Field Measurements of Air Conditioners with and without TXVs

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ABSTRACT

This paper summarizes field measurements of 4,168 air conditioners with and without TXVs. Approximately 72 percent of the air conditioners had improper refrigerant charge and 44 percent had improper airflow. Average energy savings for correcting RCA are 12.6 ± 2.3 percent. The paper provides detailed EER measurements and the relative efficiency improvement for sixteen TXV and forty-nine non-TXV air conditioners. EER measurements of air conditioners with improper RCA indicate a relative efficiency gain of 21 ± 7 percent for TXV and a gain of 17.1 ± 2.8 percent for non-TXV air conditioners. The difference in efficiency gain between TXV and non-TXV air conditioners is 3.9 ± 0.3 percent at the 90 percent confidence level. The uncertainty associated with field measurements of capacity and EER was evaluated using the propagation of error technique and the overall uncertainty error is ± 4.4 percent. The paper indicates proper RCA is much more effective than a TXV in terms of delivering rated efficiency performance, especially if TXV sensing bulbs are improperly attached to the vapor line or are not insulated. The paper describes an easy-to-use method to verify RCA using PDA software or automated voice telephony. The paper should be of value to anyone interested in reducing peak air conditioning demand.

Introduction

Approximately 6 million new residential and small commercial split-system, heat pump, and small packaged air conditioners are installed in the United States each year (ARI 2003). Studies have shown that approximately 50 to 67 percent of these systems are installed with improper Refrigerant Charge and Airflow (RCA) causing them to operate 10 to 20 percent less efficiently than if they were properly installed (Blasnik et al. 1995; Hammarlund 1992, 85-87; Neme et al. 1998). With roughly 57.5 million existing residential and 35 million small commercial air conditioners in the United States, the potential savings from proper RCA are significant (EIA 1999; 2001).

Refrigerant charge and airflow are relatively easy to check and correct with proper training, equipment, and verification methods. Unfortunately, most air conditioning technicians either do not have proper training and equipment or do not have easy-to-use RCA verification methods. Consequently, many new and existing air conditioners have improper RCA causing reduced efficiency, noisy systems, and premature compressor failure. To address this problem, the California Energy Commission (CEC) adopted residential building standards in 2001 (CEC Standards) requiring either the Alternative Calculation Method (ACM), thermostatic expansion valve (TXV), or proper RCA (CEC 2001, 132). Most air conditioners are installed using the ACM which is a computer method to show compliance with the annual energy budget requirements of the standards. The standards require inspections by the California Home Energy Efficiency Rating System (CHEERS) to verify installation of TXV or proper RCA under the prescriptive approach or the ACM (if these are selected). The CHEERS organization has reported zero demand for verification of proper RCA on new or existing applications (Hamilton

2003). The largest air conditioning distributor in California has indicated 75% of their sales for new and existing applications are non-TXV (Bourdon 2003).

Several studies show approximately 50 to 67 percent of air conditioners suffer from improper RCA, and this reduces efficiency by roughly 10 to 20 percent (Downey 2002, 53-67; Palani et al. 1992; Parker 1997; Rodriguez 1995). Three studies have shown that improper RCA can be mitigated by installing a TXV device (Davis 2001a; 2001b; Farzad 1990). The studies found TXV systems only had a clear advantage when the system is undercharged, and found no difference in performance at the rating condition between TXV and non-TXV (i.e., fixed orifice) when systems were properly installed. Unfortunately, TXVs have their own performance problems associated with incorrect installation leading to a phenomenon known as "valve hunting." This can occur when the evaporator coil experiences reduced heat loads caused by many problems including low airflow, dirty or icy coils, and low refrigerant charge (Tomczyk 1995). Under these circumstances the TXV can lose control and successively overfeed and then underfeed refrigerant to the evaporator while attempting to stabilize control causing reduced capacity and efficiency. Overfeeding liquid to the evaporator can also damage the compressor. The tendency for hunting can be reduced by correcting RCA, by relocating the TXV sensing bulb to a better location inside the evaporator coil box, and by insulating the sensing bulb.

Field and factory-installed TXV sensing bulbs are often installed without insulation (see **Figure 1**). This practice is not recommended by manufacturers who instruct technicians to insulate the sensing bulb to prevent ambient air from causing false readings, and to tightly clamp the bulb to the vapor line with good linear thermal contact at the recommended orientation (i.e., 4 or 8 'o'clock when viewed in cross section) to guard against false readings due to air or liquid in the suction line (ADP 2003; Allstyle 2001; Carrier 2002; Emerson 1998). Unfortunately, most installers do not do this. Field inspections found sensing bulbs installed without insulation, without adequate linear contact, and at incorrect orientations (see **Figure 2**).

Figure 1. Uninsulated TXV Bulb in Attic

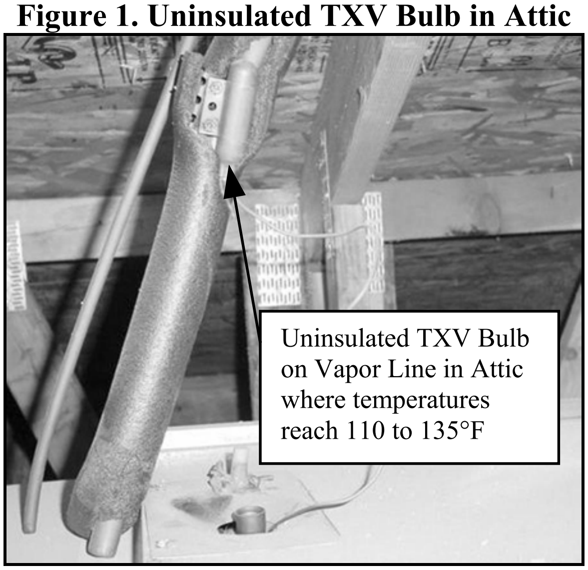
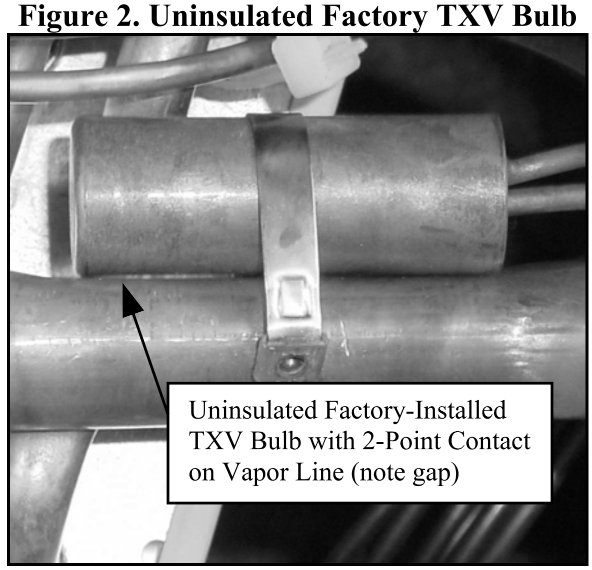


Figure 2. Uninsulated Factory TXV Bulb



Factory-installed TXVs with uninsulated sensing bulbs inside the evaporator coil box will be influenced by the mixed supply-air temperatures which are typically 10-20°F higher than vapor line temperatures. Field-installed TXVs with uninsulated sensing bulbs located in attics or garages will be influenced by attic or garage temperatures which are 50 to 80°F higher than vapor line temperatures (e.g., attic temperatures range from 110 to 130°F compared to vapor line temperatures of 35 to 50°F). The three laboratory studies (Davis 2001a; 2001b; Farzad 1990) measured TXV-equipped air conditioners with the evaporator coil box, TXV, and well-insulated sensing bulb located in conditioned space and this is not typical of field conditions. Furthermore, none of these three studies recommended TXVs as a substitute for proper RCA.

