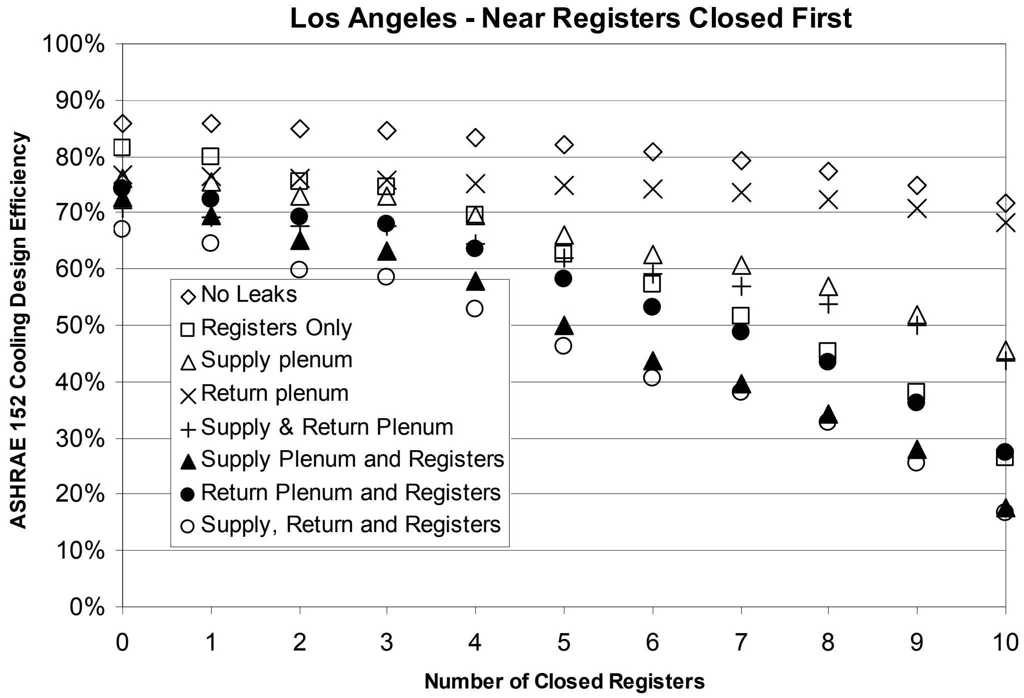

Bakersfield - Far Registers Closed First
ASHRAE 152 Heating Seasonal Efficiency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
7
8
9
10
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

