CODES AND STANDARDS ENHANCEMENT INITIATIVE (CASE)

Residential Zoned Ducted HVAC Systems

2013 California Building Energy Efficiency Standards

California Utilities Statewide Codes and Standards Team September 2011

This report was prepared by the California Statewide Utility Codes and Standards Program and funded by the California utility customers under the auspices of the California Public Utilities Commission.

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Project Team

Bruce A. Wilcox, Rick Chitwood and John Proctor designed and carried out the research and analysis for this project.

1. Purpose

This report recommends new mandatory requirements for zoned ducted HVAC systems in the California 2013 Title 24 – Part 6 Building Energy Efficiency Standards. It also proposes eliminating the current compliance credit for zoned systems and proposes that the current prescriptive standard for airflow and fan watt draw become a mandatory item for the 2013 Standards.

2. Overview

a. Measure Title	**Residential Zoned Ducted HVAC Systems**
b. Description	A mandatory requirement in the Low Rise Residential Standards for new single family homes and existing homes undergoing HVAC alterations or replacement to ensure the efficient functioning of air conditioners, furnaces, and heat pumps that employ ducted zoned systems. The requirement includes three items, one of them specific to ducted, multi-zone systems: 1. Eliminating bypass ducting that recirculates cooled or heated air back into the return system. 2. Specifying that the system provide at least 350 CFM per ton through the unit under all operating modes, with that airflow delivered to the house (this will be a mandatory requirement for all systems). 3. Specifying that the watt draw of the system shall be no greater than 0.58 W/CFM as specified in Reference Residential Appendix RA3. In addition, this CASE proposes elimination of the energy savings compliance credit for zoned systems under the performance approach.
c. Type of Change	**Mandatory Measure –** The change would add a mandatory measure whenever a multi-zoned system is installed or altered. **Compliance Option –** The change would eliminate multi-zoning from the list of existing compliance options for meeting the Standards using the performance approach. **Modeling –** The change would eliminate the special modeling for zoned systems. Otherwise it would not modify the calculation procedures or assumptions used in making performance calculations. **Documents –** The following documents are affected: 1. Standards Sections 150, 151, and 152 2. Residential ACM Approval Manual 3. Residential CF-4R and CF-6R

d. Energy Benefits

Figure 1 shows the energy savings in each climate zone for the 2,700 ft^2 Prototype D single family home with a multi-zoned system that provides ≥ 350 CFM per ton, ≤ 0.58 watts per CFM and no bypass versus the field measured CFM per ton, watts per CFM and 50% bypass.

Climate Zone	Electricity (kWh/yr)	Demand (kW)	Natural Gas (Therms/yr)	Time Dependent Valuation Electricity (mTDV/yr)	Time Dependent Valuation \Gas (mTDV/yr)
01	0	0.00	17	0.00	2.97
02	55	0.12	16	4.88	2.94
03	34	0.10	9	3.78	1.67
04	124	0.29	12	9.26	2.21
05	0	0.00	13	0.00	2.18
06	130	0.28	5	8.91	0.81
07	93	0.22	2	7.59	0.22
08	256	0.46	3	14.82	0.60
09	372	0.62	6	21.68	0.95
10	433	0.69	6	24.11	1.08
11	670	0.85	13	36.83	2.38
12	308	0.52	13	20.09	2.43
13	714	0.86	12	35.29	2.19
14	625	0.77	12	31.05	2.19
15	1749	1.44	1	67.18	0.19
16	282	0.58	24	20.38	4.30
Statewide	**318**	**0.49**	**8**	**18.02**	**1.41**

Figure 1. Energy Benefits

e. Non-Energy Benefits

Eliminating the bypass will improve installation quality and provide better control over delivery velocities, potentially reducing noise. It will also reduce the excessive drying effect on house air and reduce the probability of mold growth in the air conditioner.

f. Environmental Impact

The measure has no adverse environmental impact.

Material Increase (I), Decrease (D), or No Change (NC): (All units are lbs/year)

	Mercury	Lead	Copper	Steel	Plastic	Others (Identify)
Per Unit Measure[1]	NC	NC	NC	NC	NC	
Per Prototype Building[2]	NC	NC	NC	NC	NC	

g. Technology Measures	This change does not encourage or require a particular technology. This change prohibits bypass ducts.
h. Performance Verification of the Proposed Measure	HERS field verification using standard sampling is required for the airflow and watt draw specifications. Building inspectors can verify that bypass ducts are not installed.
i. Cost Effectiveness	Based on the analysis in Section 4 of this CASE, Figure 2 shows the life-cycle cost in each climate zone for the 2,700 ft^2 Prototype D with a dampered zoned system exhibiting a typical: 1. Cooling efficiency degradation of 9.1% due to low airflow half of the time with all zones calling for cooling, 2. Cooling efficiency degradation of 25.7% due to the recirculation at 50% bypass half the time, 3. Heating efficiency degradation of 1.9% half the time with all zones calling, and 4. Heating efficiency degradation of 6.8% half the time with one zone calling. The measure is designed to ensure at least 350 CFM per ton and no greater than 0.58 watts per CFM in all modes as well as the elimination of the recirculation bypass. The measure eliminates the bypass damper and ducts, and adds more supply ductwork and registers. Cost Savings: 1. Bypass damper $84 2. Bypass duct $10 3. Bypass takeoffs $10 4. Bypass elbows $32 5. Bypass insulation $5 6. Labor $30 7. Total = $171 Cost Increase: 1. Flex duct $10 2. Wyes $45 3. Boots $45 4. Registers $60 5. Labor $65 6. Total = $225 Net Cost Increase: $54 + $130 HERS verification = $185 Figure 2 shows the measure’s energy savings, cost and life-cycle cost (LCC) for each zone. A positive LCC means the measure is cost effective in that zone.

Climate Zone	Energy Savings	Cost	LCC
01	$514	$185	$329
02	$1,356	$185	$1,171
03	$945	$185	$760
04	$1,987	$185	$1,802
05	$379	$185	$194
06	$1,683	$185	$1,498
07	$1,351	$185	$1,166
08	$2,670	$185	$2,485
09	$3,919	$185	$3,734
10	$4,363	$185	$4,178
11	$6,790	$185	$6,605
12	$3,900	$185	$3,715
13	$6,490	$185	$6,305
14	$5,756	$185	$5,571
15	$11,667	$185	$11,482
16	$4,274	$185	$4,089
Statewide	**$3,364**	**$185**	**$3,179**

Figure 2. Life-Cycle Cost

j. Analysis Tools	Analysis tools are not needed since the measure is mandatory and cannot be traded for any other efficiency measures.
k. Relationship to Other Measures	This is a companion measure to making a verified minimum 350 CFM per ton and maximum 0.58 watts per CFM mandatory on all ducted systems proposed through the Residential Ducts CASE report. The proposed return duct design exception to verified airflow and watts per CFM would not apply to dampered multi-zoned systems.

3. Methodology

3.1 Introduction

The primary purpose of zoning ducted air conditioners, heat pumps, and furnaces is to improve comfort. Increased comfort is attained by having the capacity of the HVAC system (cooling or heating delivered) follow the shift in load as it changes across the house. For example, it is common for two-story homes to be too hot on the second floor in both summer and winter. Zoning has the capability of diverting more of the HVAC capacity to the area with the higher load. Another common example is a home with a significant area of west-facing and east-facing windows. In the summer, the east rooms overheat in the morning and the west rooms overheat in the afternoon.

A letter sent to the California Energy Commission on June 6, 2011 by Mr. Glenn Hourahan, Senior Vice President of the Air Conditioning Contractors of America (ACCA), included the following conclusions:

> "Properly designed and installed systems improve comfort.
>
> A properly designed and installed system may or may not save a significant amount of energy, or may increase energy use to some extent."
> (Hourahan 2011)

Providing the most agreeable temperature to all the zones is comfortable, but it carries with it the distinct possibility of increased energy consumption. Since the most common home is single zoned and has only one thermostat placed near the center of the house, temperatures in the rooms distant from that thermostat will vary, sometimes significantly. If zoning is added, the more distant rooms can be conditioned to a more comfortable temperature. This increased conditioning requires more energy.

The National Association of Home Builders (NAHB) report, "Field Investigation of Carrier Residential Zoning System" (Kenney & Barbour 1994) notes that:

> "Studies have demonstrated that a multi-zone system will use more energy than a central thermostat system when a constant setpoint is used. A 35 percent increase was documented (Oppenheim 1991) as a direct result of a multi-zone system being more responsive to the cooling needs of the entire house... While there is an increase in energy consumption, a zone system does provide more uniform temperatures and better thermal comfort throughout the house than that offered by a central thermostat."

The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) Transactions Paper, "Energy Implications of Blower Overrun Strategies for a Zoned Residential Forced Air System" by Oppenheim[1] (1991) states:

[1] This is possibly the Oppenheim 1991 paper referred to in the NAHB report quoted above. However the reference is not clear.

> "Zoning with a no-thermostat setup (Test 2) used more electricity for cooling than the system in a central configuration (Test 1) with no thermostat setpoint scheduling. The reason is that by having temperature control at three points instead of just one, the air-conditioning unit was more responsive to the house load."

This CASE topic was initiated for a number of reasons. The number of dampered multi-zoned systems installed in new California homes is significant. The PIER Efficiency Characteristics and Opportunities for New California Homes (ECO) project found that 12% of the ducted systems were dampered multi-zoned systems (Proctor, Chitwood & Wilcox 2011). Dampered multi-zoned systems use a single air conditioner /furnace to supply conditioned air to various zones of the house by opening and closing dampers in the duct system. They also typically recirculate conditioned supply air back into the return of the air conditioner/furnace, thereby lowering the efficiency of the unit. They deliver reduced heating and cooling to the house when only one zone is operating. When operated with single speed equipment, they deliver the reduced capacity at nearly the same expense of energy, dropping the system efficiency.

The ECO report postulated that by eliminating some of the common practices used in the dampered multi-zoned systems, those systems could be retained as a potential comfort item for customers without excessively increasing energy use.

3.2 Literature Review/Data Collection

3.2.1 Literature Review

The primary literature used to advocate for zoned systems consists of the two research reports on monitoring the NAHB research house (Kenney & Barbour 1994 and Oppenheim 1991). These two reports were supplied by Air-Conditioning, Heating, and Refrigeration Institute (AHRI) for inclusion in this CASE study. ACCA also provided their proposed Zoning manual for the study (Rutkowski 2011). Additional literature reviewed includes Leslie & Kazmer (1989) on a different research house, Levins (1985 and 1989), Temple (2005), and Heflin & Keller (1993). Each of these reports is discussed below.

Figure 3 illustrates the mixed results from these studies. In four of seven heating cases in heating and four of six cooling cases, the energy consumption increased with the zoning configuration.

Study Author(s)	**Energy Use Compared to Not Zoned**		**Notes**
	Heating	**Cooling**	
Kenney & Barbour			
	148% ↑		5°F set up/down in each zone part of the day with basement
	76% ↓	71% ↓	5°F set up/down in each zone part of the day without basement
Oppenheim (from Kenney & Barbour)			
		135% ↑	No temperature set up
Oppenheim/Carrier			
		121% ↑	No temperature set up
		84% ↓	10°F temperature set up in every zone part of the day
Oppenheim/ASHRAE			
	107% ↑		Central with no modulation and 8-hour 12°F setback, zoned with modulating furnace and two additional setback periods on bedroom zones
	88% ↓		Central with no modulation and 8-hour 12°F setback, zoned with modulating furnace and 22 hours of setback on bedroom zones
Leslie & Kazmer			
	112% ↑		With basement conditioned
	99% ↔		No basement, zoning set back 12°F in the bedroom zone for 10 hours a day
Heflin & Keller			
	118% ↑	113% ↑	41% bypass
Temple			
		106% ↑	No bypass, no setback

Figure 3. Energy Consumption Zoned vs. Central System

↑*indicates increase in energy use;* ↓*indicates decrease,* ↔ *indicates no change.*

Kenney & Barbour

This reference was supplied by the AHRI. It discusses a test of the NAHB Laboratory Test House operated with the following characteristics:

- A single speed blower
- An AFUE 91.5 furnace
- A single speed air conditioning condensing unit
- Five zones (two bedroom zones, one first floor living zone, and two basement zones)
- One of the two basement zones was conditioned in this study.
- When operated in the multi-zone mode, the thermostats in the zones were set up 5°F in cooling and down 5°F in heating during “unoccupied periods.” Based on the occupant

heat and moisture simulation data, the "unoccupied periods" appear to be: upstairs zone = 14.5 hours, downstairs bedroom zone = 8 hours, downstairs living zone = 11 hours.