This paper provides field measurements of air conditioner performance with and without proper RCA for air conditioners equipped with fixed orifice expansion devices (i.e., non-TXV) and TXV devices. This paper demonstrates the importance of proper RCA for air conditioners to deliver their rated efficiency, and describes an easy-to-use third-party RCA Verification system to help technicians install air conditioners with proper RCA.

Field Measurements

Field measurements of refrigerant charge and airflow were made over a three-year period on 4,168 split, packaged, and heat pump air conditioners. Field measurements of the Energy Efficiency Ratio (EER) were made to determine in-situ efficiency before and after correcting RCA on a sample of 72 randomly selected air conditioners out of the population of 4,168.[1] This paper compares performance measurements of sixteen TXV and forty-nine non-TXV air conditioners from the sample to compare efficiency performance with and without TXVs as a function of proper RCA. Field measurements, measurement equipment, and measurement tolerances are provided in **Table 1**.

Table 1. Field Measurements, Measurement Equipment, and Tolerances

Field Measurement	Measurement Equipment	Measurement Tolerances
Temperature in degrees Fahrenheit (°F) of return and supply wetbulb and drybulb and outdoor condenser entering air	4-channel temperature data loggers with 10K thermisters. Calibration of wetbulb and drybulb temperatures were checked using sling psychrometers	Data logger: ± 0.1°F Thermisters: ± 0.2°F Sling psychrometer: ± 0.2°F (wetbulb and drybulb)
Pressure in pounds per square inch (psi) of vapor and suction line	Compound pressure gauge for R22 and R410a	Refrigerant pressure: ± 2 % for R22 and ± 3 percent for R410a
Temperature (°F) of vapor and suction lines	Digital thermometer with clamp-on insulated type K thermocouples	Digital thermometer: ± 0.1°F Type K thermocouple: ± 0.1% °F
Temperature (°F) of actual and required superheat and subcooling	Digital thermometer with clamp-on insulated type K thermocouples	Digital thermometer: ± 0.1°F Type K thermocouple: ± 0.1% °F
Airflow in cubic feet per minute (cfm) across air conditioner evaporator coil	Digital pressure gauge and fan-powered flow hood, flow meter pitot tube array, and electronic balometer	Fan-powered flowhood: ± 3% Flow meter pitot tube array: ± 7% Electronic balometer: ± 4%
Ounces (oz.) of refrigerant charge added or removed	Digital electronic charging scales	Electronic scale: ± 0.5 ounces or ± 0.1% whichever is greater
Total power in kilowatts (kW) of air conditioner compressor and fans	True RMS 4-channel power data loggers and 4-channel power analyzer	Data loggers, CTs, PTs: ± 1% Power analyzer: ± 1%

Return and supply temperatures were measured inside the return and supply plenums. Temperature and power were measured at one minute intervals. Airflow was measured before and after making any changes to the supply/return ducts, opening vents, or installing new air

[1] EER is the cooling capacity in thousand British Thermal Units per hour (kBtuh) divided by total air conditioner electric power (kW) including indoor fan, outdoor condensing fan, compressor, and controls. The Btu is the energy required to raise one pound of water one degree Fahrenheit. EER values are typically measured under laboratory conditions of 95°F condenser entering air and 80°F drybulb and 67°F wetbulb evaporator entering air.

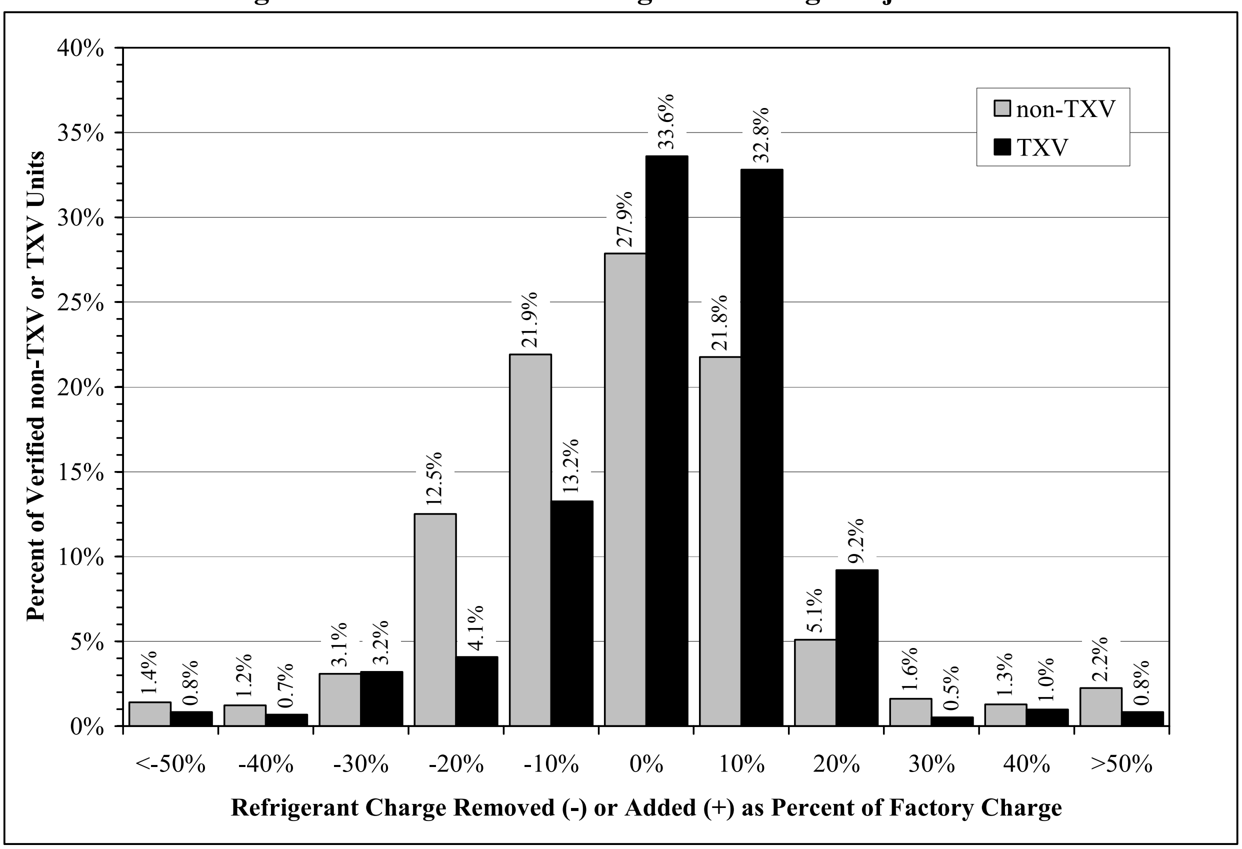
filters that would affect airflow. Return and supply enthalpies were derived from the temperature measurements using standard psychrometric algorithms (Kelsey 2004). EER was derived from the combination of enthalpy, airflow, and power measurements. Measurements were made to evaluate the relative change in efficiency not the absolute efficiency, and all measurements of air conditioner performance were made within minutes of any efficiency improvements, but at least 15 minutes after any refrigerant charge adjustments. Measurement tolerances are less important than the relative performance change.

