Laboratory Measurements and Diagnostics of Residential HVAC Installation and Maintenance Faults

Robert Mowris, Ean Jones, and Robert Eshom, Robert Mowris & Associates, Inc.

ABSTRACT

Laboratory test results are provided of residential heating, ventilating, and air-conditioning (HVAC) installation and maintenance faults on a new 13-SEER split-system air conditioner. Test conditions differ from those used to rate cooling systems to match typical installations in California. Equipment was set up in three chambers to model indoor, outdoor, and hot-attic conditions. Tests were conducted using thermostatic expansion valve (TXV) and piston metering devices (non-TXV). Test results are provided for the following faults: low airflow, coil blockage, refrigerant under/over charge, duct leakage, ducts/equipment in hot-attic conditions, improper TXV sensing bulb installation, non-condensables, and restrictions. Baseline tests using the "code tester" instead of forced-air unit (FAU) are within +/-3.2% of the rated Seasonal Energy Efficiency Ratio (SEER) of 13 with ducts, evaporator, and FAU located in conditioned space. The SEER is 8% less with the FAU in conditioned space. With ducts, evaporator, and FAU in hot-attic conditions, the peak efficiency is 11% less and seasonal efficiency is 29% less. Moderate to severe non-condensables reduce efficiency by 13 to 38% and increase power by 6 to 28%. Refrigerant restrictions reduce efficiency by 30 to 59%. The combination of multiple faults including low airflow, undercharge, duct leakage, and condenser coil blockage reduce efficiency by 58% to 73%. Laboratory measurements are used to develop methods to differentiate non-condensables, restrictions, and coil blockage from refrigerant charge faults. If refrigerant-system faults are detected manufacturers recommend recovering charge, making corrections, evacuating to 500 microns, and weighing in factory charge.

Introduction

Residential and commercial heating, ventilating, and air conditioning (HVAC) consumption in the United States accounts for 30% of average summer peak-day electricity loads, 13% of total electricity use, and 44% of total natural gas use [USEIA 2009]. A 2002 study published by the Hewlett Foundation indicates that improved HVAC installation and maintenance represents one of the largest economically achievable opportunities for energy efficiency savings [Rufo 2002]. This paper provides laboratory test results of a new 3-ton split-system 13-SEER air conditioner using R-22 refrigerant. Test conditions differ from those used to rate cooling systems to match typical installations in California. The equipment was set up in three chambers to simulate both AHRI 210/240 indoor and outdoor conditions and hot attic conditions. Laboratory test results are provided for HVAC faults that occur due to installation and maintenance deficiencies and degradation. Tests were conducted using thermostatic expansion valve (TXV) and non-TXV piston metering devices. Test results are provided for the following faults: uninsulated TXV sensing bulb, low airflow, ducts and equipment in 118°F hot attic, evaporator/condenser coil blockage, duct leakage, improper refrigerant charge, non-condensables, and restrictions.[1]

The tests were performed to support California energy efficiency programs promoting quality installation and maintenance in order to evaluate the effectiveness of refrigerant charge diagnostic protocols, measurement tools, and procedures [ANSI/ACCA 2007]. Some programs rely on the California Energy Commission (CEC) refrigerant charge and airflow (RCA) protocol which requires verification of subcooling (SC) for TXV units or superheat (SH) for non-TXV units (CEC 2008). Other programs rely on proprietary protocols.[2] Yuill and Braun evaluated the CEC RCA protocol and reported 41% correct diagnosis for non-TXV and 64% correct diagnosis for TXV equipped systems (Yuill and Braun 2012). Laboratory tests and field observations of technicians indicate that generic RCA protocols, inaccurate tools, and improper procedures can cause false alarms, misdetection, and misdiagnosis (Mowris et al. 2013). Laboratory tests of unit-specific manufacturer refrigerant charge (RC) protocols indicate fewer problems diagnosing refrigerant charge faults when no other faults are present due to wider tolerances and multi-step procedures (Mowris et al. 2013). Nevertheless, both types of protocols have limitations and neither can diagnose refrigerant charge faults from non-condensables, restrictions, condenser or evaporator heat transfer issues, low airflow, or expansion valve failure.