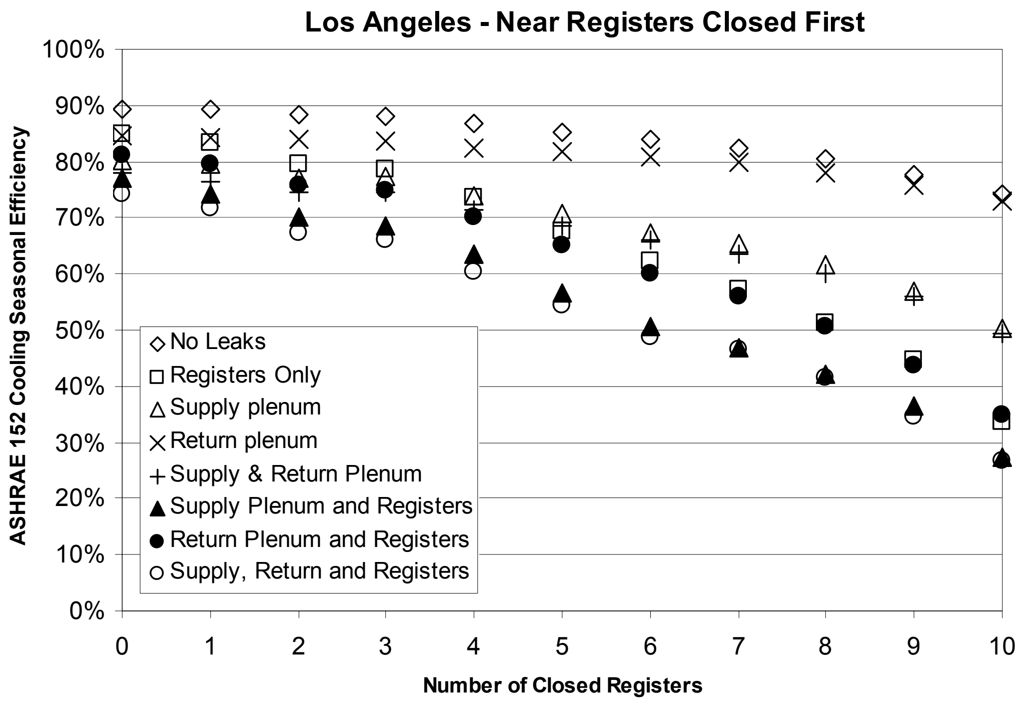

Bakersfield - Far Registers Closed First
ASHRAE 152 Cooling Design Efficiency
Number of Closed Registers
100%
80%
60%
40%
20%
0%
-20%
-40%
0
1
2
3
4
5
6
7
8
9
10
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers


Bakersfield - Far Registers Closed First
ASHRAE 152 Cooling Seasonal Efficiency
Number of Closed Registers
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
7
8
9
10
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers


Los Angeles - Near Registers Closed First
ASHRAE 152 Heating Design Efficiency
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers


Los Angeles - Near Registers Closed First
ASHRAE 152 Heating Seasonal Efficiency
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers


Los Angeles - Near Registers Closed First
ASHRAE 152 Cooling Design Efficiency
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

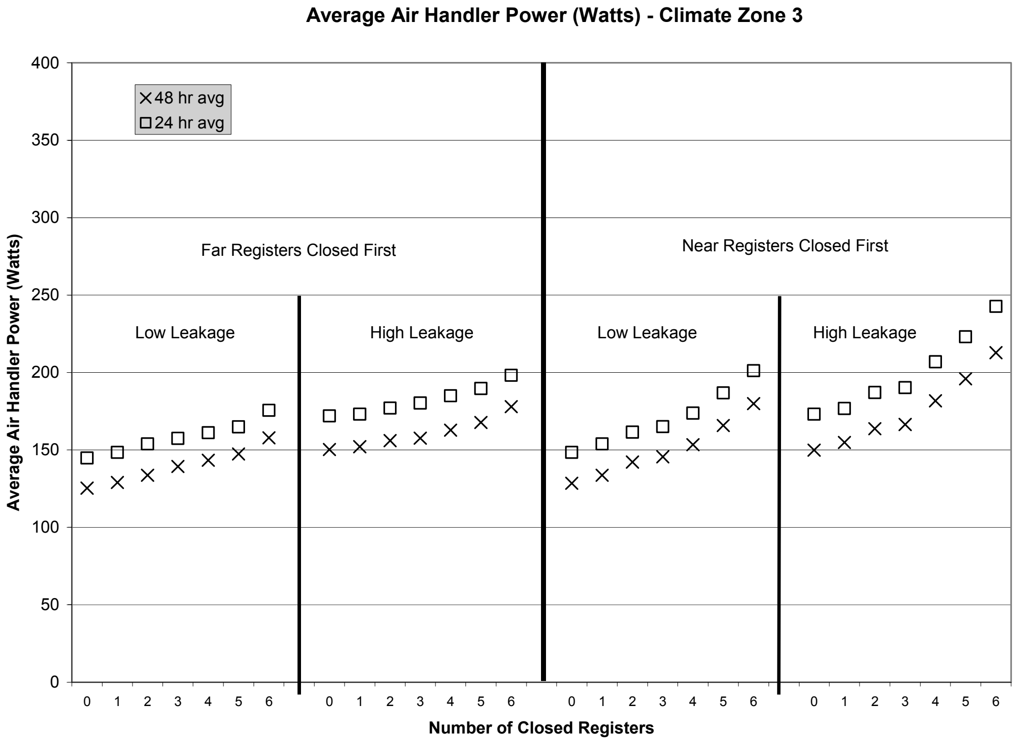

Los Angeles - Near Registers Closed First
ASHRAE 152 Cooling Seasonal Efficiency
Number of Closed Registers
No Leaks
Registers Only
Supply plenum
Return plenum
Supply & Return Plenum
Supply Plenum and Registers
Return Plenum and Registers
Supply, Return and Registers