- Air returns are present in every zone.

The test showed 34% increase in heating costs when the zoned system was operated with the basement zone conditioned.

The test showed a 29% reduction in cooling energy consumption with zoning and the temperature setpoint adjustments.

The test showed a problem with recovery time when the zones went from unoccupied to occupied (conditioned vs. temperature floating).

The report states:

> "Zoned systems are known to encourage energy conservation. This has resulted in agencies such as the California Energy Commission to provide performance credits for zoned heating and cooling systems."
>
> "Moreover, zoning can cause higher operating costs if thermostat setup/setback is not used; however, the level of comfort is dramatically increased over the central thermostat."
>
> "Studies have demonstrated that a multi-zone system will use more energy than a central thermostat system when a constant setpoint is used. A 35 percent increase was documented (Oppenheim 1991) as a direct result of a multi-zone system being more responsive to the cooling needs of the entire house... While there is an increase in energy consumption, a zone system does provide more uniform temperatures and better thermal comfort throughout the house than that offered by a central thermostat."
>
> "Zoning can improve thermal comfort, especially in areas that are underheated or ground coupled. However, increased operating cost is required to achieve higher levels of thermal comfort."
>
> "Setback schedules can significantly reduce operating costs, however some degree of thermal discomfort should be expected."
>
> "Only in mild temperatures, outside air greater than 51°F, did the zones recover from the five degree setback. In all other cases, the zones did not recover to 71°F in the allotted two hours."

The cooling savings conclusions of the 1994 study are questionable due to two incongruities in the report. First, there is an unexplained, random distribution of air conditioner efficiency against outdoor temperature for the system operated as a whole house (single zone) system. But in the zoned operation, the study shows a typical air conditioner efficiency pattern against outdoor temperature. The reported efficiency of the unit as a whole house system was substantially lower than when operated as a zoned system in all but the highest temperatures. This is shown in Figure 4 (an overlay of the study's Figures 3.2.2 and 3.2.3).

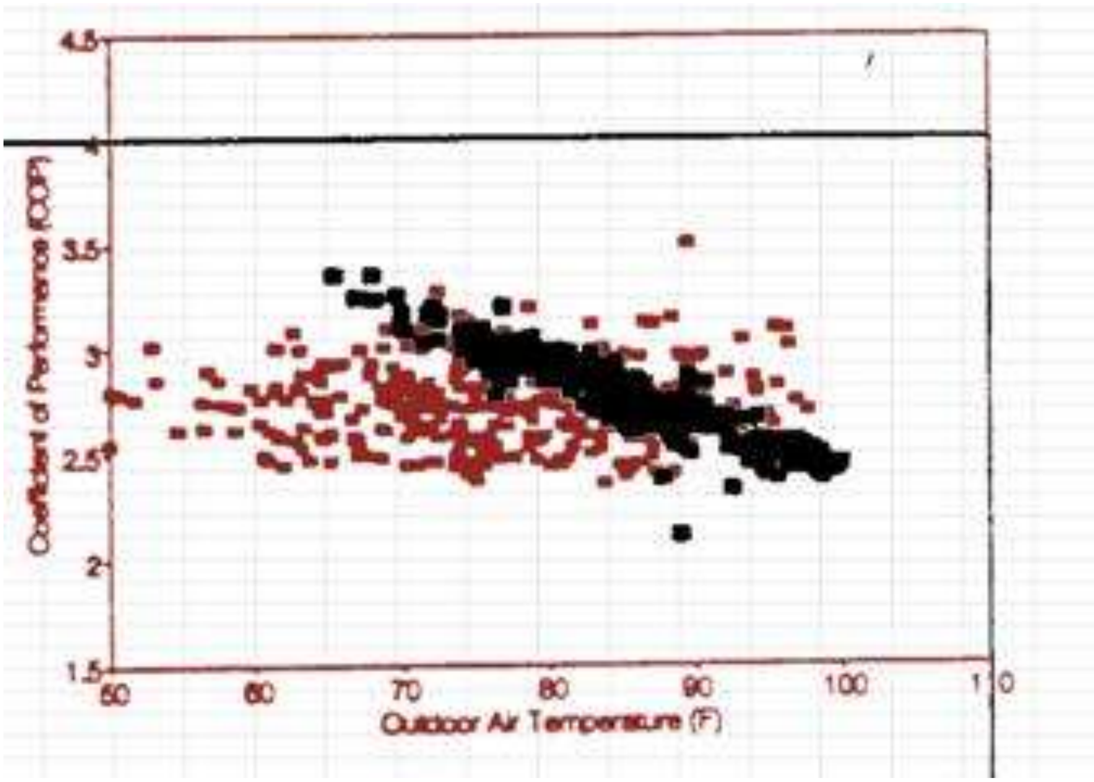

Figure 4. Overlay of AC Efficiency (watts cooling/watts energy consumed) in NAHB study

Whole house single zone operation in red; five zone operation in black

Second, the report states that "both systems experienced approximately the same percentage of hours in each temperature bin." However the graphs in the report show vastly different "Typical Record Year" temperature bins — a statistic that should be identical between the two graphs.

The study reported excess humidity (above 60% Rh) occurring in the zoned configuration twice as often as with the whole house configuration, There were over 400 occurrences in the basement and 130 occurrences in the first-floor bedroom in the multi-zoned configuration compared to 180 and 60 occurrences respectively in the whole house configuration.

Oppenheim

This reference was supplied by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). It discusses a test of the National Association of Homebuilders (NAHB) Laboratory Test House operated with the following characteristics:

- No bypass duct
- A variable speed blower
- A prototype modulating furnace
- A two-speed air conditioner condensing unit
- Three zones for cooling
- The basement was not conditioned.

- The thermostats in the two bedroom zones were set at a consistent 85°F, 15 hours a day every day (this was a set point temperature increase of 10°F for this unoccupied house).
- The first-floor living zone thermostat was set at a consistent 85°F, 9 hours a day every day.
- There is no mention of the presence of returns in the zones. They are assumed to be present since this is the same test house as was used in the Kenney and Barbour study.

The test showed 21% increase in energy consumption when no temperature setpoint adjustments were used.

The test showed a 16% reduction in energy consumption with the temperature setpoint adjustments.

Leslie & Kazmer

This reference discusses a test at a Laboratory Test House in Chicago, Illinois, operated with the following characteristics:

- No bypass duct
- A variable speed blower
- A modulating (variable capacity) 82% AFUE furnace
- A two-speed air conditioner
- Bedroom, common, and basement zones
- When operated in the heating multi-zone mode, the bedroom thermostats were set down 12°F for 10 daytime hours.
- Also when operated in the heating multi-zone mode, the basement thermostat was set down 12°F for 15 nighttime hours.
- Air returns are present in every zone.

The test showed 12% increase in heating energy consumption when the zoned system was operated with the basement zone conditioned.

The test showed a 1% reduction in heating energy consumption with zoning **and the temperature setpoint adjustments**.

The report states:

> "Zoned heating provided superior comfort compared to central heat, especially in the basement. However, the cost of providing this comfort was high."
>
> "A test of zoning without basement heat showed energy savings during cold weather but not during moderate weather."
>
> "Modulating the furnace during central heat reduced energy consumption during moderate weather but not during cold weather."

Levins

These two papers addressed severe zoning wherein the returns and supplies were fully blocked off and towels were placed under the doors. Levins concluded: “Temperatures in closed-off rooms floated with the outdoor temperature variations, but no savings were observed in the overall heat pump electrical usage or in the house cooling load.”

Heflin & Keller

The authors of this paper were the senior engineer and director for split system development at Carrier Corporation. This paper discusses a series of laboratory tests of zoning bypasses on single speed residential air conditioners and heat pumps. The data from the tests are in Appendix B.

Figure 5 shows the loss of efficiency from recirculating air through a bypass. The left hand axis shows the percentage of efficiency relative to no bypass. The bottom axis displays the percentage airflow providing cooling or heating to the conditioned space. When 50% of the air is bypassed, the efficiency falls to 77% of its full value or a 23% loss in efficiency.

This paper did not present data on the reduction in sensible heat ratio as the amount of bypass increases. It is well known, however, that the recirculation bypass ducts reduce the sensible heat ratio and that the sensible energy efficiency ratio (EER) drops faster than the total EER, as plotted in Figure 5.

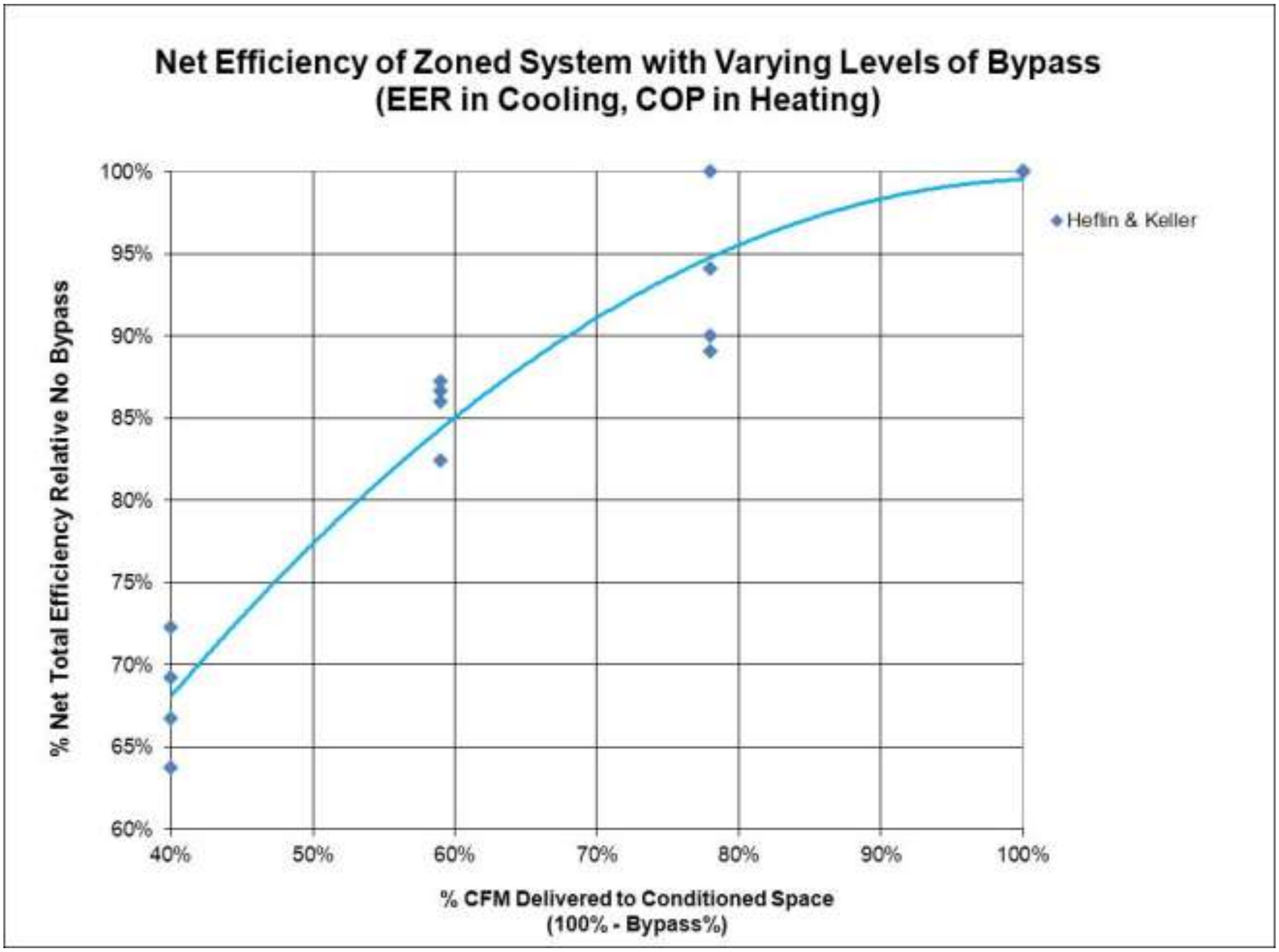

Figure 5. Net Zoned System Efficiency with Bypass (Carrier Lab Data)

This paper states:

> "Capacity and EER drop significantly with increasing air bypass for both the air conditioner and heat pump. The capacity and the EER of the air conditioner decreased 47% and 46% respectively with an increase in bypass from 0% to 79% for DOE A test conditions."