The research sample design was based on randomly selected samples of units and installation contractors. Measurements were made on two to five ton air conditioner systems from 32 manufacturers and installed by more than 40 technicians. New and old systems were examined with labeled Seasonal Energy Efficiency Ratios (SEER) ranging from 7 to 18.[2]

Field Measurement Results

Approximately 72 percent of the 4,168 air conditioners had improper refrigerant charge outside the manufacturers' performance tolerances of ±5°F for superheat and ±3°F for subcooling. Approximately 44 percent of the 3,198 air conditioners had improper airflow outside the manufacturers' tolerances of ±3°F for temperature split. **Figure 3** shows the distribution of refrigerant charge adjustments for 3,927 non-TXV and 241 TXV air conditioning units.

Figure 3. Distribution of Refrigerant Charge Adjustments



[2] SEER is an adjusted rating based on steady-state EER measured at standard conditions of 82°F outdoor and 80°F drybulb/67°F wetbulb indoor temperature multiplied by the Part Load Factor with a default of 0.875 (ARI 2003).

Approximately 72.2 percent or 2,836 non-TXV-equipped air conditioners were improperly charged, while 1,091 were properly charged. There were 1,253 overcharged units with an average charge removal of 14.0 ± 0.5 percent of the recommended factory charge at the 90% confidence level, and 1,583 undercharged units had an average charge addition of 16.7 ± 0.7 percent of the factory charge. Approximately 66.4 percent or 160 TXV-equipped air conditioners were improperly charged and 81 were properly charged. There were 46 overcharged units with an average charge removal of 8.3 ± 4.1 percent of the factory charge, and 114 undercharged units had an average charge addition of 13.0 ± 1.8 percent.

The average measured airflow improvement was 9.8 ± 2.5 percent at the 90 percent confidence level. The average measured pre-retrofit airflow was 279 ± 10 cfm for non-TXV systems and 308 ± 17 cfm for TXV systems. The average absolute refrigerant charge adjustment was 15.5 ± 0.4 percent of the factory charge at the 90 percent confidence level. The relative efficiency gains due to refrigerant charge and airflow improvements are shown in **Tables 2** and **3** for sixteen TXV and forty-nine non-TXV air conditioners respectively. Sites labeled "n/a" had improper RCA but the customer either refused corrections or no refrigerant change was necessary. The TXV efficiency gain excludes sites 3 and 4 where customers refused charge corrections, site 8 where the efficiency gain was undefined (i.e., pre-capacity and pre-EER were zero due to a leaky system with no refrigerant charge), and sites 12, 13, and 14 where no charge adjustment was necessary. Charge adjustments in parentheses are software recommendations.

Measurements of EER were made at non-standard temperature conditions (i.e., not at 95°F outdoor temperature or 80°F dry-bulb/67°F wet-bulb inlet conditions). The absolute EER measurements are not directly comparable to laboratory measurements of EER at standard conditions where airflow, return air temperatures, and condenser entering air temperatures are carefully controlled. The relative efficiency gains shown in **Tables 2** and **3** are applicable to normal operating conditions since laboratory studies indicate the change in EER (as a function of airflow and charge) is independent of operating conditions (Farzad 1993; O'Neal 1990).

Table 2. EER Measurements and Efficiency Gain for TXV Air Conditioners

Site	Tons	Factory Charge oz.	Charge Adjust +Add –Remove	Pre-EER	Post-EER	Relative Efficiency Gain	Average Outdoor Temp °F	Ave. Ret. DB/WB Temp °F	Notes
1	4	140	40%	11.2	13.1	17%	80	78/63	R410A
2	3	100	18%	9.9	12.1	22%	82	77/63	R22
3	5	114	Refused (9%)	10.4	n/a	n/a	82	75/64	R410A
4	4	170	Refused (7%)	11.6	n/a	n/a	89	77/65	R22
5	3.5	100	16%	10.9	11.8	8%	79	75/62	R410A
6	2.5	96	-78%	8.3	11.8	43%	90	79/66	R410A
7	5	176	11%	10.8	11.7	8%	88	70/60	R22
8	4	162	n/a (100%)	0	n/a	n/a (100%)	86	85/69	R22
9	4	170	15%	10.3	12.4	20%	86	74/63	R22
10	5	200	9%	10.5	11.3	8%	95	77/65	R22
11	3	150	34%	9	12.3	37%	95	79/69	R22
12	5	200	0%	10.8	n/a	n/a	96	75/65	R22
13	3.5	170	Refused (6%)	n/a	n/a	n/a	80	74/61	R22
14	5	166	0%	11	n/a	n/a	84	77/65	R22
15	4	103	-31%	7.1	9.7	36%	87	80/67	R22
16	3	53	28%	6.4	7.0	9%	70	65/59	R22
Ave	**4**	**142**	**25%**	**9.4**	**11.3**	**21%**	**86**	**78/63**	

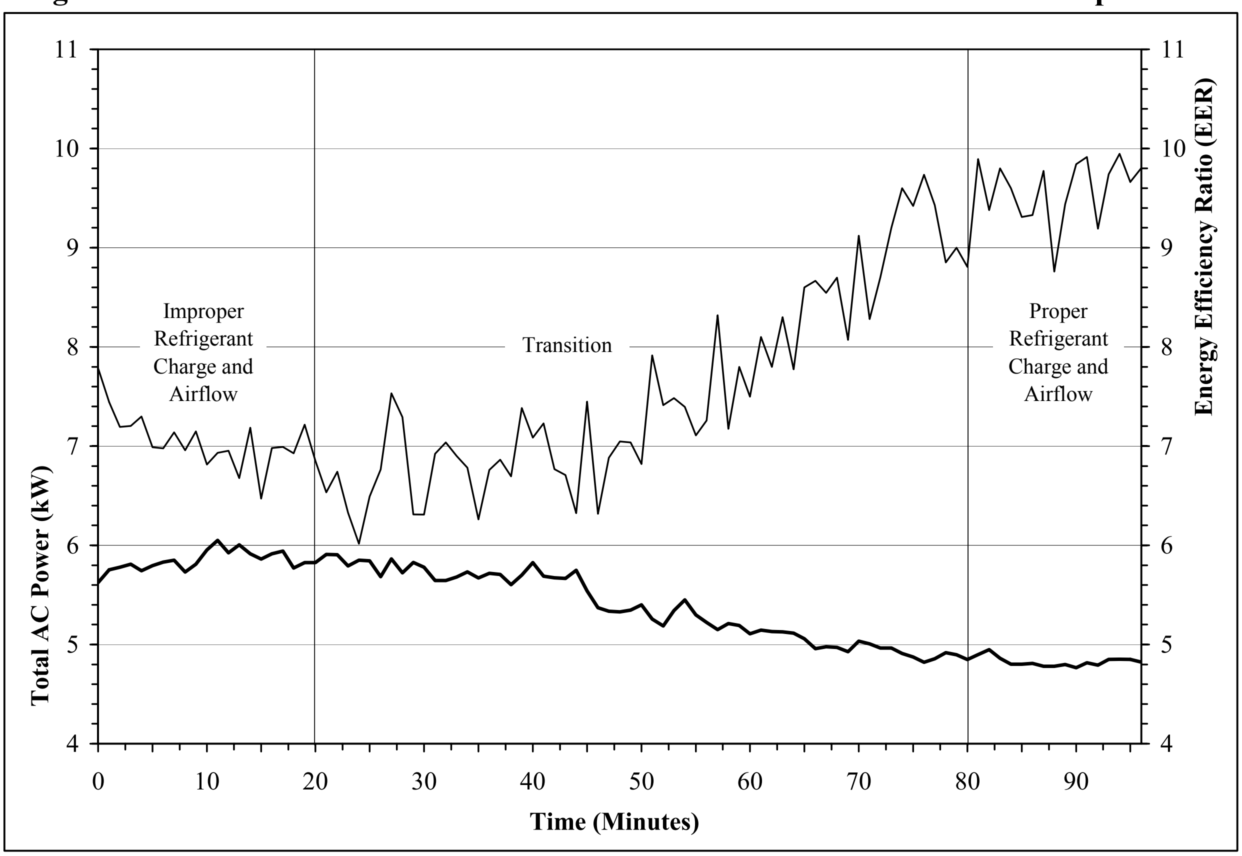
Table 3. EER Measurements and Efficiency Gain for non-TXV Air Conditioners