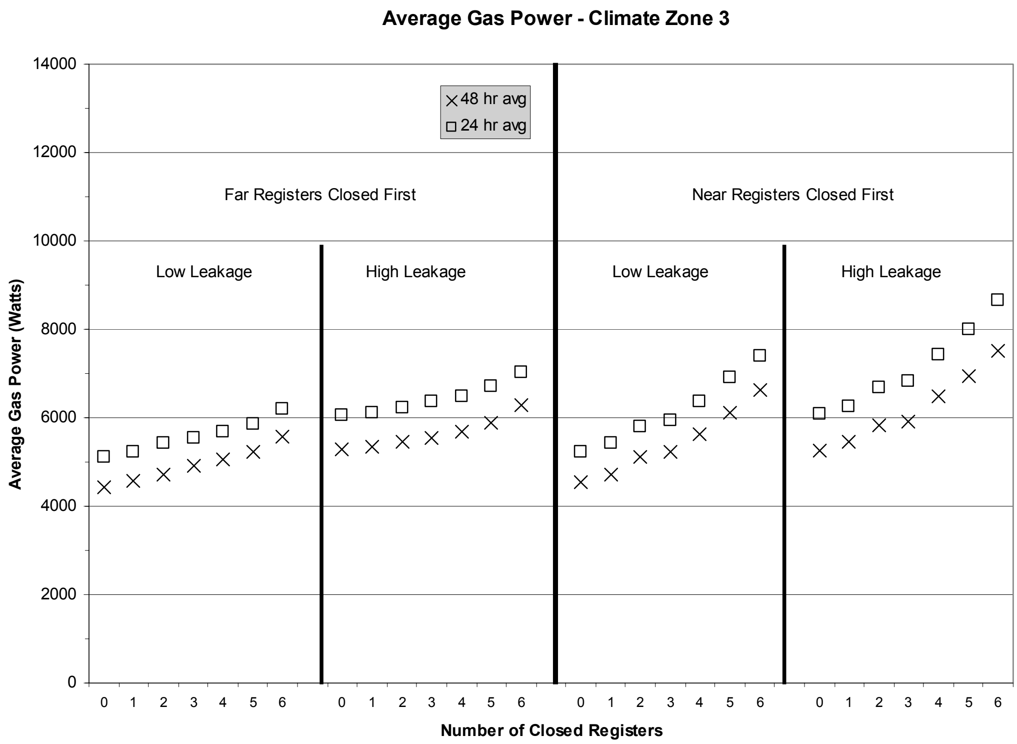
In the following tables – the grey cells indicate that no registers may be closed and still meet the minimum efficiency specification. The underlined values are those that are different from the table given for Sacramento in the main part of this report.