Note that the reduction in capacity produces an almost equal reduction in efficiency. This is because the watt draw of the condensing unit changes very little as the indoor coil gets colder.

Heflin & Keller, commenting on the field studies by Leslie & Kazmer, Levins, and Oppenheim, noted: "None of the studies employed a bypass duct." The report continues, "Moreover, the fact that the homes were unoccupied and zoning separation (closed doors) was maintained throughout testing caused energy losses to be minimized. Thus the documented field studies could be considered a 'best case scenario' in terms of energy savings."

The report states:

"Without setback/setup schedules, zoned systems typically used more energy than the unzoned systems...."

"Most of the savings resulted from setback/setup."

Temple

This reference discusses a test of a new townhouse in Pittsburg, Pennsylvania, which operated with the following characteristics:

- No bypass duct
- A variable speed blower
- A two-speed air conditioner
- Bedroom, common, and basement zones
- Three zones
- Air returns are present in two zones.

The test showed 6% increase in cooling energy consumption when the system was operated with zoned control.

Rutkowski (ACCA Manual Zr)

Air Conditioning Contractors of America is producing a manual titled "Zoned Comfort Systems for Residential Low-Rise Buildings" (Rutkowski 2011). The manual, which is currently in a public review draft, includes an equation (Figure 6) for estimating the supply dry bulb temperature based on the bypass factor and other operating conditions. The equation assumes a sensible heat ratio of 1.0, which is not achieved in the field. The result is an overestimate of the sensible cooling delivered to the house.

While the equation produces an overly optimistic view of the sensible capacity of an air conditioner operating with a bypass, plotting the results of that equation shows that the reduction in efficiency from a bypass is approximately 31% for a 50% bypass. Figure 7 shows the numbers from that calculation for a 3 ton unit with 1050 CFM through the unit and varying levels of bypass. The results are plotted in Figure 8 and compared to the field data for unit #2.

$$LDB\ (^\circ F) = (-17.0 \times BPF^2 - 10.5 \times BPF + 52.3) + 0.19 \times (OAT - 95) + 0.6^*(EDB_O - 75) + 0.57 \times (28.5 - B/C)$$

Where:
Cooling coil sensible heat ratio = 1.0
LDB = Settled dry-bulb temperature of leaving air
BPF = Bypass factor under investigation
OAT = Outdoor air dry-bulb temperature
EDB_O = Entering dry-bulb temperature, just before the bypass damper opens
B/C = Btuh per blower Cfm for the AHRI rating condition (total Btuh for a specified blower Cfm at 95° F OAT; 80° F EDB and 67° F EWB)

Accuracy

Figure 7-2 and the settled air temperature equation are for a specific piece of 2010 air-cooled equipment. The

Figure 6. ACCA Manual Equation

% CFM to Residence	100%	90%	80%	70%	60%	50%
BPF	0	0.1	0.2	0.3	0.4	0.5
OAT (°F)	95	95	95	95	95	95
EDB (°F)	75	75	75	75	75	75
B/C	32	32	32	32	32	32
LDB (°F)	50.3	49.1	47.5	45.6	43.4	40.8
Temperature Split (°F)	24.7	25.9	27.5	29.4	31.6	34.2
CFM	1050	945	840	735	630	525
CapS (BTUh)	28,004	26,449	24,925	23,318	21,511	19,389
Relative Sensible Capacity	100%	94%	89%	83%	77%	69%

Figure 7. Inputs and Results from ACCA Equation

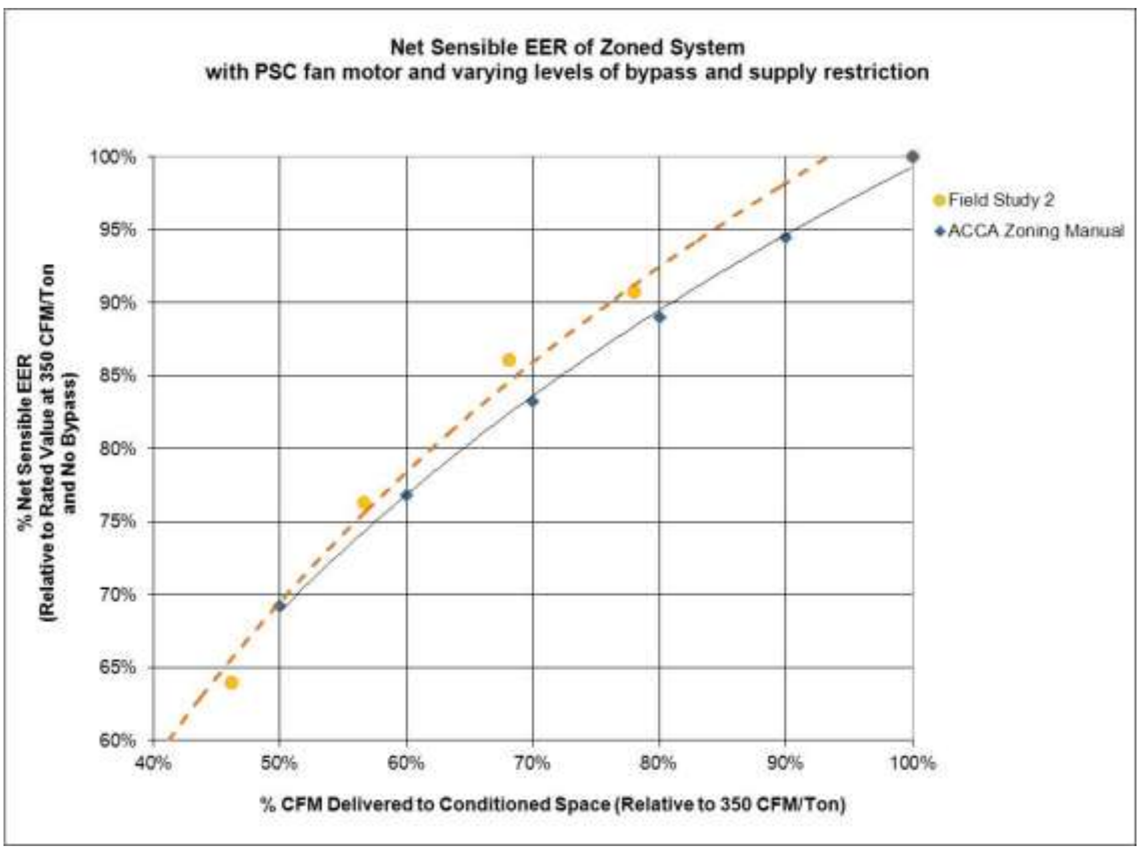

Figure 8. ACCA Manual Z Equation Approximates Field Unit 2

Literature Review Summary

The Heflin and Keller paper illustrates the severe penalty associated with bypass ducts.

From the literature review, it is also clear that **even without a bypass duct or a dump zone** and even with modulating furnaces or air conditioners, the savings from zoned systems are far from certain. In many studied cases the energy consumption increases with the use of the zoned systems.

3.2.2 Field Measured Performance of Zoned AC Systems

Rick Chitwood measured HVAC characteristics of 80 new California homes for the Efficiency Characteristics and Opportunities for New California Homes (ECO) project (Proctor, Chitwood & Wilcox 2011). That randomized survey included 10 dampered multi-zoned systems. Nine of the systems were two-zone systems and one was a three-zone system.

As displayed in Figure 9 and Figure 10, the ECO project found that the multi-zoned systems had significantly lower airflow and higher watt draws than single zoned systems. The differences were always significant at the .05 level. The result of the low airflow and high fan watts is reduced capacity and efficiency (both sensible and total).

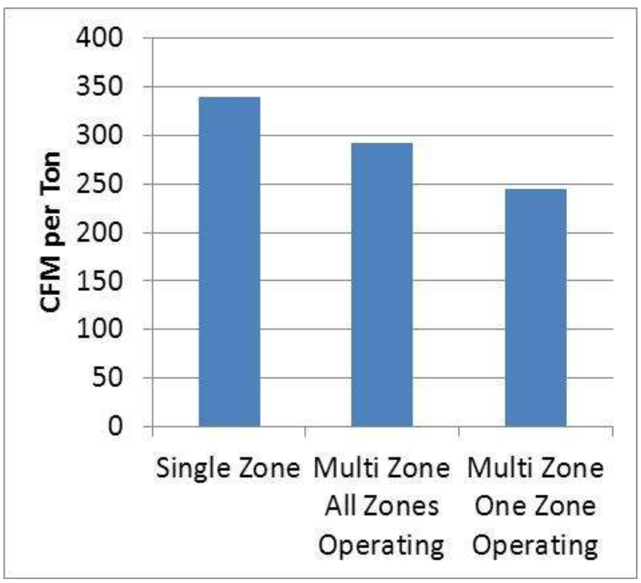

Figure 9. Airflow Reduction with Multi-Zoned HVAC Systems

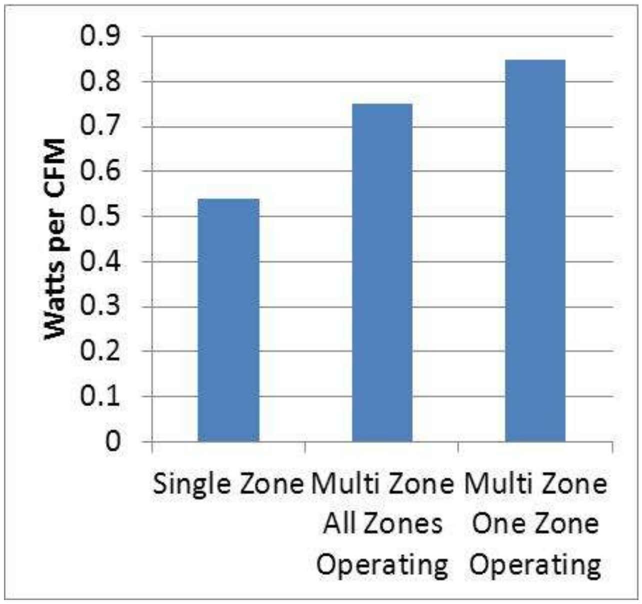

Figure 10. Normalized Fan Watt Draw Increase with Multi-Zoned HVAC Systems

Three of the zoned systems were studied intensively to confirm the energy savings potential. The details of this follow-up investigation are in Section 4.3.1.

3.3 Measure Cost Analysis

As explained in Section 4, this measure proposes to eliminate the bypass and, as one option, add additional supply ducts and registers to consistently deliver full capacity to the home while concentrating that capacity largely in the zone needing cooling or heating.

Figure 11 shows the net cost of removing the bypass and increasing the number of supply ducts and registers; costs are based on purchasing a low volume of materials and are derived from HVAC contractors' estimates of labor savings and labor increases for a 2700 ft^2 zoned production home. The costs for HERS verification and builder markup are added to arrive at the cost to the home buyer per square foot of conditioned floor area

Item	Cost
Net labor	$35
Net materials	$19
Subcontractor overhead and profit	$54
Total subcontractor invoice to builder	$108
HERS verification	$130
Total cost to builder	$238
Builder markup 30%	$71
Total cost to home buyer	$309
Cost to home buyer per square foot of conditioned floor area	$0.11

Figure 11. Net Cost of Bypass Elimination and Additional Supplies

We estimated the Time Dependent Valuation (TDV) energy savings of this measure for each climate zone by using simulations of the 2,700 ft^2 Prototype D, run with the 2013 Residential Standards Development Software. This simulation model used an initial SEER and EER degraded by 17%, and then compared it to the minimum allowable SEER and complementary EER. This simulation model also used an initial AFUE degraded by 4.4% and compared it to the minimum allowable AFUE. Efficiency degradations are derived in Section 4 of this report.

For these runs we assumed the home complied with all of the other provisions of the 2008 prescriptive standards except HVAC airflow and fan watt draw.