Site	Tons	Factory Charge oz.	Charge Adjust +Add –Remove	Pre-EER	Post-EER	Relative Efficiency Gain	Average Outdoor Temp °F	Ave. Ret. DB/WB Temp °F	Notes
17	3	69	-24%	8.2	8.8	7%	90	82/60	R22
18	3.5	130	-7%	9.6	10	4%	91	84/72	R22
19	4	112	38%	8.5	9.9	16%	90	81/67	R22
20	5	158	-15%	8.6	9.8	14%	81	75/63	R22
21	3	78	-13%	9.6	10	4%	64	61/53	R22
22	3.5	164	17%	11.3	11.7	4%	94	84/72	R22
23	4	113	-9%	7.5	8.5	13%	99	80/64	R22
24	4	103	-10%	8.9	9.5	7%	82	79/63	R22
25	3.5	67	27%	8.4	9.4	12%	88	68/57	R22
26	4	76	-29%	6.8	8.5	25%	91	81/70	R22
27	3.5	66	6%	6.4	7.5	17%	96	76/67	R22
28	4	62	-16%	8.3	9.5	14%	71	67/55	R22
29	3.5	115	-32%	5.3	7.4	40%	86	85/72	R22
30	4	106	-40%	5.5	7.3	33%	71	69/57	R22
31	3.5	115	-38%	6	8.4	41%	90	81/67	R22
32	3	69	-18%	8.2	9.3	14%	75	75/61	R22
33	4	122	-23%	6.4	7.3	14%	80	79/67	R22
34	4	100	-17%	7.3	8.8	21%	76	70/58	R22
35	3	52	-14%	8.5	8.9	5%	88	70/58	R22
36	3.5	99	-22%	6.8	10	47%	72	71/61	R22
37	3	63	-8%	5.7	7.8	36%	88	76/65	R22
38	3.5	82	7%	9.1	9.8	8%	84	76/66	R22
39	4	105	4%	8	8.4	5%	84	74/64	R22
40	4	87	29%	6.8	8.1	18%	90	76/65	R22
41	4	103	-48%	5	7.1	42%	94	85/67	R22
42	3	87	9%	5.4	5.7	6%	94	78/64	R22
43	4	151	-20%	5.4	6.1	13%	102	89/71	R22
44	3	61	-10%	5.9	7.3	24%	100	86/65	R22
45	3	71	-6%	6.7	7.1	6%	84	74/65	R22
46	3	84	-13%	6.5	7.4	14%	97	82/67	R22
47	4	87	14%	7.3	10.4	42%	83	78/64	R22
48	3	65	19%	7.7	n/a	n/a	95	87/70	R22
49	3.5	88	19%	6.1	6.8	11%	83	78/63	R22
50	4	124	19%	8.7	9.3	7%	101	89/68	R22
51	4	82	-34%	8.2	9.4	15%	102	83/68	R22
52	4	100	-22%	7.1	8.7	23%	89	79/63	R22
53	4	122	-22%	6.9	8.4	22%	95	81/67	R22
54	3.5	79	-10%	5.9	6.8	15%	92	84/66	R22
55	4	93	13%	7.9	8.2	4%	77	75/64	R22
56	4	73	23%	5.7	6.8	19%	113	84/73	R22
57	2.5	53	-9%	8	8.6	8%	73	70/60	R22
58	3	120	-33%	6.8	8.7	28%	72	69/61	R22
59	4	134	-6%	4.1	5.2	27%	100	82/73	R22
60	3	85	-24%	8.4	8.7	4%	98	81/70	R22
61	4	142	-9%	6.3	7.8	24%	103	83/70	R22
62	3.5	82	-12%	6.9	7.8	13%	91	83/73	R22
63	3	82	-2%	7.7	8	5%	92	82/68	R22
64	4	109	-23%	9	10.8	20%	91	78/65	R22
65	4	97	-17%	7.5	8.7	15%	92	84/64	R22
Ave	**3.6**	**95.6**	**18.3%**	**7.3**	**8.4**	**17.1%**	**88.5**	**78/65**	

Several laboratory studies indicate the efficiency degradation for TXV units is roughly 5 percent at plus or minus 20 percent of the correct charging condition (Davis 2001a; 2001b; Farzad 1993). Findings from this study indicate an average efficiency gain of 21 ± 7 percent for TXV air conditioners with an average charge adjustment of 25 ± 12 percent (see **Table 2**). The student t-test was used to evaluate the mean efficiency difference between field and laboratory measurements and the differences were found to be statistically significant (i.e., 0.003 probability of t less than 3.78). The average efficiency gain for non-TXV air conditioners is 17.1 ± 2.8 percent (see **Table 3**). The difference in efficiency gain between TXV and non-TXV air conditioners is 3.9 ± 0.3 percent at the 90 percent confidence level. These findings indicate TXV and non-TXV air conditioners have comparable efficiency gains due to proper RCA irrespective of whether they are over- or under charged. Findings from this study also indicate TXVs are less effective than proper RCA in terms of delivering rated efficiency. The primary reasons for this are due to sensing bulbs installed without insulation, without adequate linear contact, or at incorrect orientations.

Field measurements for a 4-ton TXV air conditioner are shown in **Figure 5** (site 15). The TXV air conditioner at site 15 used 5.8 kW when overcharged and 4.8 kW when properly charged for a savings of 1 kW. The EER increased by 37 percent from 7.1 to 9.7.