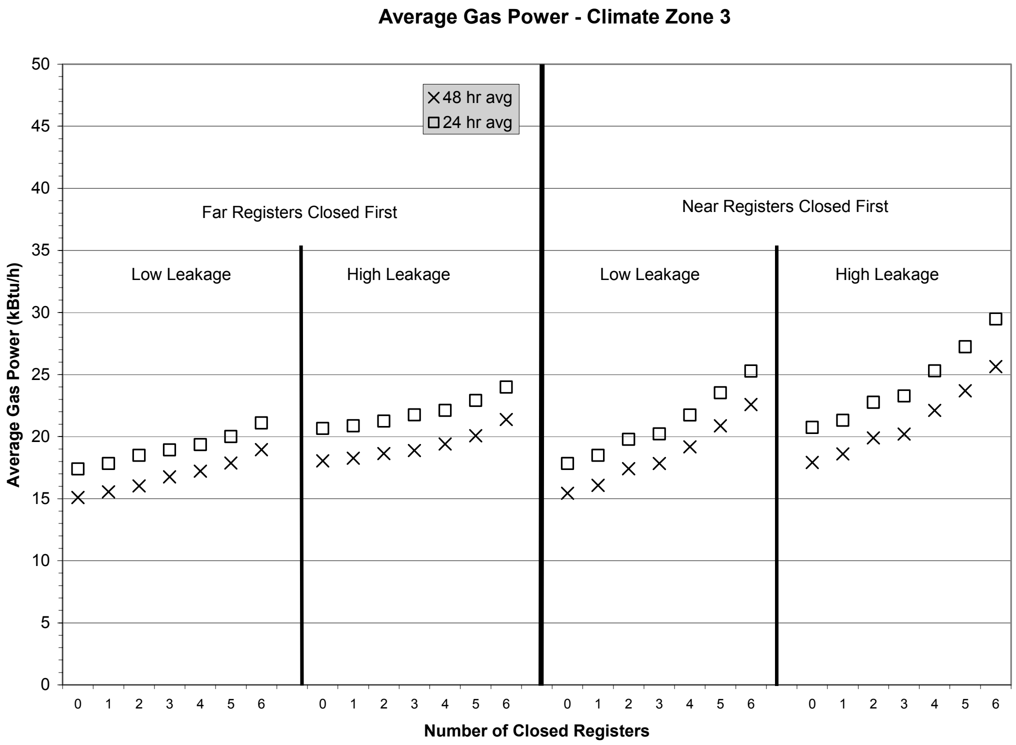
Table G1. Maximum number of registers that can be closed and still meet a minimum efficiency specification (Bakersfield)																
Minimum efficiency	**90%**				**80%**				**70%**				**60%**			
Seasonal Heating/Cooling	**H**		**C**		**H**		**C**		**H**		**C**		**H**		**C**	
direction	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
No leak	7	8			10	10	7	9	10	10	10	10	10	10	10	10
Leak at registers					3	6	1	2	4	8	3	6	6	8	5	8
Leak at supply plenum					1	5			5	8	3	7	8	9	6	8
Leak at return plenum	8	9			10	10	3	7	10	10	10	10	10	10	10	10
Leak at return & supply plenum					2	6			6	8	1	6	9	9	6	8
Leak at supply plenum and registers									2	6	0	1	4	8	3	6
Leak at return plenum and registers					3	6			5	8	3	6	7	8	4	8
Leak at registers, return & supply plenum									3	6			4	8	2	6

Table G2. Maximum number of registers that can be closed and still meet a minimum efficiency specification (Los Angeles)																
Minimum efficiency	**90%**				**80%**				**70%**				**60%**			
Seasonal Heating/Cooling	**H**		**C**		**H**		**C**		**H**		**C**		**H**		**C**	
Direction	**1**		**1**	**2**	**1**		**1**		**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
No leak	8				10		8		10		10		10		10	
Leak at registers					3		2		5		4		7		6	
Leak at supply plenum					3		1		7		5		9		8	
Leak at return plenum	8				10		7		10		10		10		10	
Leak at return & supply plenum					3				7		4		9		8	
Leak at supply plenum and registers									3		2		4		4	
Leak at return plenum and registers					3				5		4		7		6	
Leak at registers, return & supply plenum									3		1		4		4	