3.4 Cost-effectiveness Analysis

Life-cycle costs were calculated using the approach specified in the Life-Cycle Cost Methodology prepared for the 2013 California Building Energy Efficiency Standards (Architectural Energy Corporation 2011).

3.5 Stakeholder Interaction and Feedback

This work was publicly vetted through our stakeholder outreach process. This involved obtaining feedback on the direction of the proposed changes through in-person meetings, webinars, email correspondence and phone calls.

All of the main approaches, assumptions and methods of analysis used to develop this measure have been presented for review at public stakeholder meetings. At each meeting, the utilities' CASE team invited feedback on the proposed language and analysis thus far, and sent out a summary of what was discussed at the meeting.

A record of the stakeholder meeting presentations, summaries and other supporting documents can be found at www.h-m-g.com/T24/Res_Topics/Residential_Topics.htm. Stakeholder meetings were held on the following dates and locations:

- April 14, 2010, San Ramon Conference Center, San Ramon, CA
- April 12, 2011, Buehler Alumni and Visitors Center, UC Davis, CA
- June 14, 2011, Stakeholder meeting with Honeywell, 418 Mission Ave., San Rafael, CA
-

4. Analysis and Results

There are two primary methods by which the common multi-zoned dampered system lowers the capacity and efficiency of an air conditioner. These are:

- Lower airflow due to the additional restriction of zoning dampers, and
- Recirculation through the air conditioner due to the use of a bypass duct.

Both of these items lower the evaporator coil temperature, which lowers the capacity and efficiency of the unit.

In Sections 4.1 through 4.3 below, these items are examined individually with respect to their effect on system efficiency.

Section 4.4 summarizes the savings from eliminating the bypass and obtaining airflow in excess of 350 CFM per ton.

4.1 The Effect of Lowered Evaporator Coil Temperature

The reverse Carnot cycle establishes a theoretical Coefficient of Performance[2] (COP_C) of a vapor compression air conditioner. That Coefficient of Performance is stated as:

COP_C = Tevap / (Tcond – Tevap)

Where

Tevap is the evaporator (inside coil) temperature and

Tcond is the condenser (outside coil) temperature

The Carnot cycle is a clearly unattainable ideal, but it make two things perfectly clear:

1. Higher condenser temperatures reduce the efficiency of the air conditioner.
2. Lower evaporator temperatures reduce the efficiency of the air conditioner.

Figure 12 graphs the COP_C of a unit with a condenser temperature of 95°F and varying evaporator temperatures.

[2] EER = COP * 3.414

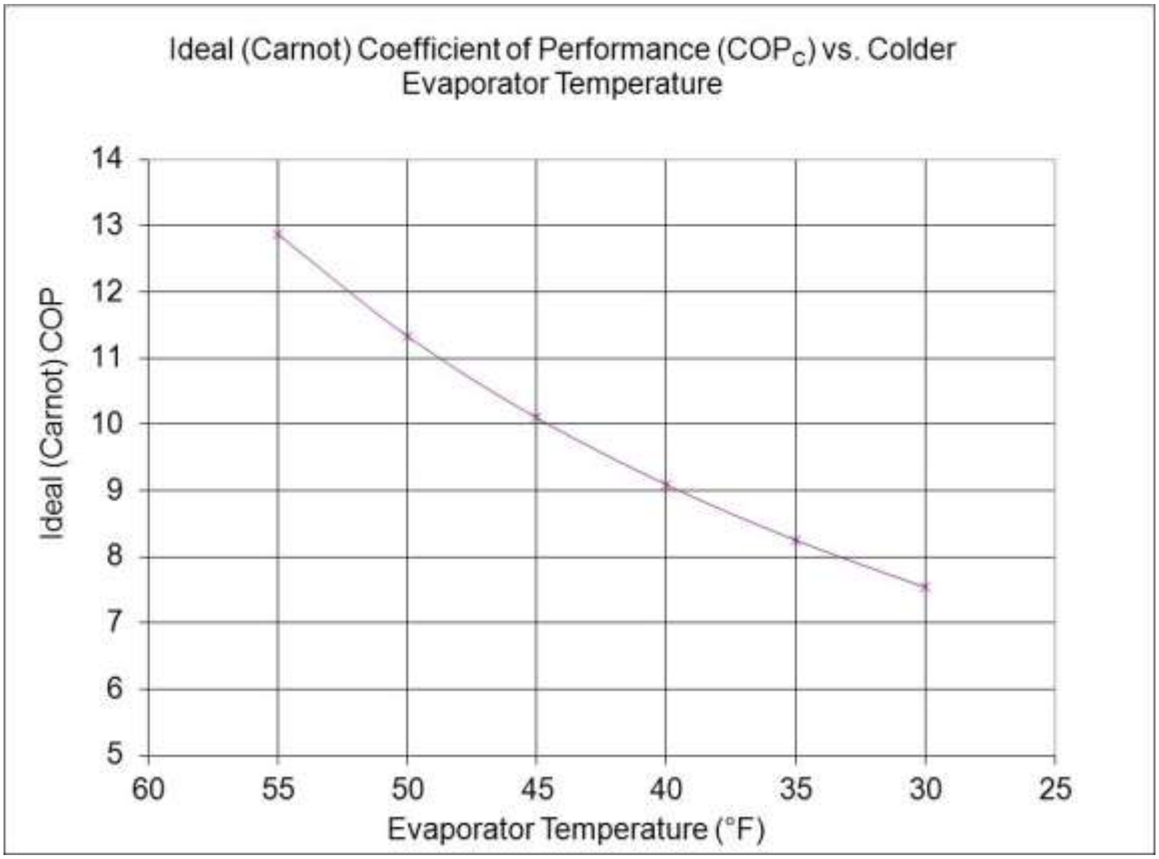

Figure 12. Air Conditioner Efficiency Falls with a Colder Evaporator Coil

Low evaporator coil temperatures are produced when the airflow is low and when cold air is introduced into the return plenum.[3]

4.2 Low Airflow and Its Impact

Airflow in the ducted systems tested in the 80-home ECO report was lower than recommended for dry climates such as California. This problem was identified prior to the 2008 Title 24 Standard. In an attempt to deal with this problem, the 2008 Title 24 Standard prescribes a minimum 350 CFM per ton and a maximum 0.58 watts per CFM as the basis for a new home energy budget.

Figure 13 reports the field data in the ECO report. Almost two-thirds of the Whole House Single Zone Ducted systems did not meet those criteria. One hundred percent of the Multi-Zone Ducted systems did not meet those criteria <u>even with all the zone dampers open.</u>

[3] For additional information on the vapor compression cycle, see the online paper, "Design of Vapor-Compression Refrigeration Cycles" (Northwestern University, no date).

Parameter	Whole House Single Zone Meeting Criteria	Whole House Single Zone Not Meeting Criteria	Multi-Zone All Zones Operating	Multi-Zone One Zone Operating
Fan Watts (Mean)	569	572	829	783
Problem Units (Percent with W/CFM >0.58 or CFM/ton < 350)	0%	63%	100%	100%
Fan Watts per CFM (Mean of Problem Units)	0.48	0.57	0.75	0.85
CFM per Ton (Mean if CFM/ton < 350)	407	309	292	244

Figure 13. Single Zone vs. Multi-Zone Airflow and Watt Draw

Laboratory tests at Purdue University (Shen, Braun & Groll 2004) show the efficiency effect of low airflows outside the range normally published in the manufacturers' extended data tables. As displayed in Figure 14, these tests show that the efficiency is reduced to 75% of its full value when the airflow is reduced to 50% of its baseline value.

The data for this graph are in Section 7.1 – Appendix A.

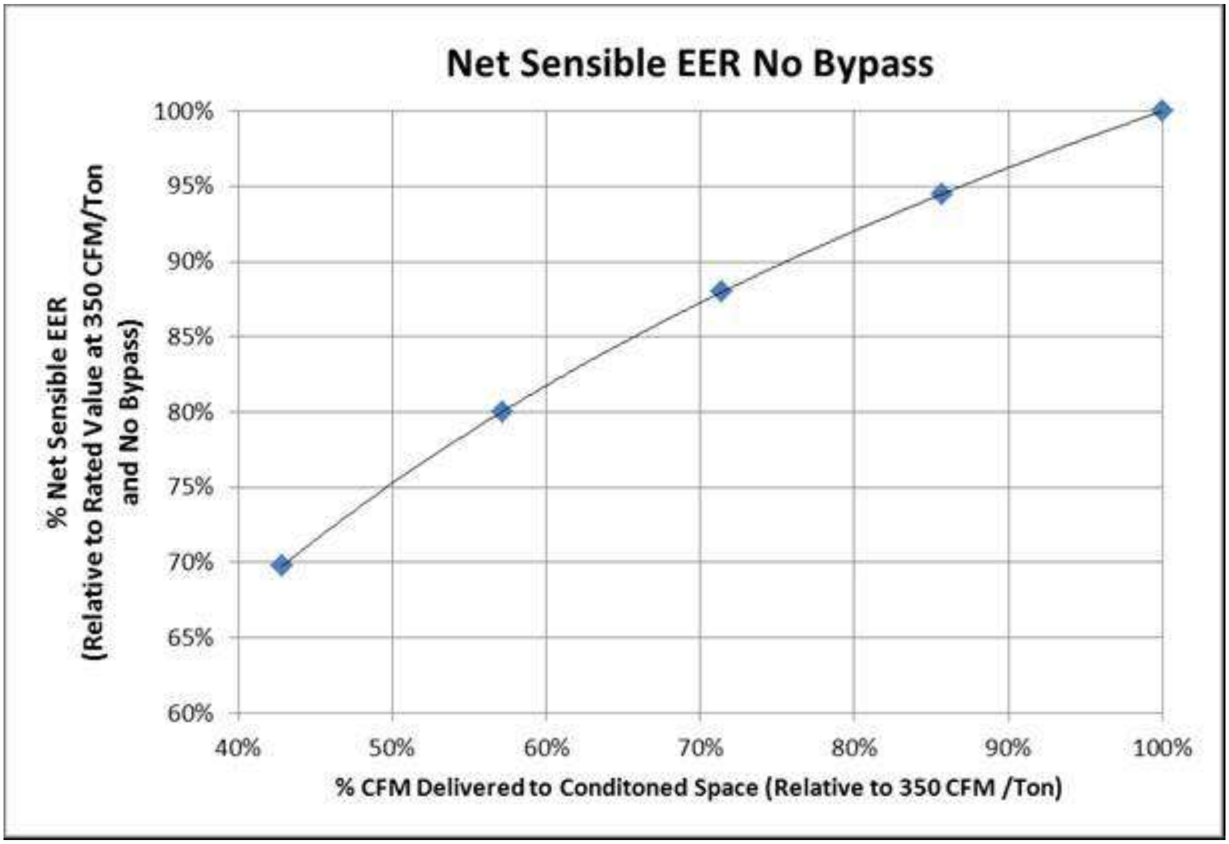

Figure 14. Normalized Sensible EER vs. Supply CFM (laboratory test data)

It is nearly universally accepted that the evaporator airflow for dry climates like California's should exceed 350 CFM per ton. The comments of stakeholders on this matter are quoted in Section 4.2.1.

4.2.1 Stakeholder Comments Concerning 350 CFM per Ton Minimum Airflow

Mr. Hourahan of ACCA discussed the 350 CFM per ton minimum airflow:

> "In fact, this is poor practice for most of the country. This is near the lower limit of some OEM equipment, and may be below the low limit for some equipment."
> (Hourahan 2011)

Mr. Hourahan also concludes:

> "System merit should be based on correct design and installation.
>
> Code should require correct design and installation."
> (ibid)

Mr. Aniruddh Roy of the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) wrote a letter discussing some of AHRI's thoughts on zoning. The letter succinctly points out that proper airflow is essential to all systems, particularly zoned systems:

> "When you include zoning on a poorly designed duct system, the poor performance is multiplied."
>
> "Supply airflow must be maintained..."

"We are sure you will agree that there are many poorly designed and installed duct systems in California."
(Roy 2011)

4.2.2 Impact of Low Evaporator Airflow

The impact of low evaporator airflow and the savings attributable to improving the airflow are fully developed in Section 7.3 – Appendix C.