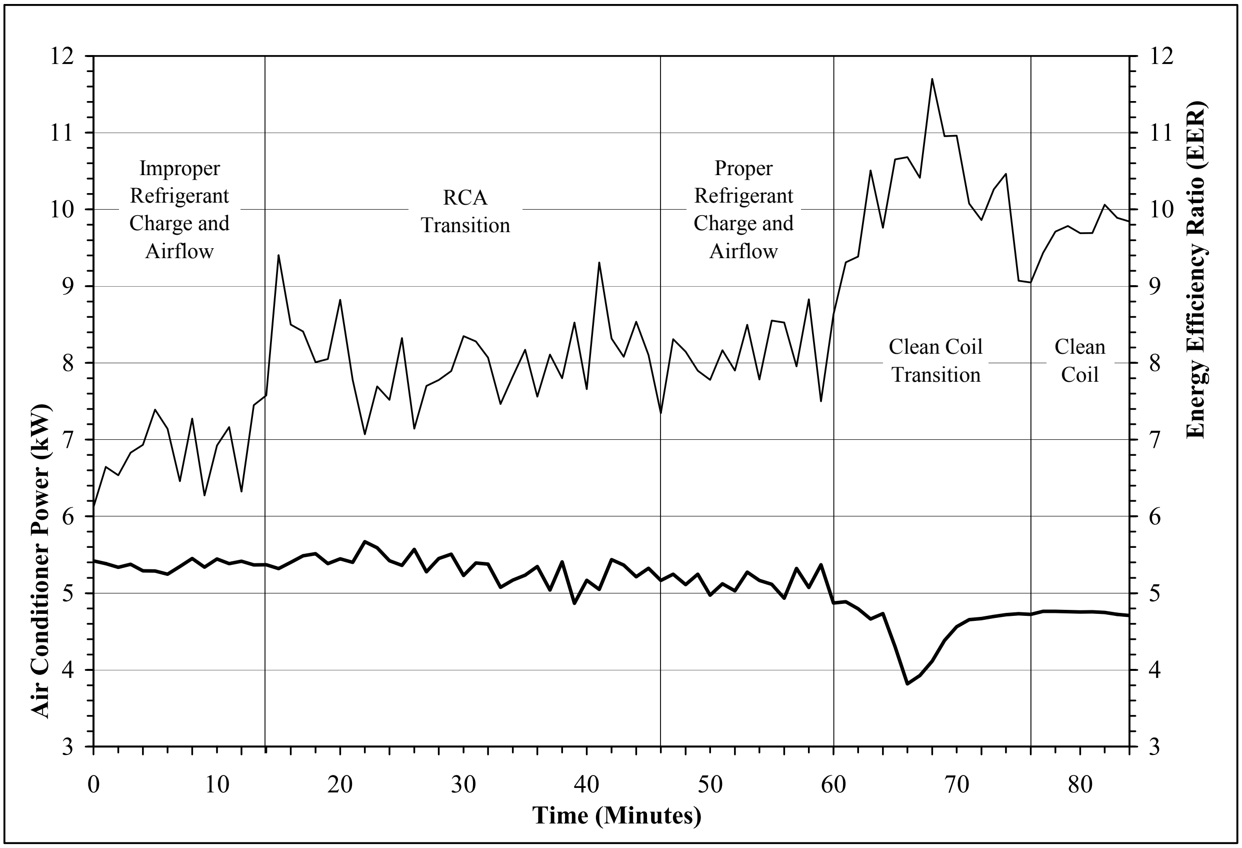
Figure 5. Measurements of a 4-ton TXV Air Conditioner with and without Proper RCA



Field measurements for a 4-ton non-TXV air conditioner are shown in **Figure 6** (Site 26). The non-TXV air conditioner at site 26 used 5.4 kW when overcharged and 5.1 kW when properly charged for an absolute savings of 0.3 kW. The EER increased by 25 percent from 6.8

to 8.5 with proper RCA. The EER further increased to 9.6 with a clean and dry condensing coil with total absolute savings of 0.7 kW.

Figure 6. Measurements of 4-ton Non-TXV Air Conditioner with and without Proper RCA



Uncertainty Associated with Field Measurements of Capacity and EER

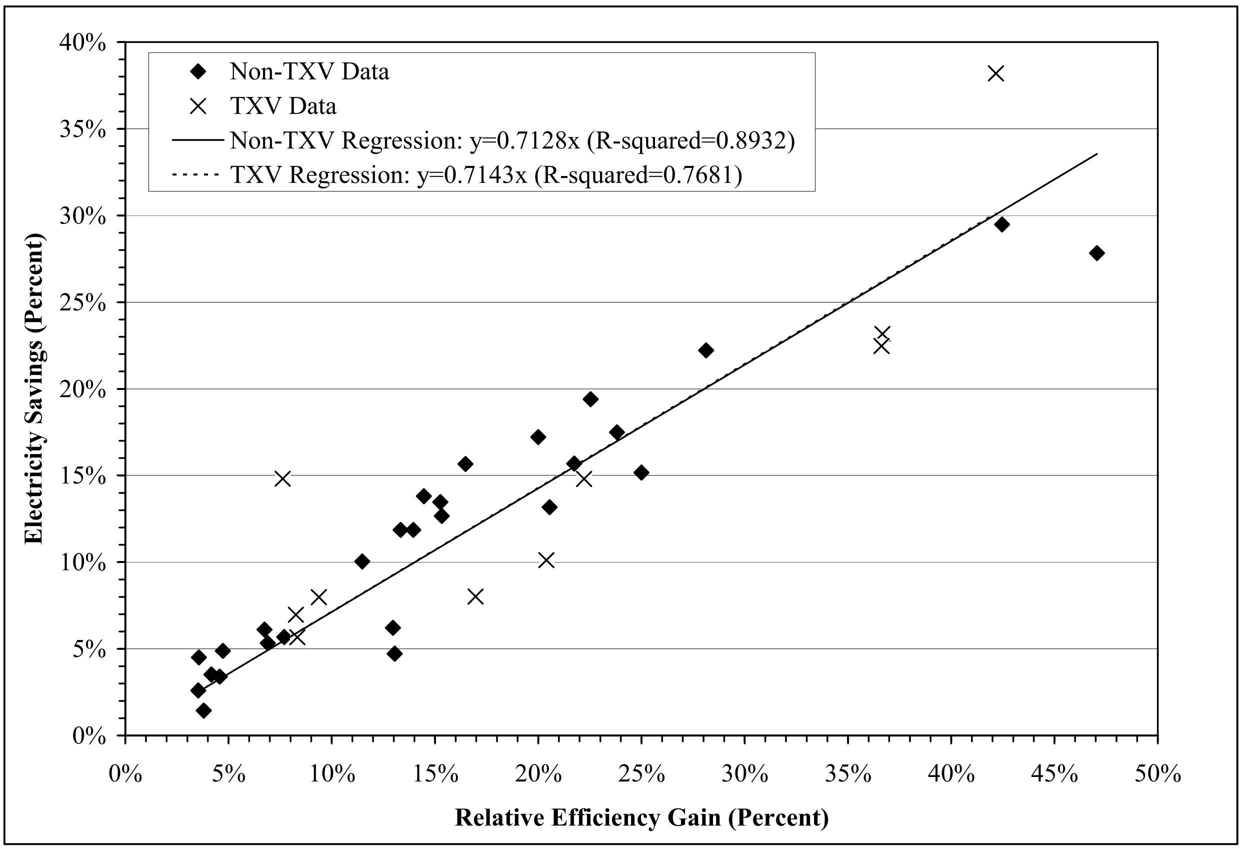
The uncertainty associated with field measurements of capacity and EER was evaluated using the propagation of error technique including the following factors: sensor accuracy; recording system accuracy; data display or recording resolution; and sampling error (ASHRAE 2002; Hall et al. 2004, 191-195). The uncertainty associated with instrument error is ± 2.8 percent, and the measurement error is ± 3.4 percent. Therefore, the total uncertainty error is ± 4.4 percent and this is close to uncertainty errors reported in laboratory studies (Davis 2001b).

Load Impact Results

The load impacts associated with improper RCA are based on field measurements, engineering analysis, and EZ SIM and eQuest/DOE-2.2 building simulations calibrated to billing data (Hirsch 2002; Robison 2000; Stellar 2002). Building models were developed independently using EZ SIM and eQuest/DOE-2.2 for a subset of 37 buildings included in the 72 audit sites. EZ SIM models were calibrated to monthly billing data and eQuest/DOE-2.2 models were calibrated to annual cooling energy consumption developed using the PRInceton Scorekeeping Method (PRISM, Fels 1995).

Average load impacts per unit are 292 ± 99 kWh for TXV and 262 ± 61 kWh for non-TXV air conditioners or 15.2 ± 5.6 percent for TXV and 11.7 ± 2 percent for non-TXV units. The average savings per unit for both types of systems are 270 ± 58 kWh or 12.6 ± 2.3 percent. The relative efficiency gains versus electricity savings for both systems are shown in **Figure 7**. The regression equations are virtually identical except the R-squared value is lower for TXV units due to the smaller sample. The average peak kW savings are 0.32 ± 0.06 kW based on data collected during summer weekdays at 21 sites for a period of 2 to 4 weeks before and after making RCA adjustments as shown in **Figure 8**. Extrapolating to the 2,996 air conditioners that received proper RCA yields gross savings of 808,920 ± 173,768 kWh per year and peak demand savings of 959 ± 180 kW. Assuming an eight year effective useful lifetime yields gross lifecycle savings of 6,471,360 ± 1,390,144 kWh.