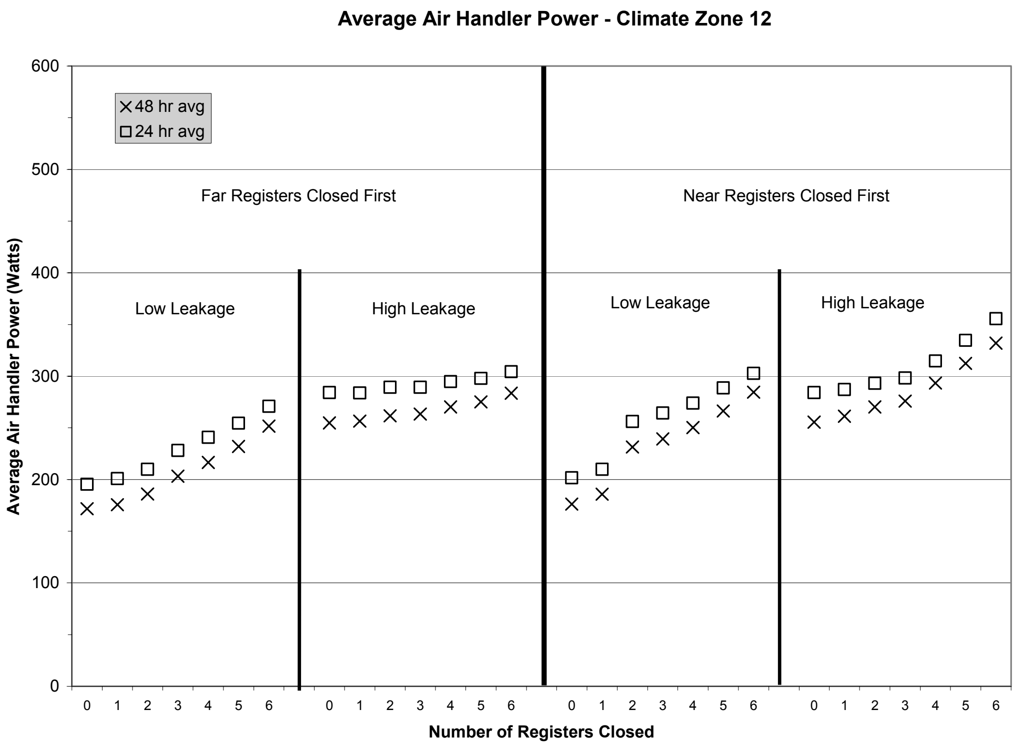
Appendix F. REGCAP Calculated Gas and Electricity Consumption