In summary:

- The percentage air conditioning savings for improving multi-zoned units with all dampers open from an average 292 CFM per ton to an average 371 CFM per ton is 9.1%
- The percentage gas heating savings for improving airflow through the furnace heat exchanger is 1.9%.

4.3 The Bypass

The second problem found with California multi-zone dampered system is the bypass duct. Figure 15 shows the most common California multi-zone dampered HVAC configuration. A single speed air conditioner and furnace supply two zones through dampers. There is a bypass between the supply plenum and the return plenum. The bypass flow is controlled by a bypass damper.

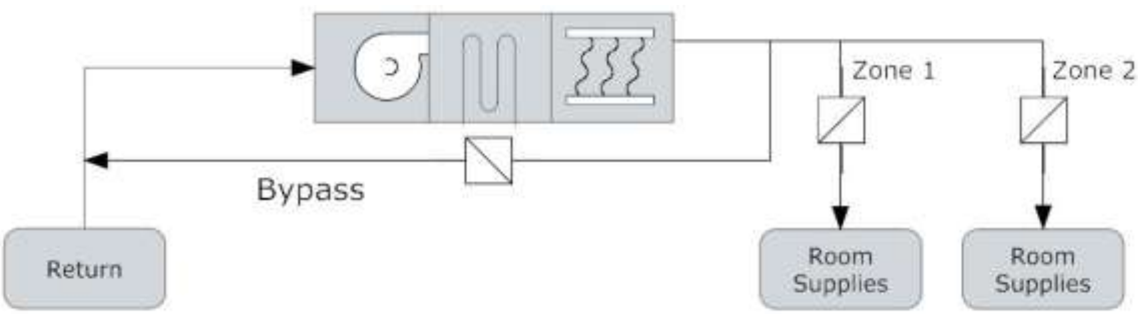

Figure 15. Typical California Zoned HVAC System

Zoned systems throttle the flow to the inoperative zone to reduce the cooling delivered to that zone. The throttling increases the static pressure in the supply plenum and if no other adjustments were made, the air velocity and noise would increase in the operating zone.

In order to avoid the noise, the contractors install a bypass with a damper that opens to relieve the static pressure and maintain nearly the same flow to the operative zone. Bypasses mitigate the increased velocity and noise at the zone calling for heat or cooling.

A "perfect" bypass would bypass all the "excess" air back into the return plenum of the air conditioner/furnace, thereby lowering the evaporator coil temperature in cooling and raising the furnace inlet temperature in heating. This reduces the capacity and efficiency of the air conditioner and furnace.

Mr. Hourahan of ACCA notes that bypass ducts cause a lower cooling coil temperature (Hourahan 2011).

This reduced cooling coil temperature is the major fundamental flaw with bypass ducts. The lower evaporator temperature lowers the total and sensible capacity of the air conditioner.

4.3.1 The Bypass Problem

Figure 16 illustrates the bypass problem by showing an extreme situation.

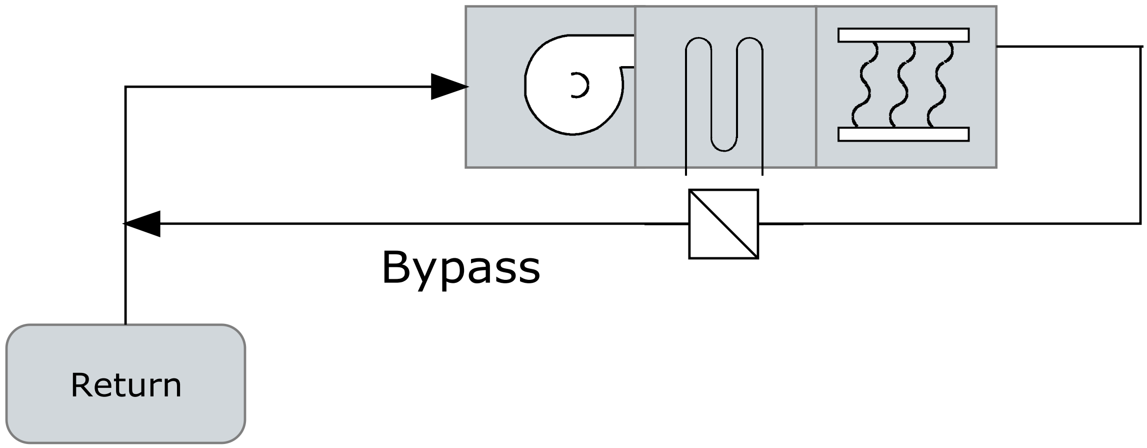

Figure 16. Clarifying the Bypass Problem

In this situation, the return temperature in cooling would fall until the return temperature and the supply temperature were the same and there was no heat transfer across the evaporator coil. As we approach this situation, the watt draw of the compressor, condenser fan, and evaporator fan change very little. The result is an ever-decreasing efficiency.

In heating the same phenomenon applies; the return temperature would rise until the supply temperature and the return temperature were the same and no heat exchange would occur, but the amount of gas burned would remain the same.

In both of these cases, the units normally have safety devices to avoid this extreme situation. Nevertheless, the problem is still with us with any bypass.

4.3.2 The Bypass in the Field Tests

In reality no contractor would build the system illustrated in Figure 16. However, putting the units in the field through varying levels of bypass revealed that some systems come remarkably close to this situation.

In every case the capacity reductions are significant, as shown in Figure 17**Error! Reference source not found.**. The field experiments showed a return plenum temperature reduction in the median case (Field 2) of 11.5°F and a capacity reduction of 25% with a 31% bypass

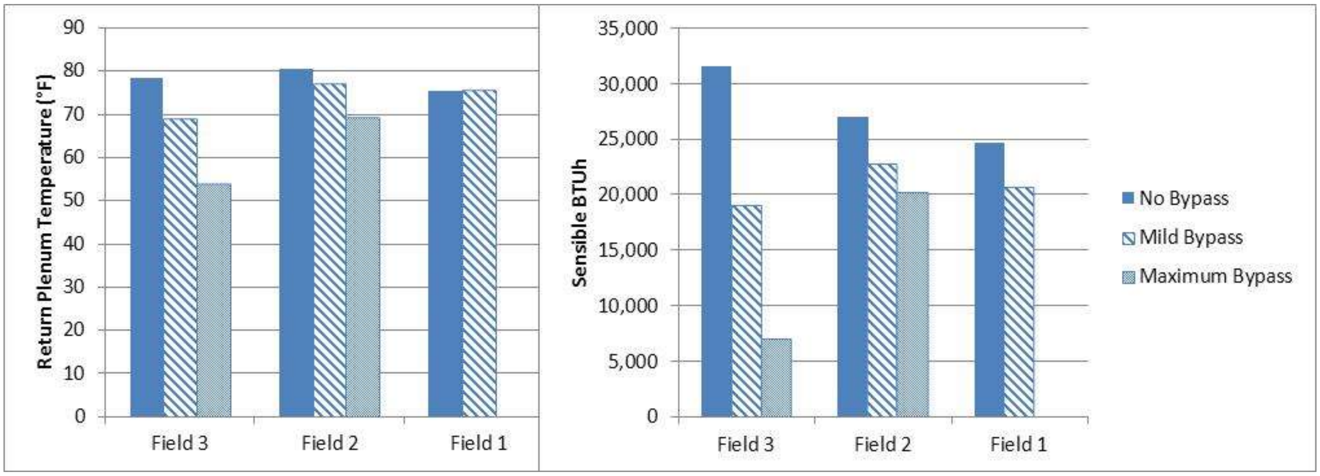

Figure 17. Three Field Units
Operated with Varying Bypass in One Zone Operation
("No Bypass" is all zones open and a closed bypass)

4.3.3 Alternatives to the Bypass

The ACCA Zoning Manual Zr (Rutkowski 2011) lists six strategies as alternatives to the bypass. The elimination of the bypass leaves a number of other options to control airflow including damper stop relief, selective throttling, and most importantly variable airflow/variable capacity air conditioners.

The Oppenheim ASHRAE paper (Oppenheim 1991) is based on an experiment that used physical isolation between zones. The paper notes that any improvement in efficiency is dependent on modulating airflow (a variable speed blower) and modulating refrigerant flow (a variable or multi-speed compressor):

> "Modulating airflow over the indoor cooling coil requires control of the refrigerant flow rate. By effectively controlling both airflow over the evaporator coil and the refrigerant flow, an air conditioner can operate efficiently over a wide range."

Capacity Diversion

One alternative to the bypass is diverting the capacity from one zone to another when the later zone has a higher load. This can be easily accomplished with a design similar to that shown schematically in Figure 18. The design of this type of system would only require minor revisions to the duct design process in ACCA Manual D (Rutkowski 1995). The design process would treat the return system, the dampered supply runs and the undampered supply runs with separate available static pressures.

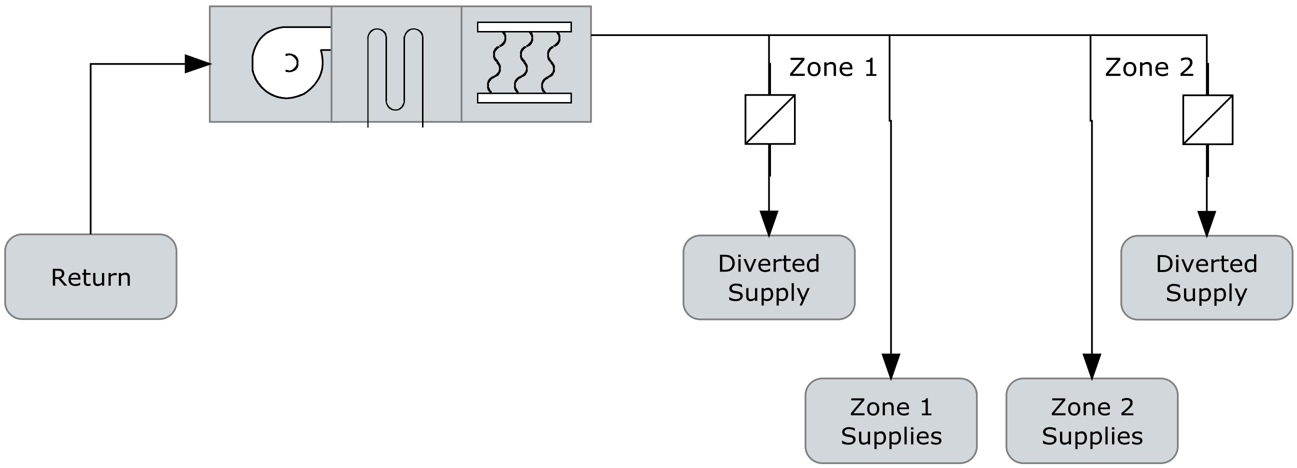

Figure 18. A Two-Zone System with Capacity Diversion

4.4 Savings from Eliminating the Bypass and Obtaining at Least 350 CFM per Ton

The intensive study of three zoned systems in this project combined with the existing literature provide sufficient information on the combined savings from eliminating the bypass and ensuring at least 350 CFM per ton delivered to the home.

There are two cases: the system with all zones operating and the system with one zone operating.

For the first case, the savings are due to the difference in efficiency between the average airflow of the zoned systems (all zones calling) and the efficiency at the new average efficiency when at least 350 CFM per ton is attained. The calculations are in Section 7.3 – Appendix C. The savings are based on the laboratory data in Figure 14.

In the second case, the savings are derived from an average of the median field tested unit as confirmed by the Carrier paper on bypasses (Kenney & Barbour 1994) and a conservative model based on the manufacturers' extended data tables. The calculations are in Section 7.4 – Appendix D.

While the three field tests are not sufficient to estimate the effect of the bypass, there are additional data that make this estimation possible. Specifically, these data are obtained from modeling from the manufacturers' extended data tables, independent laboratory tests at Purdue, laboratory tests at Carrier Corporation, and models promulgated by the Air Conditioning Contractors of America.

Figure 19 displays the measured data from the three field units.