Test Equipment and Laboratory Setup

The tested split-system air conditioning equipment is a nominal 3-ton (36,000 Btu/hr) unit with a Seasonal Energy Efficiency Rating (SEER) of 13 and an Energy Efficiency Rating (EER) of 11.2 when equipped with a hard shut-off (HS) TXV, time delay relay (TDR), and R-22 refrigerant.[3] A manifold with isolation valves was used to test the HS-TXV and non-TXV (piston) expansion devices commonly found on older equipment. Outlet tubes from the expansion devices merged to supply liquid refrigerant to the evaporator coil. The outdoor unit consists of a condenser, compressor, and condenser fan. The indoor unit consists of an evaporator coil, FAU, and appropriate supply and return ducts to connect the unit to measurement equipment and the indoor chamber conditions. The equipment was manufactured in 2010, but is currently unavailable in the United States due to the phase out of R-22 refrigerant.

Laboratory tests were conducted according to AHRI Standard 210/240-2008 with modifications to obtain "application" Energy Efficiency Ratio* (EER*) and Seasonal Energy Efficiency Ratio (SEER*) [ANSI/AHRI 2008].[4] Test modifications include locating ducts, evaporator, and FAU in hot attic conditions of 118°F dry-bulb and 78°F wet-bulb temperature to simulate typical peak cooling applications in California and other hot climates where ducts are located in unconditioned attics. Test modifications also included duct leakage on supply and return ducts, longer ducts with bends typical of field installations, and line-set lengths of 25 and 50 feet between the condenser and evaporator. The unit was also tested with equipment located

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[1] The 118°F hot attic temperature is 3°F less than 122°F maximum for black shingles, radiant barrier, and 1:150 enhanced ventilation and 18°F less than black shingles, radiant barrier and 1:300 standard ventilation (Parker 2008).

[2] See http://www.ac-quality.com/contractors/about_qm or http://www.hvacoptimization.com/.

[3] AHRI Rating is for the condenser and evaporator pair tested with no FAU, hard shut-off TXV, and TDR that continues fan operation after compressor turns off to recover latent cooling from evaporator and increase efficiency.

[4] The ARI 210/240 EER_A and EER_B indoor air dry-bulb temperature is 80°F and the wet-bulb is 67°F. The EER_A outdoor air dry-bulb is 95°F. The EER_B outdoor air dry-bulb is 82°F. The SEER outdoor air dry-bulb is 82°F, indoor air dry-bulb is 80°F, and indoor air wet-bulb is 57°F.

in conditions of 80°F dry-bulb and 67°F wet-bulb (per the AHRI 210/240 test).[5] The "application" efficiency ratings are the combined equipment plus distribution system efficiency typical of California residential applications, but not equivalent to published AHRI ratings. The air conditioning equipment was tested with its AHRI-rated configuration including HS-TXV with copper sensing bulb/strap, 25-feet line set and test chamber "code tester" fan to verify the rating (ANSI/ASHRAE 1987).[6] The unit was also tested with an HS-TXV with stainless-steel sensing bulb/strap and non-TXV.

Tests were performed at an AHRI-certified laboratory located in the United States. The laboratory is used by manufacturers to certify air conditioners and heat pumps for AHRI testing. The test facility consists of climate-controlled indoor, outdoor, and hot attic chambers where ducts, evaporator, and FAU are located. The air conditioner, liquid-line filter drier, metering devices (TXV and non-TXV), sight glasses, and standard test equipment were assembled and installed in the test chambers by laboratory technicians. Prior to charging with refrigerant, the system was pressurized to 300 psig with nitrogen and held for 60 minutes to absorb moisture and check for leaks. After the nitrogen leak test, a vacuum pump was used to evacuate the system to below 500 micron mercury (μHg) vacuum held for 30 minutes (ASHRAE 2010).