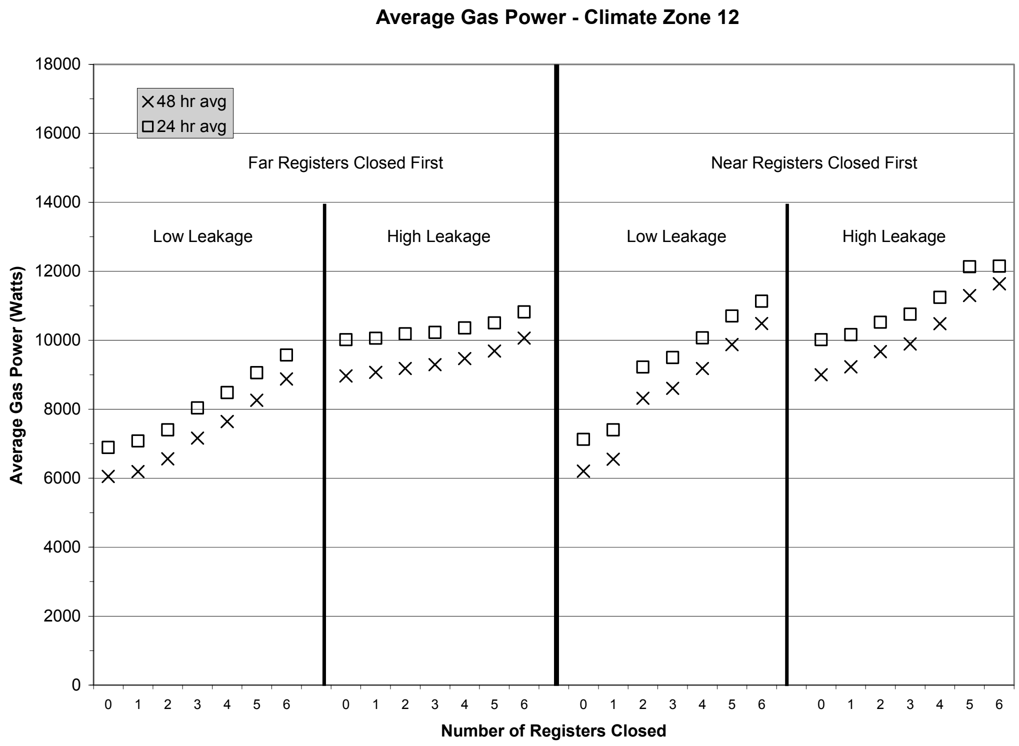


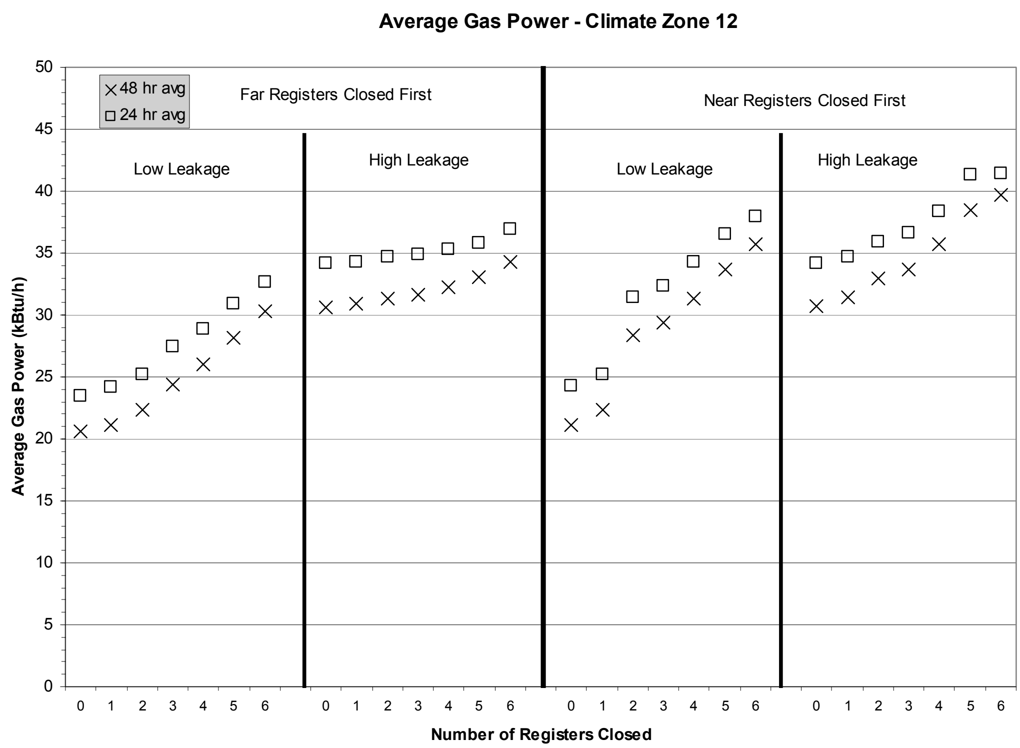


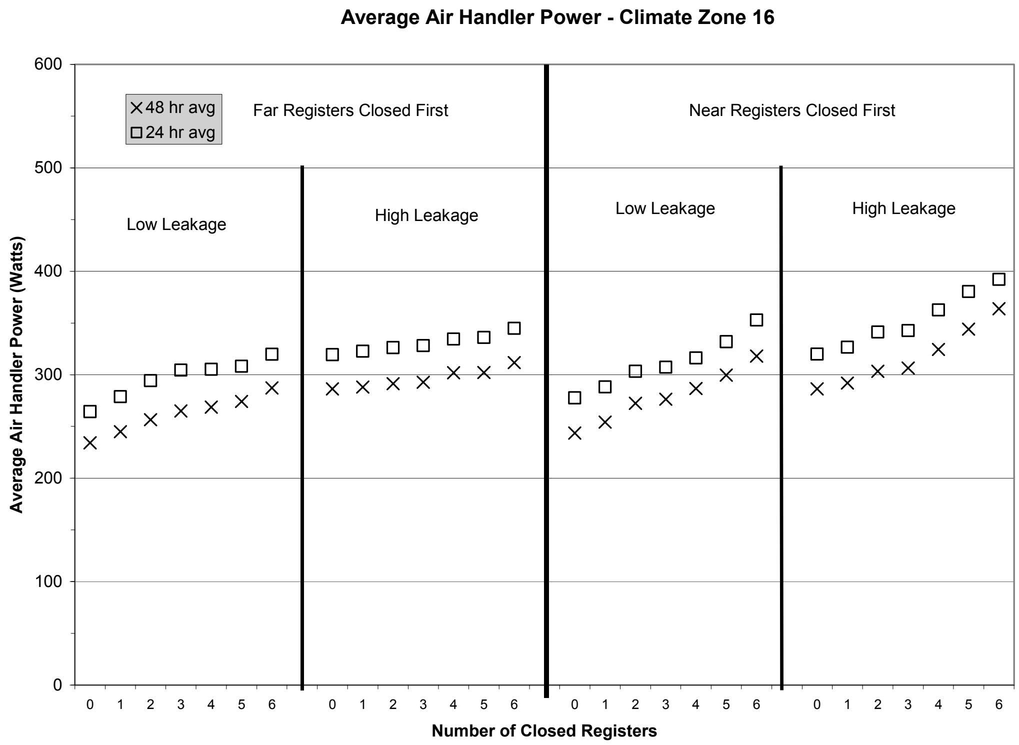
Average Gas Power - Climate Zone 3
48 hr avg
24 hr avg
Far Registers Closed First
Near Registers Closed First
Low Leakage
High Leakage
Low Leakage
High Leakage
Average Gas Power (kBtu/h)
Number of Closed Registers