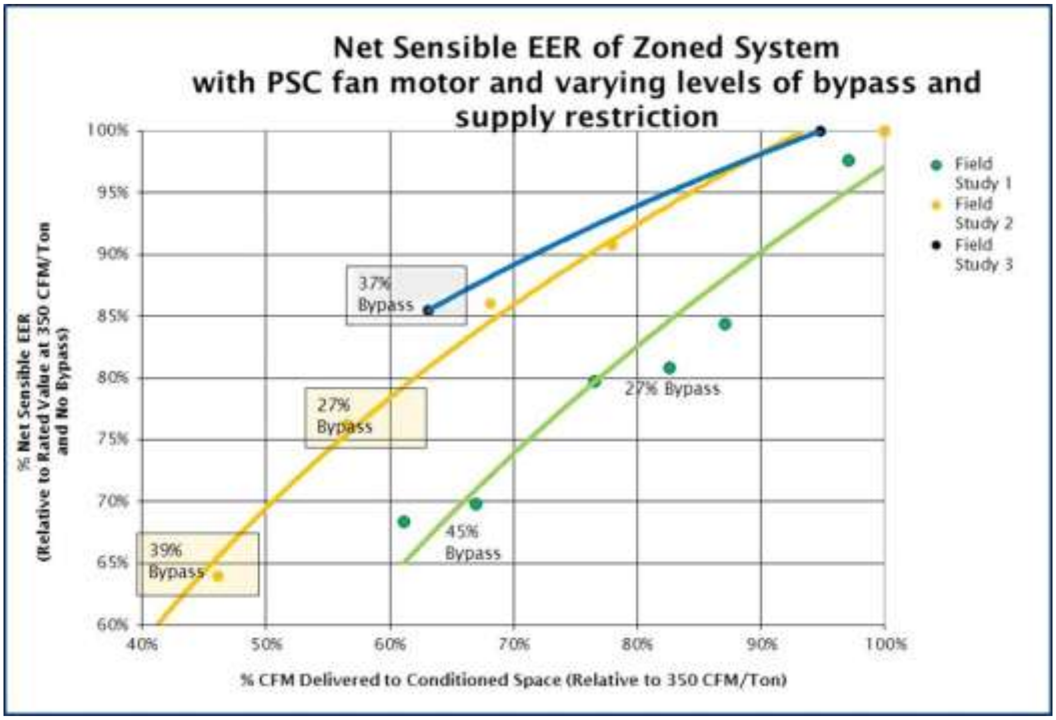

Figure 19. Field Test — Net Sensible EER with Varying Bypass Flows and Zoning

5. Recommended Language for the Standards Document, ACM Manuals, and the Reference Appendices

SUBCHAPTER 7

LOW-RISE RESIDENTIAL BUILDINGS – MANDATORY FEATURES AND DEVICES

SECTION 150 – MANDATORY FEATURES AND DEVICES

Any new construction in a low-rise residential building shall meet the requirements of this Section.

(m) **Air-distribution System Ducts, Plenums, and Fans.**

Add:

11. HVAC System Bypass Duct. Bypass ducts that deliver supply air to the return system shall not be used.

12. Zonally Controlled Central Forced Air System. Central forced air systems shall simultaneously demonstrate, in every zonal control mode, an airflow from the residence, through the circulation blower and delivered to the house greater than 350 CFM per ton of nominal cooling capacity and a blower Watt draw of less than 0.58 W/CFM as specified in Reference Residential Appendix RA3.

SUBCHAPTER 9

LOW-RISE RESIDENTIAL BUILDINGS—ADDITIONS AND ALTERATIONS IN EXISTING LOW-RISE RESIDENTIAL BUILDINGS

SECTION 152 – ENERGY EFFICIENCY STANDARDS FOR ADDITIONS AND ALTERATIONS IN EXISTING BUILDINGS THAT WILL BE LOW-RISE RESIDENTIAL OCCUPANCIES

Add:

(b) **Alterations**. Alterations to existing residential buildings or alterations in conjunction with a change in building occupancy
to a low-rise residential occupancy shall meet Section 150 (m) 11 and 12 as well as either Item 1 or 2 below

Residential Compliance Manual

~~4.5.2 Zonal Control~~
~~An energy compliance credit is provided for zoned heating and air-conditioning systems, which save energy by providing selective conditioning for only the occupied areas of a house. A house having at least two zones (living and sleeping) may qualify for this compliance credit. The equipment may consist of one air-conditioning system for the living areas and another system for sleeping areas or a single system with zoning capabilities, set to turn off the sleeping areas in the daytime and the living area unit at night (see Figure 4-19).~~

~~There are unique eligibility and installation requirements for zonal control to qualify under the Standards. The following steps must be taken for the building to show compliance with the Standards under this exceptional method:~~

~~1. **Temperature Sensors**. Each thermal zone, including a living zone and a sleeping zone, must have individual air temperature sensors that provide accurate temperature readings of the typical condition in that zone.~~
~~2. **Habitable Rooms**. Each habitable room in each zone must have a source of space heating and/or cooling (if zonal credit for cooling is desired) such as forced air supply registers or individual conditioning units. Bathrooms, laundry, halls and/or dressing rooms are not habitable rooms.~~
~~3. **Non-closeable Openings**. The total non-closeable opening area (W) between adjacent living and sleeping thermal zones (i.e., halls, stairwells, and other openings) must be less than or equal to 40 ft².~~
~~All remaining zonal boundary areas must be separated by permanent floor-to-ceiling walls and/or fully solid, operable doors capable of restricting free air movement when in the closed position.~~

~~4. **Thermostats**. Each zone must be controlled by a central automatic dual setback thermostat that can control the conditioning equipment and maintain preset temperatures for varying time periods in each zone independent of the other.~~
~~Other requirements specific to forced air ducted systems include the following:~~

~~1. Each zone must be served by a return air register located entirely within the zone. Return air dampers are not required.~~
~~2. Supply air dampers must be manufactured and installed so that when they are closed, there is no measurable airflow at the registers.~~
~~3. The system must be designed to operate within the equipment manufacturer's specifications.~~
~~4. Air is to positively flow into, through, and out of a zone only when the zone is being conditioned. No measurable amount of supply air is to be discharged into unconditioned or unoccupied space in order to maintain proper airflow in the system.~~
~~Although multiple thermally distinct living and/or sleeping zones may exist in a residence, the correct way to model zonal control for credit requires only two zones: one living zone and one sleeping zone. All separate living zone components must be modeled as one single living zone:the same must be done for sleeping zones.~~

Figure 4-19– Zonal Control Example

6. Bibliography and Other Research

Architectural Energy Corporation. January 14, 2011. "Life-Cycle Cost Methodology" prepared for the 2013 California Building Energy Efficiency Standards. Online document retrieved June 28, 2011 from: www.energy.ca.gov/title24/2013standards/prerulemaking/documents/general_cec_documents/2011-01-14_LCC_Methodology_2013.pdf

Hourahan, G. June 6, 2011. Letter to Ron Yasney, Contract Manager, California Energy Commission.

Mr. Hourahan is the Senior Vice President – Technical for the Air Conditioning Contractors of America. ACCA is a national trade association representing professional HVAC contracting businesses. This letter discussed multi-zoned systems with the purpose of dissuading the Commission from adopting the proposed changes. The conclusion of his five-page letter included the following statements, which succinctly point out the need for the changes in this proposal:

- Properly designed and installed systems improve comfort.
- A properly designed and installed system may or may not save a significant amount of energy, or may increase energy use to some extent.
- System merit should be based on correct design and installation.
- Code should require correct design and installation

Heflin, C. & F. Keller. 1993. "Steady-State Analysis of Single-Speed Residential Split Systems with Zoning Bypass." *ASHRAE Transactions*, Vol. 99, Part 2, Paper number 3693, Pages 40-51. American Society of Heating Refrigeration and Air-Conditioning Engineers. Atlanta GA.

Kenney, T. & C. Barbour. August 31, 1994. "Field Investigation of Carrier Residential Zoning System." Final Report prepared for Carrier Corporation by NAHB Research Center, Inc. Upper Marlboro, MD.

This reference was supplied by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). It discusses a test of the National Association of Homebuilders (NAHB) Laboratory Test House, as discussed in Section 3.2.1 of this report.

Leslie, N., & K. Kazmer. 1989. "Performance of a Residential Zoned Heating System in an Unoccupied Research House." *ASHRAE Transactions*, Vol. 95, Part 1, Pages 903-909. American Society of Heating Refrigeration and Air-Conditioning Engineers. Atlanta, GA.

Levins, W. December 1985. "Experimental Measurements of Heating Season Energy Savings from Various Retrofit Techniques on Three Unoccupied Houses." *Proceedings of the ASHRAE/DOE/BTECC/CIBSE Conference-Thermal Performance of the Exterior Envelopes of Buildings III*. From Heflin and Keller.

Levins, W. December 1989. "Measured Performance of Zoning in Single-Family Houses." *Proceedings of the ASHRAE/DOE/BTECC/CIBSE Conference*. Orlando, FL. From Heflin and Keller.

Lindeburg, M. 1990. *Mechanical Engineering Reference Manual*. Eighth Edition. Equation 10.66, Page 10-14. Professional Publications Inc. Belmont, CA.

Northwestern University. No Date. “Design of Vapor-Compression Refrigeration Cycles.” Online document retrieved June 28, 2011 from: www.qrg.northwestern.edu/thermo/design-library/refrig/refrig.html

This reference discusses the vapor compression cycle including the Carnot cycle, the effect of the temperature of the heat source/evaporator, the effect of the temperature of the heat sink/condenser, and other topics.

Oppenheim, P. 1991. “Energy Implications of Blower Overrun Strategies for a Zoned Residential Forced Air System.” *ASHRAE Transactions,* Vol. 97, Part 2, Pages 354-362. American Society of Heating Refrigeration and Air-Conditioning Engineers. Atlanta, GA.

This reference was supplied by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). It discusses a test of the National Association of Homebuilders (NAHB) Laboratory Test House, as discussed in Section 3.2.1 of this report.

Oppenheim, P. 1992. “Energy-Saving Potential of a Zoned Forced-Air Heating System.” *ASHRAE Transactions,* Vol. 98, Part 1, Pages 1247-1257. American Society of Heating Refrigeration and Air-Conditioning Engineers. Atlanta, GA.

Proctor, J., R. Chitwood, & B. Wilcox. 2011. “Efficiency Characteristics and Opportunities for New California Homes (ECO).” Prepared for California Energy Commission. Publication pending. Report on Contract Number: PIR-08-019.

This reference is the source for the data on the performance of 10 random multi-zoned systems with dampered zones.

Roy, A. May 17, 2011. Letter to Mr. Bruce Wilcox.

Mr. Aniruddh Roy is the Regulatory Engineer with the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). AHRI is the trade association representing manufacturers of heating, cooling, water heating, and commercial refrigeration equipment. This letter discussed multi-zoned systems with the purpose of dissuading the Commission from adopting the proposed changes. In his letter he noted that:

- The AHRI Zoning Members stress the importance of maintaining adequate airflow (CFM) through the A/C Unit at all times.
- When you include zoning on a poorly designed duct system, the poor performance is multiplied.
- Supply airflow must be maintained....
- We are sure you will agree that there are many poorly designed and installed duct systems in California.

Rutkowski, H. 1995. *Residential Duct Systems Manual D.* Air Conditioning Contractors of America. Washington, D.C.

Rutkowski, H. 2011. Unpublished draft of *ACCA Manual Zr: Zoned Comfort Systems for Residential Low-Rise Buildings.* Air Conditioning Contractors of America. Washington, D.C.

Shen, B., J. Braun, & E. Groll. 2004. "Other Steady-state Tests for ASHRAE Project" in Steady-state Tests1, Section Title: Series V: Change indoor airflow rate under wet condition. Ray W. Herrick Laboratories, The School of Mechanical Engineering, Purdue University. West Lafayette, IN.

This reference is reproduced in Appendix A.

Sun Power Association. 1990. "Short Term Evaluation of Savings Due to Furnace Components." Sun Power Association. Wheat Ridge, CO.

Temple, K. 2005. "Field Performance of a Zoned Forced-Air Cooling System in an Energy-Efficient Home." *ASHRAE Transactions,* Vol. 111, Part 2, Paper DE-05-4-1. American Society of Heating, Refrigeration, and Air-Conditioning Engineers. Atlanta, GA.

Modera, Mark. Telephone and email communications, 2010 and 2011, Professor, Civil and Environmental Engineering, Sempra Energy Chair in Energy Efficiency, Director, Western Cooling Efficiency Center. University of California, Davis.