Baseline Tests

Unique baseline tests are performed for each set of tests since each setup can cause slight variations between baseline tests. **Table 1** provides a comparison of test findings to the AHRI rating for a typical residential installation. Tests 318-2 were performed with the code-tester fan (no FAU), HS-TXV with copper bulb/strap, and ducts and evaporator located in conditioned space at 80°F dry-bulb and 67°F wet-bulb temperatures. Tests 318-2 measured 11.3 +/- 0.36 EER and 12.63 +/- 0.4 SEER which are within +/-3.2% of the 11.2 EER and 13 SEER rated values.[7] Tests 310 were performed with an HS-TXV with stainless-steel bulb/strap and ducts, evaporator, and FAU in conditioned space causing a 4% reduction in EER^*_A and 8% reduction in SEER* compared to the AHRI rating. Tests 303 were performed with the same equipment as tests 310, but with ducts, evaporator, and FAU in hot attic conditions. Tests 303 have 15% lower EER^*_A and 29% lower SEER* than the AHRI ratings. Comparing tests 303 to 310 shows that locating equipment in hot attic conditions reduces EER* by 11% and SEER* by 23%. Monitoring studies show homes with ducts in hot attics use up to 30% more space cooling energy (Cummings 1991).The manufacturer RC protocol is correct for all tests, i.e., actual SC is within +/-3°F of the unit-specific manufacturer 7°F target.[8]

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[5] AHRI 210/240 prescribes supply air fan power of 0.365W/cfm of supply air with fan heat of 1.250 Btuh/cfm. The tested unit supply fan power was 0.470 W/cfm.

[6] The "code tester" is the airflow measuring apparatus described in Section 5.3 Test Chambers (Code Testers), ANSI/ASHRAE 41.2-1987 (RA92).

[7] Efficiency values (i.e., EER and SEER) are based on air-side calculations. The uncertainty of EER and SEER calculations is +/-2.8% based on laboratory measurement tolerances and 5.5% based on ANSI/AHRI 210/240 tolerances. S. Klein. 1992. Engineering Equation Solver v8.897. http://www.fchart.com/ees/.

[8] Target subcooling is based on manufacturer data. Subcooling measures the heat removed from refrigerant after it changes to liquid and is defined as the difference between condenser saturation temperature and liquid line temperature. Delta subcooling is the difference between actual and target subcooling.

Table 1. Baseline TXV tests with equipment in conditioned space and hot attic

Description	Duct Leakage	EER^*_A Capacity (Btuh)	EER^*_A	EER^*_A Impact %	Delta SC (°F)	Manufacturer RC Protocol	SEER*	SEER* Impact %	Test
AHRI Rating (no FAU, HS-TXV, TDR)	2%	33,800	11.2		NA	Correct chg	13.0		n/a
Code tester, HS-TXV copper bulb/strap, ducts/evaporator in conditioned space, no TDR	2%	35,607	11.3	1%	3.0	Correct chg	12.63	-3%	318-2
FAU, HS-TXV steel bulb/strap, ducts/evap/FAU in conditioned space, no TDR	2%	35,030	10.7	-4%	-0.8	Correct chg	11.9	-8%	310
Above + ducts/evap/FAU in hot attic conditions no TDR	2%	31,054	9.5	-15%	-2.8	Correct chg	9.2	-29%	303

Baseline and multiple fault tests for the non-TXV are presented in **Table 2**. Baseline Tests 300 were performed with ducts, evaporator, and FAU in conditioned space. Tests 189-4 were performed with ducts, evaporator, and FAU in the hot attic chamber. Tests 189-4 have 10% lower EER^*_A and 18% lower SEER* compared to Tests 300 (exclusive of duct leakage). Tests 409 were performed with multiple faults including 25% low airflow 10% undercharge, 30% duct leakage, and 50% condenser coil blockage. Tests 409 have 58% lower EER^*_A and 73% lower SEER* than Tests 300. The baseline for developing diagnostic tests for non-condensables is referenced to ducts, evaporator, and FAU in hot attic conditions (TXV tests 303 and non-TXV tests 189-4). The CEC RCA protocol indicates an overcharge and low airflow for the baseline Tests 300 (80°F cool attic), and correct RCA for the hot attic tests. For the multiple-fault tests the CEC RCA protocol correctly indicates undercharge and low capacity.