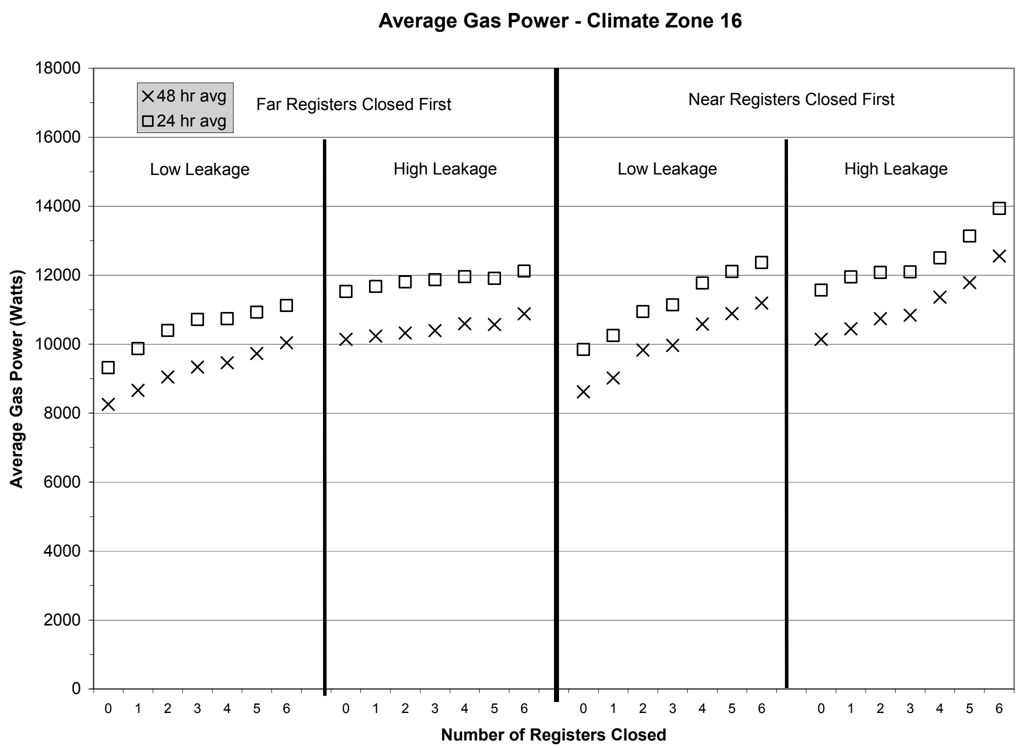
Average Air Handler Power - Climate Zone 12
48 hr avg
24 hr avg
Far Registers Closed First
Near Registers Closed First
Low Leakage
High Leakage
Low Leakage
High Leakage
Average Air Handler Power (Watts)
Number of Registers Closed


Average Gas Power - Climate Zone 12
48 hr avg
24 hr avg
Far Registers Closed First
Near Registers Closed First
Low Leakage
High Leakage
Low Leakage
High Leakage
Average Gas Power (Watts)
Number of Registers Closed