7. Appendices

7.1 Appendix A: "Series V: Change indoor airflow rate under wet condition" (95°F outdoor dry bulb /80°F indoor dry bulb /67°F indoor wet bulb)

(Shen, Braun & Groll 2004)

System	**Indoor Airflow Rate [CFM]**							
Measurements	1202	1114	1015	925	795	698	607	518
$T_{evap,air,in,drybulb}$ [˚F]	82.30	80.33	80.22	79.68	80.76	80.14	79.85	79.57
$T_{evap,air,out,drybulb}$ [˚F]	60.83	59.21	58.19	56.88	55.45	53.53	51.88	49.51
$T_{evap,air,in,dew}$ [˚F]	61.22	61.22	61.00	60.82	60.86	60.42	60.17	59.97
$T_{evap,air,out,dew}$ [˚F]	56.35	54.44	53.15	52.30	50.49	48.42	46.87	44.52
$T_{cond,air,in,drybulb}$ [˚F]	96.66	96.63	96.55	96.54	96.84	96.63	96.53	96.50
$T_{cond,air,out,drybulb}$ [˚F]	114.31	113.90	113.47	113.19	113.28	111.98	111.09	109.98
m_{ref} [g/s]	67.58	65.66	64.09	62.48	61.01	56.63	51.53	46.90
$Power_{comp}$ [kW]	3.01	2.99	2.97	2.94	2.92	2.86	2.77	2.68
$Power_{fan}$ [kW]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
$Q_{cooling,ref}$ [Btu/h]	37448	36673	35904	35035	34012	31859	29332	26857
$m_{air,cond}$ [cfm]	2885	2885	2885	2885	2885	2885	2885	2885
$m_{dryair,evap}$ [kg/s]	0.6636	0.621	0.5672	0.5183	0.4405	0.3871	0.3372	0.278
Charge [lbm]	6.41	6.41	6.41	6.41	6.41	6.41	6.41	6.41
P_{atm} [atm]	0.994	1.000	1.000	1.000	0.986	0.984	0.983	0.983
EER [NU]	11.91	11.94	11.74	11.46	11.16	10.71	10.17	9.69
SHR [NU]	72%	65%	63%	63%	61%	60%	59%	58%

Figure 20: Change in Indoor Airflow Rate Under Wet Conditions

7.2 Appendix B: Experimental Results for Air Conditioners and Heat Pumps with Varying Amounts of Bypass

(Heflin & Keller 1993)

Bypass %	***Fixed Orifice AC EER(total)***	***TXV AC EER(total)***	***TXV Heat Pump EER(total)***	***Orifice Heat Pump COP***
0	10.6	10.2	7.44	2.84
22	10.6	9.6	6.7	2.53
41	9.19	8.77	6.49	2.34
60	7.66	6.81	5.15	1.81
79	5.74	4.03	3.54	1.18

Figure 21: Experimental Results for Air Conditioners and Heat Pumps with Varying Amounts of Bypass

7.3 Appendix C: Savings from Achieving at Least 350 CFM per Ton

The savings from achieving at least 350 CFM per ton evaporator airflow are based on the following data and assumptions:

1. The average airflow for units meeting the 350 CFM criterion will be about 371 CFM/ton. (407 * .37 + 350 * .63). Refer to Figure 13.
2. The average airflow for multi-zoned units with all zones calling is 292 CFM/ton. Refer to Figure 13.

A curve was fitted to the Purdue University data (Shen, Braun & Groll 2004), as shown in Figure 22.

The formula for the curve is Percent Net Sensible EER = 0.3571 * ln(flow per ton / 371) + .9944)

The curve fit has an excellent R^2 of .9976.

The average savings changing from 292 CFM per ton to 370 CFM per ton is:

$$1 - 0.3571 * \ln(292/371) - .9944 = 9.1\%$$

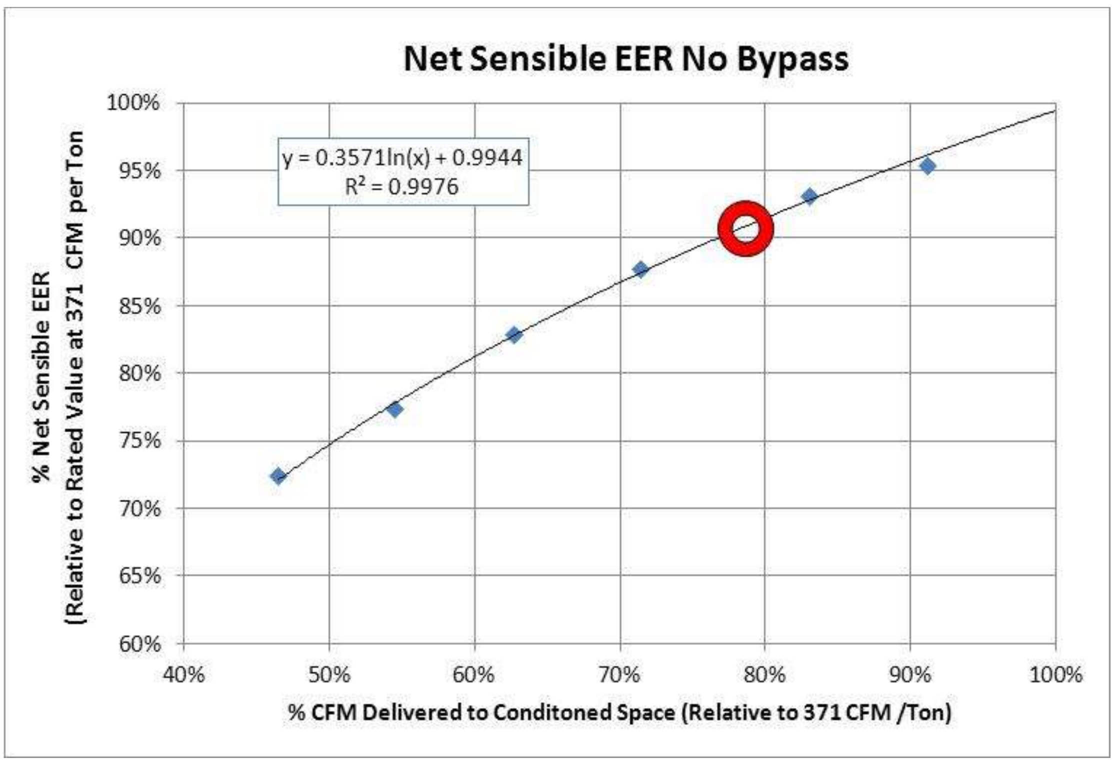

Figure 22. Normalized Sensible EER vs. Supply CFM (normalized to 371 CFM per Ton)

Increasing the airflow through the HVAC system will also increase the efficiency of the furnace or heat pump. The increase in furnace efficiency is due to the higher logarithmic mean temperature difference across the heat exchanger. The degradation in AFUE based on field testing of furnaces is 1.9% (Sun Power Association 1990).

7.4 Appendix D: Savings from Eliminating the Bypass Duct

The savings from eliminating the bypass duct are based on the following data and assumptions:

1. The bypass for the most common two zone system is a “perfect” 50% bypass. This would maintain the same airflow to the zone calling for cooling or heating.
2. The Carrier laboratory tests are the most conclusive and well-controlled measurements of the efficiency degradation due to bypasses.
3. The three field experiments provide recent additional data to supplement the Carrier laboratory tests.
4. The manufacturers’ extended data tables, when extrapolated to the lower return temperatures that occur with a bypass, provide a conservative estimate of the capacity reductions due to the bypass.
5. The ACCA bypass calculation contained in Manual Zr produce capacity reductions similar to the Carrier tests and very close to the median of the three field experiments.

7.4.1 Carrier Laboratory Data Savings Estimate

For a 50% bypass, the Carrier lab data shows an average 23% reduction in efficiency, as shown in Figure 23.

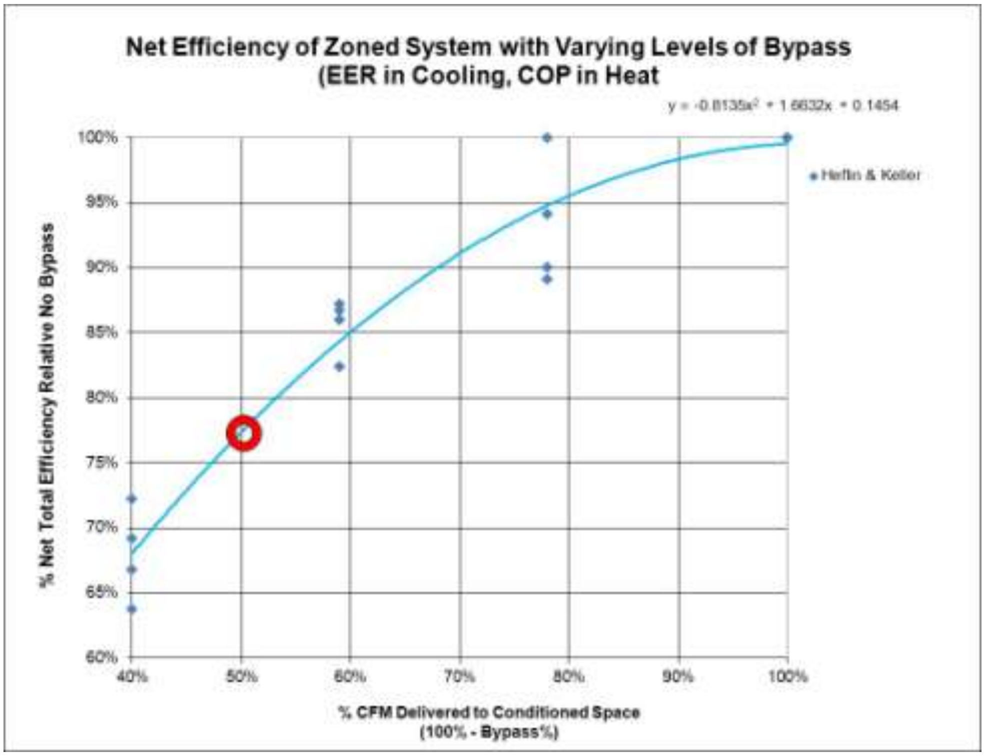

Figure 23. Carrier 23% Loss with 50% Bypass

7.4.2 Field Experiment and ACCA Zoning Manual Savings Estimate

For a 50% delivery to the house, the median Field Unit and ACCA Zoning Manual show a 31% reduction in efficiency, as shown in Figure 24.