Figure 7. Relative Efficiency Gain Vs. kWh Savings for TXV and Non-TXV Systems



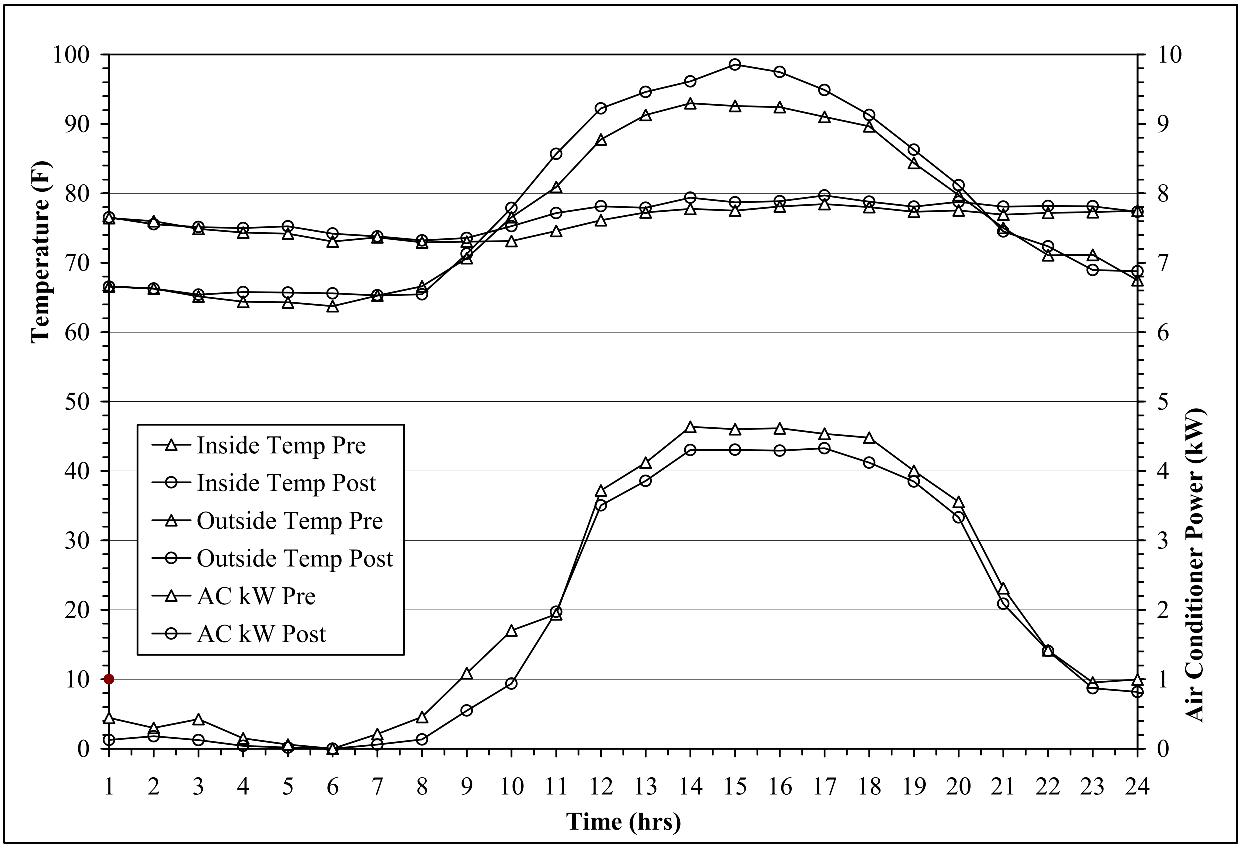
Potential Load Impacts in the United States from Proper RCA

Approximately 6 million new residential and commercial split-system, heat pump, and small packaged air conditioners are installed in the United States each year (ARI 2004).[3] Studies have shown that approximately 50 to 67 percent of these systems are installed with improper RCA causing them to operate 10 to 20% less efficiently than if they were properly installed.

[3] Total sales for split-system, heat pump and small packaged units in the 24,000 to 65,000 Btu per hour size categories based on monthly 2003 reports of US manufacturers shipments from *ARI Statistical Release* (ARI 2004).

There are approximately 57.5 million existing residential and 35 million existing small commercial air conditioners in the United States, and annual electricity consumption is 161 billion kWh/year for residential and 152 billion kWh/year for commercial (EIA 1999; EIA 2001). Assuming average savings of 12.6 ± 2.3 percent applicable to 50 percent of residential and small commercial units, the total potential savings from proper RCA are estimated at 19.6 ± 3.6 billion kWh/yr.[4] Assuming average peak demand savings of 0.32 ± 0.06 kW per unit applicable to 50 percent of existing units and average diversity of 70 percent, the potential US peak demand savings from proper RCA are estimated at 10.3 ± 1.9 GW.[5]

Figure 8. Average Weekday kW Load Profiles for 21 Sites Pre/Post Proper RCA



Market Barriers to RCA Verification

There are many market barriers to RCA verification as shown in **Table 4** (market barrier definitions are from Eto at al. 1996). Performance uncertainty is an important barrier since consumers have difficulty evaluating claims about future benefits associated with unverified energy guide labels of performance (USFTC 1996). Truth in advertising is important to consumers who assume new units will be installed properly. Unfortunately, many new air conditioners do not perform as advertised due to improper RCA, and this undermines the credibility of the energy guide labels. At a minimum, the labels should include a caveat

[4] Residential savings are estimated at 10 billion kWh/yr and commercial savings are estimated at 9.6 billion kWh/yr.
[5] Residential peak demand savings are estimated at 6.4 GW and commercial savings are estimated at 3.9 GW.

regarding SEER ratings only being valid for air conditioners installed with proper RCA according to the manufacturers' specifications.

Other important market barriers include lack of information or knowledge about the importance of RCA verification in terms of delivering rated efficiency, reducing noise, and maintaining longer life of air conditioners. Organizational practices and rules of thumb discourage or inhibit proper installation such as "add or remove refrigerant until the suction line is six-pack cold" or "shows 70 psig on the suction side and less than 250 psig on the liquid line." Service availability for new air conditioners is an important barrier for manufacturers, distributors, and dealers who are generally not verifying RCA due to lack of awareness and availability of cost effective and easy-to-use RCA verification services.

Table 4. Market Barriers to RCA Verification

Market Barrier	Description
Performance Uncertainty	Consumers have difficulty evaluating claims about future benefits associated with unverified energy guide labels of efficiency performance. The energy guide label doesn't mention RCA verification so consumers are unaware of the problem. This is related to high search costs since acquiring information to evaluate claims regarding future performance has a non-zero cost.
Higher Start-up Costs	Dealers and technicians believe the cost for RCA verification is greater than standard practices.
Lack of Information or Search Costs	The cost of identifying or learning about RCA verification in terms of delivering rated efficiency, reducing noise, and maintaining longer life of air conditioners, including the value of time spent finding or locating the service or hiring someone else to do so.
Misplaced or Split Incentive	Small commercial businesses or residential tenants are unable to make informed decisions regarding whether their air conditioner has proper RCA. Interests of property owners who make decisions are not aligned with those of tenants who would benefit from RCA verification.
Inseparability of Product Features	Consumers have difficulty acquiring energy-efficient air conditioners without also paying for undesired features. For example consumers might purchase an improperly installed air conditioner with a high SEER rating costing much more without receiving any performance advantages.
Asymmetric Information	Air conditioner dealers or manufacturers tend to advertise the benefits of high SEER air conditioners rather than proper RCA (which is assumed). This can result in consumers making sub-optimal purchasing decisions when they buy a new air conditioner.
Bounded Rationality	Dealers and consumers only consider the cost-effectiveness of high SEER air conditioners rather than considering RCA verification which is outside the boundary of their decision making process.
Organizational Practices or Customs	Organizational behavior, rules of thumb, or systems of practice when installing air conditioners discourage or inhibit proper installation such as "add or remove refrigerant until the suction line is six-pack cold or shows 70 psig on the suction side and less than 250 psig on the liquid line."
Service Availability	Manufacturers, distributors, and dealers are generally not verifying RCA due to a lack of awareness and availability of cost effective and easy-to-use RCA verification services.