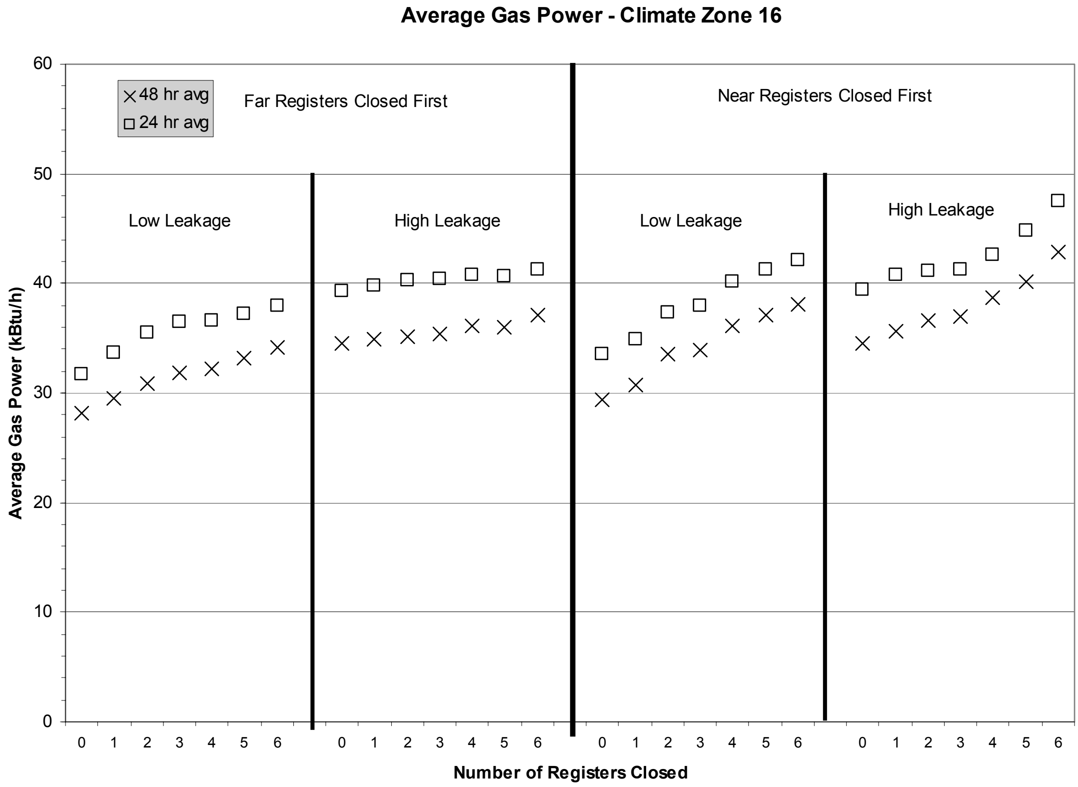

Average Gas Power - Climate Zone 12
48 hr avg
24 hr avg
Far Registers Closed First
Near Registers Closed First
Low Leakage
High Leakage
Low Leakage
High Leakage
Average Gas Power (kBtu/h)
Number of Registers Closed



Average Air Handler Power - Climate Zone 16
48 hr avg
24 hr avg
Far Registers Closed First
Near Registers Closed First
Low Leakage
High Leakage
Low Leakage
High Leakage
Average Air Handler Power (Watts)
600
500
400
300
200
100
0
0 1 2 3 4 5 6 0 1 2 3 4 5 6 0 1 2 3 4 5 6 0 1 2 3 4 5 6
Number of Closed Registers



Average Gas Power - Climate Zone 16
48 hr avg
24 hr avg
Far Registers Closed First
Near Registers Closed First
Low Leakage
High Leakage
Low Leakage
High Leakage
Average Gas Power (Watts)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 0 1 2 3 4 5 6 0 1 2 3 4 5 6 0 1 2 3 4 5 6
Number of Registers Closed


Average Gas Power - Climate Zone 16
48 hr avg
24 hr avg
Far Registers Closed First
Near Registers Closed First
Low Leakage
High Leakage
Low Leakage
High Leakage
Average Gas Power (kBtu/h)
Number of Registers Closed
0
10
20
30
40
50
60
0 1 2 3 4 5 6
0 1 2 3 4 5 6
0 1 2 3 4 5 6
0 1 2 3 4 5 6