Table 2. Baseline and multiple fault non-TXV tests w/ equip. in cond. space and hot attic

Description	Duct Leakage	EER^*_A Capacity (Btuh)	EER^*_A	EER^*_A Impact %	Delta TS (°F)	Delta SH (°F)	CEC RCA Protocol	SEER*	SEER* Impact %	Test
FAU, non-TXV, no TDR, ducts/evap/FAU in conditioned space, 50 feet line set	2%	34,542	10.5	NA	4.3	-11.3	Overcharge, low airflow	10.8	NA	300
Above + ducts/evap/FAU in hot attic 118°F	2%	31,050	9.4	-10%	2.3	-2.3	Correct RCA	8.9	-18%	189-4
Above + 25% low airflow, -10% charge, 30% duct leakage, 50% cond. coil block	30%	13,731	4.4	-58%	-7.0	30.4	Correct undercharge, low capacity	2.94	-73%	409

Thermostatic Expansion Valve Tests

TXV tests were conducted to evaluate sensing bulb insulation. **Table 3** provides insulated and uninsulated TXV sensing bulb test results with correct charge of 102 ounces and 10% to 40% overcharge with 50 feet line set and equipment located in hot attic conditions. The uninsulated TXV sensing bulb causes improper metering of refrigerant and reduces efficiency by

2%. The manufacturer RC protocol provides a false alarm for test 22 and misdetections for tests 35, 38, and 39. Test 42 (+40% charge) is correctly diagnosed. For proper operation the TXV sensing bulb must be at the correct orientation with copper straps and R-1 closed-cell insulation.

Table 3. Insulated and uninsulated TXV sensing bulb tests with equipment in hot attic

Description	EER^*_A Capacity (Btuh)	EER^*_A	EER^*_A Impact %	Delta SC (°F)	Manufacturer RC Protocol	Test
TXV R-1 insul., correct chg, 102 oz.	31,420	9.60	NA	-0.7	Correct charge	23
TXV uninsulated, correct chg, 102 oz.	30,873	9.41	-2%	-5.4	False alarm UC	22
TXV uninsulated, +10% chg, 112.2 oz	30,237	9.19	-4%	-2.9	Misdetection	35
TXV uninsulated, +20% chg, 122.4 oz	30,075	8.97	-7%	-2.9	Misdetection	38
TXV uninsulated, +30% chg, 132.6 oz	28,676	8.44	-12%	-1.2	Misdetection	39
TXV uninsulated, +40% chg, 142.8 oz	27,754	7.99	-17%	7.3	Overcharge	42

Airflow Tests

Airflow test results are shown in **Table 4** for the non-TXV unit with equipment in hot attic conditions. Airflow tests are performed with refrigerant charge of 108 ounces. Typical in-situ airflow ranges from 160 to 370 cfm/ton with an average of 320 cfm/ton (Parker et al. 2007). Lab tests indicate that low airflow reduces EER^*_A by 3 to 12%. The non-TXV tests for this specific unit, demonstrate that low airflow down to 350 cfm/ton does not cause false charge diagnostics using the CEC RCA protocol (i.e., delta SH is within +/-5°F and delta TS is within +/-3°F).[9] Low airflow at 250 cfm/ton or less causes misdiagnosed overcharge due to icing of the evaporator coil. The CEC RCA temperature split protocol correctly detects low airflow for test 65 at 302 cfm/ton and test 66 at 250 cfm/ton (i.e., delta TS greater than 3°F).[10]

Table 4. Low airflow impact on EER* (non-TXV) and hot attic

Description	EER*A Capacity (Btuh)	Airflow cfm/ton	EER*A	EER*A Impact %	Delta TS (°F)	Delta SH (°F)	CEC RCA Protocol	Test
Baseline airflow	31,302	391	9.49	NA	2.5	-3.7	Correct RCA	53
10% low airflow	29,501	351	9.19	-3%	2.8	-0.2	Correct RCA	64
23% low airflow	28,538	302	9.04	-5%	4.6	-2.2	Correct RC, low airflow	65
36% low airflow	26,174	250	8.39	-12%	5.4	-6.0	Misdiagnosed OC, correct low airflow	66

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[9] Target superheat is based on return air wetbulb and condenser entering air drybulb. Delta superheat is the difference between actual and target superheat. Superheat measures the heat added to refrigerant after it changes to vapor and is defined as the difference between suction line temperature and evaporator saturation temperature.