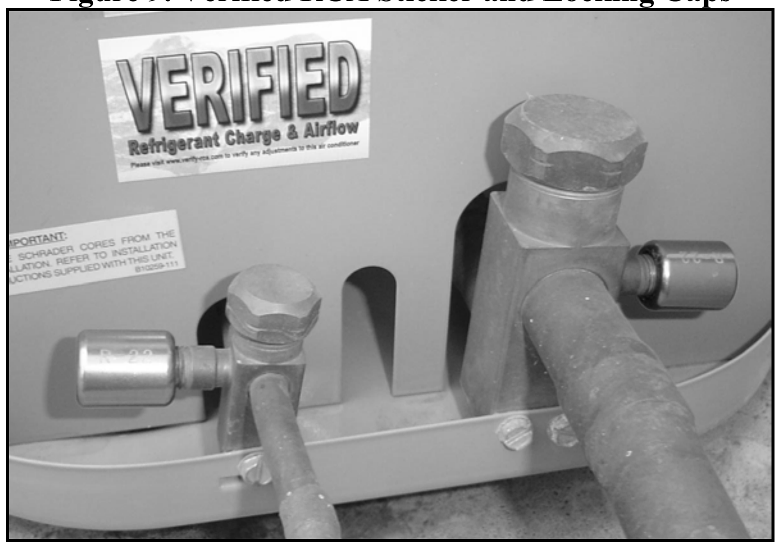
These market barriers are addressed by the RCA Verification program developed by Robert Mowris & Associates (RMA) and Alpen Software (Mowris et al. 2004).[6] The program provides several cost-effective methods to verify proper RCA. These include: 1) Personal Digital Assistant (PDA); 2) cell-phone telephony; 3) web-enabled PDA; or 4) web-enabled PDA cell phones (see **Figure 8**). The program can be deployed in any language, and since the system is automated, the cost per verified system is low. Verification information is collected and archived in a database where it is checked for accuracy and can be viewed over the internet by consumers, inspectors, dealers, and program managers. Verified jobs are randomly selected for inspections to ensure high quality results. The program provides clearly identifiable Verified RCA labels and locking, double-sealing, color-coded Schrader caps (green for R22 and red for R410a with tamper-proof keys for technicians). Locking caps are designed to maintain proper RCA for the

[6] Other products and services that address refrigerant charge and airflow verification include: Enalasys; Honeywell HVAC Service Assistant; and CheckMe (Enalasys 2004; Honeywell 2004; Proctor 2004).

life of the air conditioner (**see Figure 9**). This is important since air conditioning systems are made of welded copper pipe (like plumbing in a house), and Schrader valves are the weakest link. Air conditioners vibrate and this causes Schrader valve cores to loosen (i.e., unscrew) over time and leak refrigerant. Most air conditioners have easily removable Schrader caps or the caps do not have an integral "O-ring" seal. Safety is another reason why locking Schrader caps are important as evidenced by the recent deaths of two teenagers in Southern California due to inhalation of refrigerant as an intoxicant (LA Times 2004). The program also verifies proper installation of TXVs and sensing bulbs.

Figure 8. Verify RCA PDA

Figure 9. Verified RCA Sticker and Locking Caps



Conclusions

Field measurements of 4,168 new and existing air conditioners with and without TXVs indicate approximately 72 percent had improper refrigerant charge and 44 percent had improper airflow. EER measurements of air conditioners with improper RCA indicate a relative efficiency gain of 21 ± 7 percent for TXV and a gain of 17.1 ± 2.8 percent for non-TXV air conditioners. The difference in efficiency gain between TXV and non-TXV air conditioners is 3.9 ± 0.3 percent at the 90 percent confidence level. The uncertainty associated with field measurements of capacity and EER were evaluated using the propagation of error technique and the overall uncertainty error is ± 4.4 percent. The average measured load impacts per unit for both types of systems are 270 ± 58 kWh or 12.6 ± 2.3 percent. Average measured peak kW savings are 0.32 ± 0.06 kW based on data collected during summer weekdays at 21 sites for a period of 2 to 4 weeks before and after making RCA adjustments. Extrapolating to the 2,996 air conditioners in this study that received proper RCA yields gross savings of 808,920 ± 173,768 kWh per year and peak demand savings of 959 ± 180 kW. Assuming an eight year effective useful lifetime yields gross lifecycle savings of 6,471,360 ± 1,390,144 kWh.

Approximately 6 million new residential and commercial split-system, heat pump, and small packaged air conditioners are installed in the United States each year. Studies have shown that approximately 50 to 67 percent of these systems are installed with improper RCA causing them to operate 10 to 20% less efficiently than if they were properly installed. The total potential savings in the United States from proper RCA are estimated at 19.6 ± 3.5 billion kWh/yr and peak savings are estimated at 10.3 ± 1.9 GW.

Laboratory studies indicate the efficiency degradation for TXV units is roughly 5 percent at ± 20 percent of the correct charging condition. Findings from this study indicate an average efficiency gain of 21 ± 7 percent for TXV air conditioners with an average charge adjustment of 25 ± 12 percent. The student t-test was used to evaluate the mean efficiency difference between field and laboratory measurements and the differences were found to be statistically significant. These findings indicate TXV and non-TXV air conditioners have comparable efficiency gains due to proper RCA irrespective of whether they are over- or under charged. This study found TXVs are less effective than proper RCA in terms of delivering rated efficiency. The primary reasons for this appear to be due to sensing bulbs installed without insulation, without adequate linear contact, and at incorrect orientations.

There are many market barriers to RCA verification including: performance uncertainty; higher start-up costs; lack of information; misplaced or split incentives; inseparability of product features; asymmetric information; bounded rationality; organizational practices; and service availability. These market barriers are addressed by several products and services, including the RCA Verification program developed by Robert Mowris & Associates and Alpen Software.

Acknowledgements

This paper was made possible by funding provided by John Berlin of Northern California Power Agency through a joint contract with the California Energy Commission. Field research at customer sites was made possible with the cooperation of the following individuals, utilities, and companies: Kris Blair and Patrick Morrison, Roseville Electric Company; Peter Govea, Modesto Irrigation District; Patrick Keener, Redding Electric Utility; Steve Shallenberger, Doug Price, Scott Price, and Roger Thornton, American Synergy Corporation; Marjorie Hamilton, Southern California Edison; and Mona Yew, Pacific Gas and Electric. Review comments and suggestions were provided by Pete Jacobs, Architectural Energy Corporation, and Dr. Lori Megdal, Megdal & Associates.

References

Advanced Distributor Products (ADP). 2003. *TXV Installation Instructions.* 0991710-01 Rev 1, October 03. Stone Mountain, Ga.: Advanced Distributor Products, Available online: www.adpnow.com.