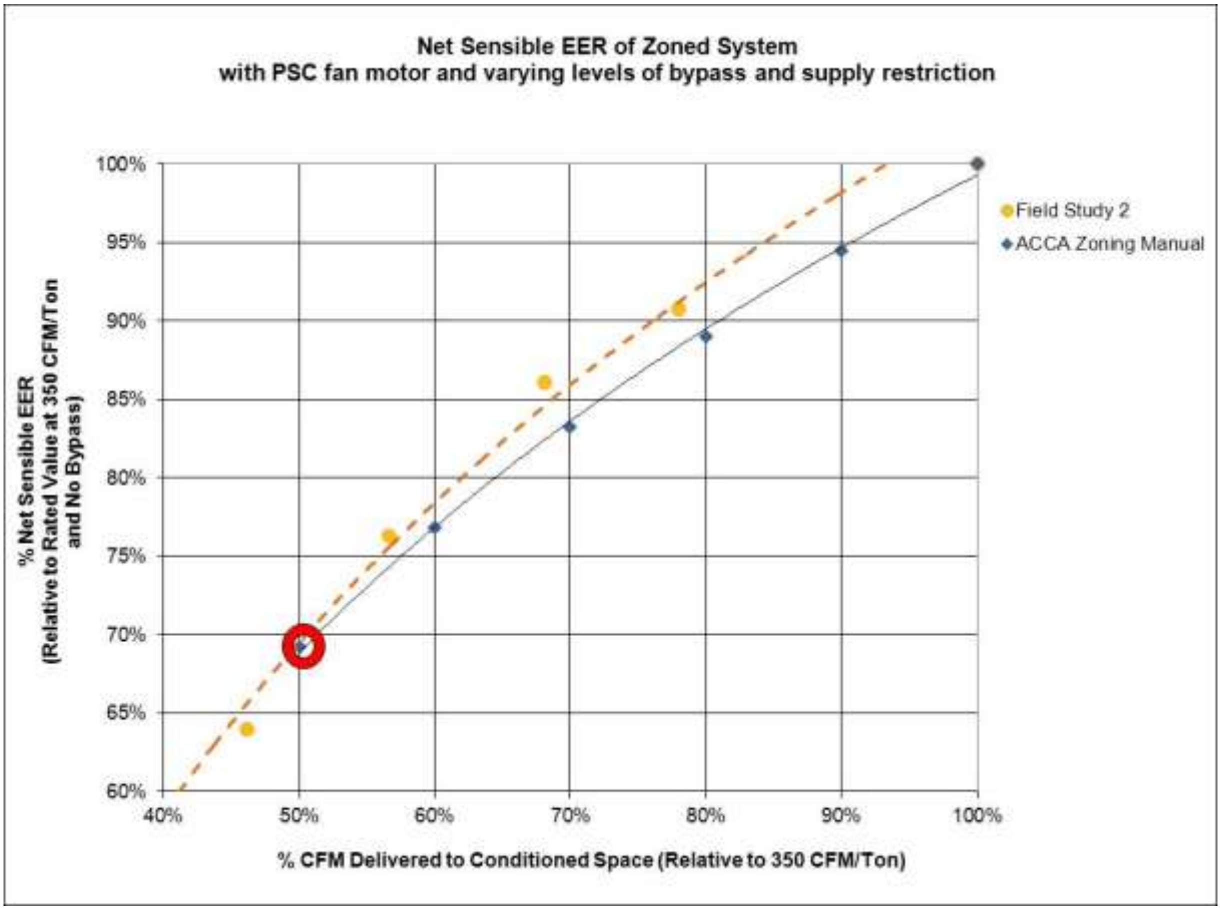

Figure 24. Median Field Test and ACCA Manual 31% Loss with 50% Bypass

7.4.3 Conservative Model Savings Estimate: Extrapolations of Manufacturer's Data Tables

For a 50% delivery to the house with a 50% bypass, conservative model shows a 22% reduction in efficiency, as shown in Figure 25.

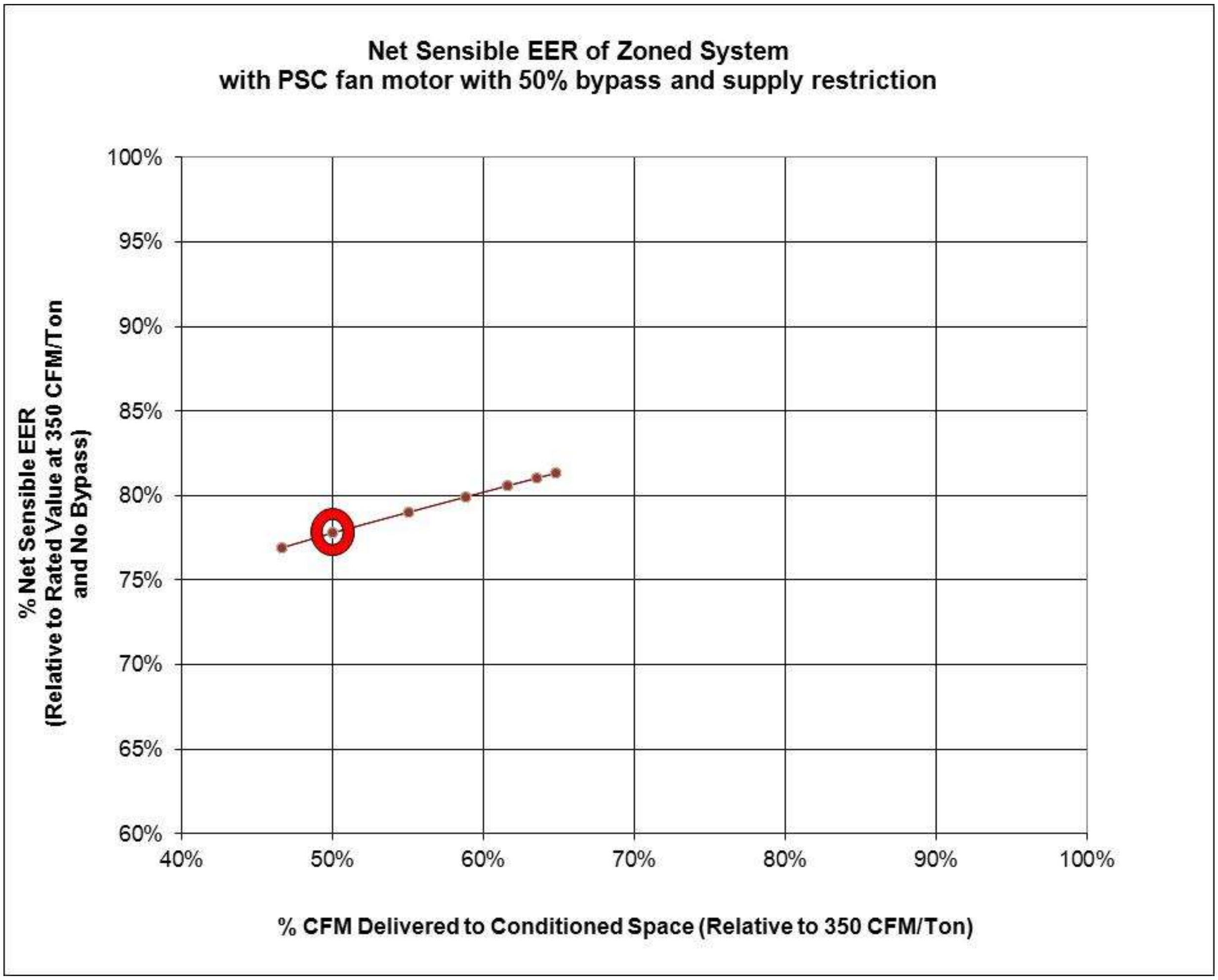

Figure 25. Conservative Model 22% Loss with 50% Bypass

7.4.4 Final Cooling Savings Estimate

For multi-zone systems operating with half the zones operating and a 50% bypass, the cooling savings was taken as an average between the modeled Sensible EER from the conservative manufacturers' extended tables (displayed as the 50% bypass line in Figure 26) and the measured Sensible EER from Unit 2 (the median unit) in the Field Study. As shown in Figure 26, the savings are 25.7% in cooling.

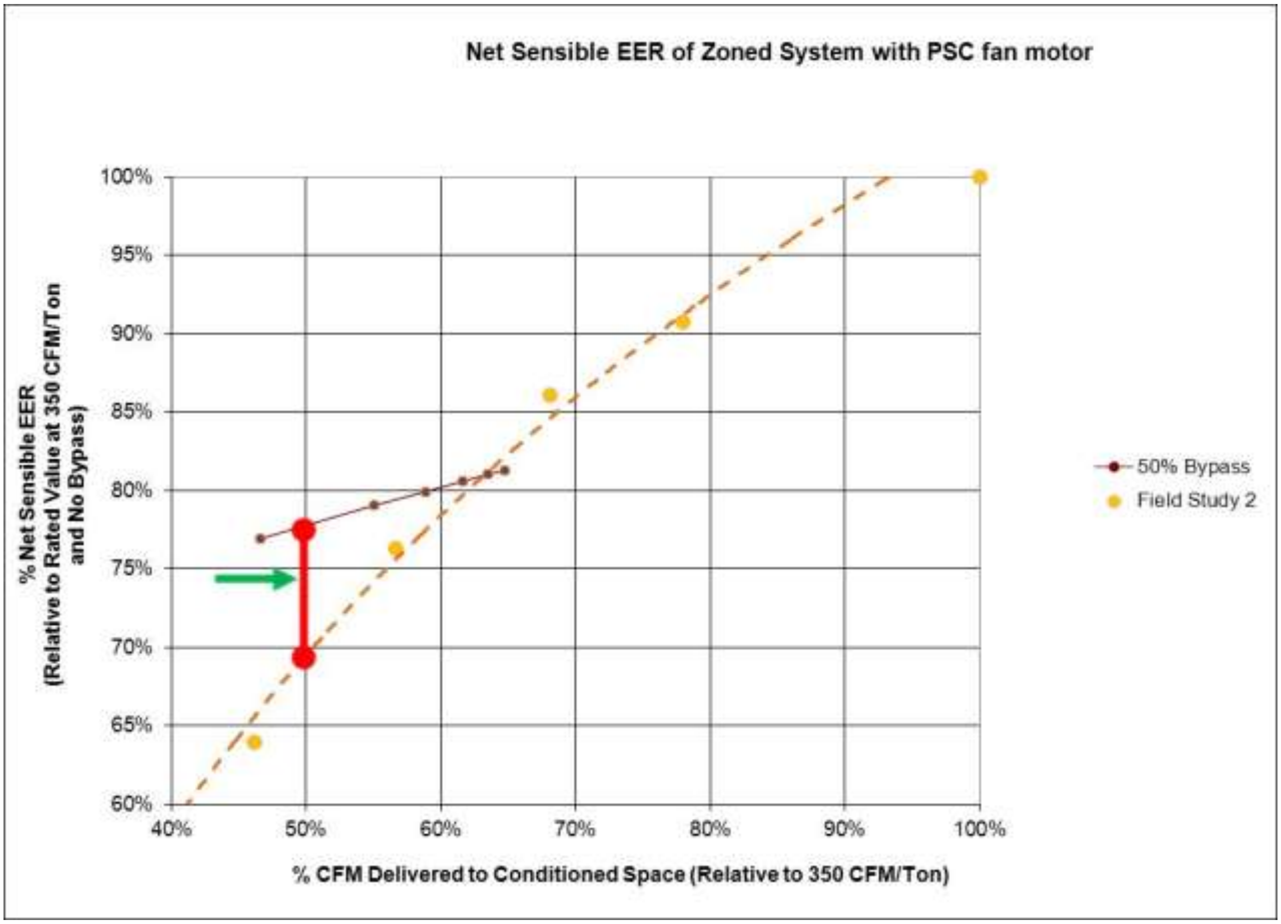

Figure 26. Estimated 25.7% Efficiency Decrease in Zoned Mode

7.4.5 Combined Cooling Savings: 50% All Zones, 50% One Zone

Average cooling savings based on 50% of time with all zones calling 50% with one zone calling

Using 9.1% from Section 7.3 and 25.7% from Section 7.4.4, the combined cooling savings is:

average(9.1%,25.7%) = 17.4%

7.4.6 Gas Furnace Heating Saving Estimate

Based on a first principles estimate and a 50% bypass used as a single pass (first order effect):

Heat exchanger heat transfer $Q = UA\Delta T_M$

Where:

ΔT_M is the logarithmic mean temperature difference

$$\Delta T_M = \frac{\Delta T_A - \Delta T_B}{ln\ \frac{\Delta T_A}{\Delta T_B}}$$

ΔT_A is the temperature difference between the gasses at one end of the heat exchanger.

ΔT_B is the temperature difference between the gasses at the other end of the heat exchanger.

(Lindeburg 1990)

Based on:

The combustion products and excess air combination temperature of 1500°F
Combustion product exiting temperature of 300°F
Average furnace heat rise from ECO (Proctor, Chitwood & Wilcox 2011) is 54.9°F

House air side entering temperature without bypass 70°F
House air side entering temperature with 50% bypass 97.5°F
House air side exiting temperature without bypass 124.5°F
Maximum house air side exiting temperature with 50% bypass 152.4°F

Logarithmic mean temperature differential without bypass:

$$\Delta T_{M1} = \frac{1500-70\ -\ 300-124.5}{ln\ \frac{1500-70}{300-124.5}} = 598$$

Logarithmic mean temperature differential with bypass:

$$\Delta T_{M2} = \frac{1500-97.5\ -\ 300-152.4}{ln\ \frac{1500-97.5}{300-152.4}} = 557$$

The heating savings are approximately 6.8%.

7.4.7 Combined Heating Savings: 50% All Zones, 50% One Zone

Average heating savings based on 50% of time with all zones calling 50% with one zone calling

Using 1.9% from Section 7.3 and 6.8% from Section 7.4.6, the combined heating savings is:

Average (1.9%,6.8%) = 4.4%