[10] The CEC RCA temperature split (TS) protocol measures the sensible temperature drop across the evaporator coil and compares this value to target temperature split (TTS) to estimate proper airflow assumed to be 350 and 400 cubic feet per minute (cfm). The TTS varies from 8.1 to 25.9°F over a range of return drybulb temperatures of 70 to 84°F and return wetbulb temperatures of 50 to 76°F. Delta TS is the difference between actual TS and TTS.

Evaporator Coil Blockage Tests

Table 5 provides evaporator coil blockage test results for the non-TXV with 25-feet line set and ducts, evaporator, and FAU in conditioned space.[11] The Test 8 baseline has refrigerant charge of 78.4 ounces. Test 10 has 50% evaporator coil blockage which causes 16% low airflow. The EER* is reduced by 5% and delta SH is outside the acceptable +/-5°F tolerance. Test 10 shows that 50% evaporator coil blockage causes the CEC RCA protocol to diagnose false overcharge (i.e., delta SH less than -5°F). Test 11 has 50% coil blockage, 16% low airflow and 10% undercharge. The EER* is 7% less than the Test 8 baseline. Test 11 delta SH is 1.0°F (within +/-5°F tolerance) and delta TS is 0.7°F (within +/-3°F tolerance). The CEC RCA protocol does not detect 16% low airflow nor 10% undercharge.

Table 5. Evaporator coil blockage impact on EER* (non-TXV) equip in conditioned space

Description	EER*A Capacity (Btuh)	Airflow cfm/ton	EER*A	EER*A Impact %	Delta TS (°F)	Delta SH (°F)	CEC RCA Protocol	Test
Baseline non-TXV	33,652	400	10.40	NA	0.0	1.1	Correct RCA	8
50% coil blockage, 16% low airflow	31,281	335	9.92	-5%	1.6	-11.1	False overcharge missed detection	10
50% coil blockage, 16% low airflow, -10% chg	30,531	336	9.66	-7%	0.7	1.0	Missed detection	11

Table 6 provides evaporator coil blockage test results for the HS-TXV unit with 25-feet line set and ducts, evaporator, and FAU in conditioned space. The Test 1 baseline has refrigerant charge of 86.4 ounces. Test 12 has 50% coil blockage which causes 15% low airflow. The EER* is reduced by 4.2%, but the unit is diagnosed with correct charge since delta SC is -0.1°F and within +/-3°F tolerance. The manufacturer protocol does not detect 15% low airflow.

Table 6. Evaporator coil blockage impact on EER* (HS-TXV) equip in conditioned space

Description	EER*A Capacity (Btuh)	Airflow cfm/ton	EER*A	EER*A Impact %	Delta TS (°F)	Delta SC (°F)	Manufacturer RC Protocol	Test
Baseline TXV	34,205	395	10.24	NA	1.2	2.1	Correct RCA	1
50% coil blockage 15% low airflow	31,239	335	9.81	-4%	1.5	-0.1	Correct charge, missed detection	12

Duct Leakage Tests

Table 7 provides duct leakage test results for the non-TXV system with ducts, evaporator, and FAU located in hot attic conditions maintained at 118°F. The baseline Test 400 2% duct leakage is measured at 25 Pascal as the percentage of total system airflow of 300 cfm/ton per the modified test procedure (25% low airflow). Duct leakage tests are performed with refrigerant charge of 108 ounces. The Test 401 6% duct leakage is the compliance value in the California Energy Commission building energy efficiency standards (CEC 2008). The Test

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[11] Tests in conditioned space were performed with 25 feet line-set requiring less refrigerant charge than tests in hot attic conditions with 50 feet line-set. Evaporator coil was blocked with plastic corrugated cardboard covering 50% of the upstream side of the evaporator cross-sectional area.

402 15% duct leakage is per Energy Star. The Test 403 30% duct leakage is common of many US homes [Parker 1998, Roberts 2010, USEPA 2011]. Tests were performed with 50% of duct leakage on the return and supply plenum. Modified AHRI 210/240 tests were conducted to obtain the following unit plus distribution system application efficiencies: EER*$_{A}$, EER*$_{B}$, and SEER*. Tests indicate that duct leakage of 6 to 30% reduces efficiency by 7 to 42% compared to baseline. The CEC RCA protocol is correct for all tests except test 403 (30% duct leakage) which is misdiagnosed with undercharge and correct airflow.