AllStyle Coil Company, L.P. (Allstyle). 2001. *Evaporator Coil Installation Instructions.* Brittmore, Texas: AllStyle Coil Company, L.P.

American Refrigeration Institute (ARI). 2003. *2003 Standard for Unitary Air Conditioning and Air-Source Heat Pump Equipment.* ARI 210/240-2003. Arlington, Va.: American Refrigeration Institute.

American Refrigeration Institute (ARI). 2004. *ARI Statistical Release of Unitary Heating and Cooling Section's Reports of U.S. Manufacturers Shipments.* Arlington, Va.: American Refrigeration Institute. Available online: http://www.ari.org/sr/2003.

American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE). 2002. *ASHRAE Guideline 14-2002 – Measurement of Energy and Demand Savings*. Atlanta, Ga.: American Society of Heating Refrigerating and Air-Conditioning Engineers.

Blasnik, M., Proctor, J., Downey, T., Sundal, J., and Peterson, G.1995. *Assessment of HVAC Installations in New Air Conditioners in SCE's Service Territory.* Rosemead, Calif.: Southern California Edison.

Bourdon, John (US Air Conditioning Sales Manager). 2003. Personal communication. Dec. 12.

California Energy Commission (CEC). *2001 Energy Efficiency Standards*. Report CEC P400-01-024. June 1, 2001. Sacramento, Calif.: California Energy Commission.

Carrier Corporation (Carrier). 2002. *Installation Instructions: Thermostatic Expansion Valve Kit*. KAATX, KHATX (R22), KSATX----PUR (R410a). Syracuse, N.Y.: Carrier Corporation.

Davis, R. 2001a. *Influence of the Expansion Device on Performance of a Residential Split-System Air Conditioner.* Report No.: 491-01.4. San Francisco, Calif. Pacific Gas and Electric.

Davis, R. 2001b. *Influence of Expansion Device and Refrigerant Charge on the Performance of a Residential Split-System Air Conditioner using R-410a Refrigerant.* Report No.: 491-01.7. San Francisco, Calif.: Pacific Gas and Electric.

Downey, T., Proctor, J. 2002. "What Can 13,000 Air Conditioners Tell Us?" In the *Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings*. 1:53-67. Washington, D.C.: American Council for an Energy-Efficient Economy.

Enalasys. 2004. Calexico, Calif.: Enalasys. Available online: http://www.enalasys.com.

Emerson Climate Technologies, Inc. 1998. *Installation Instructions Expansion Valve Kits TXV153 & TXV355.* Lewisburg, Tenn.: Emerson Climate Technologies, Inc.

Energy Information Agency (EIA). 1999. *Commercial Buildings Energy Consumption Survey.* Available online: http://www.eia.doe.gov/emeu/cbecs/tables.

Energy Information Agency (EIA). 2001. *Residential Energy Consumption Survey.* Available online: http://www.eia.doe.gov/emeu/recs/byfuels.

Eto, J. Prahl, R., Schlegel, J. 1996. *A Scoping Study on Energy Efficiency Market Transformation by California Utility DSM Programs.* LBNL-39058. Berkeley, Calif.: Lawrence Berkeley National Laboratory.

Farzad, M., O'Neal, D. 1993. "Influence of the Expansion Device on Air Conditioner System Performance Characteristics Under a Range of Charging Conditions." Paper 3622.

ASHRAE Transactions. Atlanta, Ga.: American Society of Heating Refrigerating and Air-Conditioning Engineers.

Fels, M., Kissock, K., Marean, M., and Reynolds, C. 1995. *PRISM Advanced Version 1.0 User's Guide*. Princeton, N.J.: Princeton University, Center for Energy and Environmental Studies.

Hall, N., Barata, S., Chernick, P., Jacobs, P., Keating, K., Kushler, M., Migdal, L., Nadel, S., Prahl, R., Reed, J., Vine, E., Waterbury, S., Wright, R. 2004. *The California Evaluation Framework*, Appendix to Chapter 7: 191-195. Uncertainty Calculation. San Francisco, Calif.: California Public Utilities Commission.

Hamilton, Tom (CHEERS Executive Director). 2003. Personal communication. December 12.

Hammarlund, J., Proctor, J., Kast, G., and Ward, T. 1992. "Enhancing the Performance of HVAC and Distribution Systems in Residential New Construction." In *Proceedings of 1992 ACEEE Summer Study on Energy Efficiency in Buildings,* 2: 85-87. Washington, D.C.: American Council for an Energy-Efficient Economy.

Hirsch, J. J. 2002. *eQuest and DOE-2.2 Building Energy Simulation Program.* Version 3.37, Copyright J.J. Hirsch. Camarillo, California.

Honeywell 2004. Honeywell HVAC Service Assistant. Minneapolis, Minn.: Honeywell Corporation. Available online: www.honeywell.com/building/components.

Kelsey, J. 2004. Get Psyched™ Psychrometric Software for MS Excel, Available online: www.kw-engineering.com. Oakland, Calif. kW Engineering.

Los Angeles Times. 2004. *Woman and Boy Found Dead in La Puente Home Pool ("drowned after inhaling refrigerant and losing use of their limbs").* 5-07-04. Los Angeles, California.

Mowris, R., Greenwood, D., Zlimen, I., Ross, P. 2004. Verify-RCA™, Olympic Valley, Calif.: Robert Mowris & Associates. Available online: http://www.verify-rca.com.

Neme, C., Nadel, S., and Proctor, J. 1998. *National Energy Savings Potential from Addressing HVAC Installation Problems*, Vermont Energy Investment Corporation, prepared for US Environmental Protection Agency.

O'Neal, D., Farzad, M. 1990. "The Effect of Improper Refrigerant Charging on Performance of an Air Conditioner with Capillary Tube Expansion." *Energy and Buildings* 14: 363-371.

Palani, M., O'Neal, D., and Haberl, J. 1992. *The Effect of Reduced Evaporator Air Flow on the Performance of a Residential Central Air Conditioner*, The Eighth Symposium on Improving Building Systems in Hot and Humid Climates.

Parker, D. 1997. *Impact of Evaporator Coil Air Flow in Residential Air Conditioning Systems,* FSEC-PF-321-97. Cocoa, Fla.: Florida Solar Energy Center.

Proctor, J. 2004. CheckMe!™, San Rafael, Calif.: Proctor Engineering Group. Available online: http://www.proctoreng.com/checkme/checkme.html

Robison, D. 2000. "Use of a Billing Simulation Tool for Performance Measurement and Verification." In *Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings.* 4:283-293. Washington, D.C.: American Council for an Energy-Efficient Economy.

Rodriguez, A. 1995. *The Effect of Refrigerant Charge, Duct Leakage, and Evaporator Air Flow on the High Temperature Performance of Air Conditioners and Heat Pumps*, Palo Alto, Calif.: Electric Power Research Institute.

Stellar Processes (Stellar). 2002. EZ Sim Building Simulation Tool, Version 6.0. Available online: www.ezsim.com. Portland, Oregon. Stellar Processes.

Tomczyk, J. 1995. *Troubleshooting and Servicing Modern Air Conditioning and Refrigeration Systems*. ESCO Press. Mt. Prospect, Ill.: Educational Standards Corporation.

United States Federal Trade Commission (USFTC) 1996. *Appliance Labeling Rule for Central Air Conditioners and Heat Pumps*. 16 CFR Part 305. Authorized by the Energy Policy and Conservation Act, Subchapter III, Part A, 42 U.S.C. 6291 et seq. 52 FR 46894, Dec. 10, 1987, as amended at 54 FR 28034, July 5, 1989. Available online: http://www.ftc.gov/bcp/conline/edcams/eande/index.html.