Table 7. Duct leakage impacts on EER* and SEER* for non-TXV and hot attic

Description	EER*A Capacity (Btu/hr)	EER*A	EER*A Impact %	Delta TS (°F)	Delta SH (°F)	CEC RCA Protocol	EER*B	SEER*	SEER* Impact %	Test
Baseline 2% duct leakage	28,670	9.27	NA	5.1	-3.5	Correct RC low airflow	10.62	9.17	NA	400
6% duct leakage	26,804	8.65	-7%	5.7	-3.0	Correct RC low airflow	9.81	7.93	-14%	401
15% duct leakage	23,708	7.59	-18%	4.3	1.3	Correct RC low airflow	8.47	6.95	-24%	402
30% duct leakage	18,736	5.96	-36%	2.1	5.4	Misdiagnosed	6.5	5.33	-42%	403

Condenser Coil Blockage Tests

Condenser coil blockage tests are performed with airflow of 400 cfm/ton and refrigerant charge of 108 ounces.[12] Results are shown in **Table 8**. Condenser coil blockage impacts EER*$_{A}$ by -4% to -32% and increases total air conditioner power by 3% to 27%. The CEC RCA protocol baseline clean condenser diagnostic is correct. The CEC RCA protocol misdiagnosed condenser coil blockage as an overcharge (OC) for 30 to 80% condenser blockage. The 80% condenser coil blockage test 190-2 has 40.7°F condenser over ambient (COA) defined as the condenser saturation temperature minus condenser entering air temperature. High COA indicates reduced condenser heat transfer (blockage or fan failure), non-condensables, or overcharge. Technicians following the CEC RCA protocol might remove charge from units having condenser heat transfer problems.

Table 8. Condenser coil blockage impact on EER* (non-TXV) and hot attic

Description	EER*$_{A}$ Capacity (Btu/hr)	EER*$_{A}$	EER*$_{A}$ Impact %	Delta TS (°F)	Delta SH (°F)	COA (°F)	CEC RCA Protocol	kW$_{A}$	kW$_{A}$ Impact %	Test
Baseline clean condenser	32,335	9.82	NA	2.6	1.6	15.9	Correct RCA	3.292	NA	189-2
30% condenser blockage	32,136	9.46	-4%	2.7	-8.8	19.3	Misdiagnosed OC	3.397	3%	192-2
50% condenser blockage	31,439	8.94	-9%	2.6	-13.5	23.3	Misdiagnosed OC	3.52	7%	191-2
80% condenser blockage	27,806	6.67	-32%	1.6	-12.8	40.7	Misdiagnosed OC	4.168	27%	190-2

Refrigerant Charge Tests

Table 9 provides refrigerant charge test results for the HS-TXV unit and hot attic conditions of 118°F dry bulb and 78°F wet bulb temperatures. Tests are performed with airflow

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[12] Condenser coil was blocked with plastic corrugated cardboard covering 50 to 80% of the inlet cross-sectional area. Field tests of dirty condenser coils verified the test setup based on similar condenser pressure impacts.

from 376 to 387 cfm/ton (depending on condensation or icing). The HS-TXV EER* performance is severely impacted by under charge. The manufacturer protocol correctly diagnoses all of the refrigerant charge fault tests.

Table 9. Refrigerant charge impacts on EER* and kW$_A$ for HS-TXV and hot attic

Description	EER*$_A$ Capacity (Btu/hr)	EER*$_A$	EER*$_A$ Impact %	kW*$_A$	kW$_A$ Impact %	Delta SC (°F)	COA (°F)	Manufacturer RC Protocol	Test
Baseline charge 102 oz.	31,420	9.60	NA	3.28	NA	-1.0	14.6	Correct charge	23
+10% charge 112.2 oz.	31,796	9.24	-4%	3.44	5%	12.9	22.4	Overcharge	36
+20% charge 122.4 oz.	31,730	8.84	-8%	3.59	9%	18.9	27.8	Overcharge	37
+30% charge 132.6 oz.	31,321	8.12	-15%	3.86	18%	22.3	31.6	Overcharge	40
+40% charge 142.9 oz.	30,796	8.01	-17%	3.84	17%	24.4	34.3	Overcharge	41
-10% charge 91.8 oz.	29,200	9.22	-4%	3.17	-3%	-7.1	10.7	Undercharge	45
-20% charge 81.6 oz.	25,826	8.28	-14%	3.12	-5%	-7.4	9.1	Undercharge	48
-30% charge 71.4 oz.	21,170	6.98	-27%	3.03	-8%	-7.5	6.7	Undercharge	49
-40% charge 61.2 oz.	12,242	4.24	-56%	2.89	-12%	-6.3	2.6	Undercharge	52

Table 10 provides refrigerant charge test results for the non-TXV piston and hot attic conditions of 118°F dry bulb and 78°F wet bulb temperatures. Tests are performed with airflow from 364 to 395 cfm/ton (depending on condensation or icing). Non-TXV EER* performance is severely impacted by undercharge similar to the TXV. The CEC RCA protocol correctly diagnoses all of the refrigerant charge fault tests.

Table 10. Refrigerant charge impacts on EER* and kW$_A$ for non-TXV and hot attic

Description	EER*$_A$ Capacity (Btu/hr)	EER*$_A$	EER*$_A$ Impact %	kW*$_A$	kW$_A$ Impact %	Delta TS (°F)	Delta SH (°F)	COA (°F)	CEC RCA Protocol	Test
Baseline charge 108.2 oz.	31,302	9.49	NA	3.30	NA	2.5	-4.4	17.7	Correct RCA	53
+10% charge 119 oz.	31,600	9.29	-2%	3.40	3%	2.9	-13.4	20.1	Overcharge	60a
+20% charge 129.8 oz.	31,013	9.08	-4%	3.42	4%	3.3	-13.4	20.4	Overcharge	61a
+30% charge 140.6 oz.	30,765	8.91	-6%	3.45	5%	2.7	-13.4	21	Overcharge	62
+40% charge 151.5 oz.	30,526	8.57	-10%	3.56	8%	2.6	-13.4	21.9	Overcharge	63
-10% charge 97.4 oz.	23,352	7.47	-21%	3.13	-5%	-3.5	28.8	10.1	Undercharge	55
-20% charge 86.6 oz.	20,371	6.70	-29%	3.04	-8%	-5.8	37.9	8.4	Undercharge	56a
-30% charge 75.8 oz.	12,629	4.30	-55%	2.94	-11%	-9.4	50.8	4.7	Undercharge	57a
-40% charge 64.9 oz.	9,186	3.20	-66%	2.87	-13%	-10.8	57.6	2.9	Undercharge	58

Non-condensable Tests

If proper vacuum is not achieved at installation the refrigerant system will be contaminated with non-condensable air and water vapor which can cause compressor failure. Non-condensables (NC) decrease condenser heat transfer and cooling capacity and increase condenser pressure and power input. **Table 11** provides laboratory test results for 0.3 oz (~0.3% of system charge by weight) of non-condensable nitrogen on the unit operating with the HS-TXV and hot attic conditions.[13] Tests are performed with airflow from 385 to 400 cfm/ton (depending

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[13] The 0.3 ounces or 0.3% non-condensable is based on nitrogen in an improperly evacuated 15-feet line set (262 in^3) plus evaporator coil volume (200 in^3).times the density of nitrogen at 6.535 x 10^{-4} oz./in^3.

on condensation) and refrigerant charge of 102 ounces. The impact is -13% for the EER$^*_A$, +6% for kW$^*_A$, and -13% for SEER*. The manufacturer RC protocol misdiagnoses non-condensables as an overcharge for test 505.

Table 11. Non-condensable impacts on EER* and SEER* for TXV and hot attic

Description	EER$^*_A$ Capacity (kBtuh)	EER$^*_A$	EER$^*_A$ Impact %	kW*$_A$	kW$_A$ Impact %	Delta SC (°F)	COA (°F)	Manuf. RC Protocol	SEER*	SEER* Impact %	Test
Baseline	31,054	9.48	NA	3.28	NA	-2.7	13.7	Correct	9.21	NA	303
0.3% NC	27,373	8.27	-13%	3.48	6%	15.0	25.9	Misdetection	7.98	-13%	505

Table 12 provides results for 0.3 oz (~0.3% system charge) of non-condensable nitrogen on the non-TXV unit. Tests are performed with airflow from 396 to 400 cfm/ton (depending on condensation or icing) and refrigerant charge of 108 ounces. The impact of 0.3% non-condensables is -18% for EER*$_A$, +8% for kW*$_A$, and -19% for SEER*. The impact of ~1% non-condensables (Test 501X) is -38% for EER*$_A$ and +28% for kW$_A$. The CEC RCA protocol misdiagnoses non condensables as a false undercharge for test 501 with 0.3% NC and 501X with ~1% NC. Split-system air conditioners are often evacuated with time-based procedures without a vacuum pressure gauge. Field observations indicate that many vacuum pumps have contaminated oil (Mowris et al 2013). Changing oil after every evacuation is required to achieve proper evacuations (JB 2007). Performing a vacuum to 240 µHg held at or below 500 to 1000 µHg for 30 minutes will remove non-condensables (ASHRAE 2010).

Table 12. Non-condensable impacts on EER* and SEER* for non-TXV and hot attic

Description	EER$^*_A$ Capacity (kBtuh)	EER$^*_A$	EER$^*_A$ Impact %	kW*$_A$	kW$_A$ Impact %	SC (°F)	Delta SH (°F)	COA (°F)	CEC RCA Protocol	SEER*	SEER* Impact %	Test
Baseline	31,050	9.42	NA	3.30	NA	10	2.1	16.1	Correct chg	8.86	NA	189-4
0.3% NC	27,373	7.71	-18%	3.55	8%	25.4	10.5	28.9	Misdiagnosis	7.22	-19%	501
~1% NC	20,486	5.87	-38%	4.21	28%	42.0	4.0	46.8	Misdiagnosis	NA	NA	501X

Refrigerant Restriction Tests

Moisture, copper particles, flux/brazing residue, and particulates left inside the system damage the compressor, clog metering devices, or make the metering device function improperly. Liquid line filter driers are recommended to remove moisture, acid, and particulates to prevent restrictions on field-charged split systems (Carrier 2010, Lennox 2008). **Table 13** provides laboratory test results for refrigerant restrictions on the non-TXV unit with refrigerant charge of 108 ounces. An adjustable valve on the liquid line causes a 22% increase in discharge pressure (DP) to suction pressure (SP) ratio. The impact is -30% for EER$^*_A$, -45% for EER$^*_B$, and -35% for SEER*. Power decreased by 100 W, or 3% similar to an under-charge. The CEC RCA protocol misdiagnoses the test 701 liquid line restriction as an undercharge. Adding refrigerant charge would decrease efficiency and damage the compressor.

Table 13. Refrigerant restriction impacts on EER* and SEER* for non-TXV and hot attic

Description	EER*$_A$ Capacity (kBtuh)	EER*$_A$	EER*$_A$ Impact %	EST (°F)	Delta SH (°F)	CEC RCA Protocol	EER*$_B$	SEER*	SEER* Impact %	Test
Base no restriction	32,759	9.42	NA	48.1	2.1	Correct RCA	10.64	8.86	NA	189-4
Restriction non-TXV	22,385	6.62	-30%	33.51	33.3	Misdiagnosis	5.81	5.72	-35%	701

Table 14 provides test results for restrictions on the TXV unit with refrigerant charge of 102 ounces. The impact is -36% for EER*$_A$, -55% for EER*$_B$, and -59% for SEER*. The manufacturer RC protocol for test 801 misdiagnoses the refrigerant restriction as an overcharge. Removing refrigerant charge would exacerbate icing of the evaporator and decrease efficiency.

Table 14. Refrigerant restriction impacts on EER* and SEER* for TXV and hot attic

Description	EER*$_A$ Capacity (kBtuh)	EER*$_A$	EER*$_A$ Impact %	EST (°F)	Delta SC (°F)	Manuf. RC Protocol	EER*$_B$	SEER*	SEER* Impact %	Test
Base no restriction	32,764	9.48	NA	48.5	-2.7	Correct chg	11.14	9.21	NA	303
Restriction TXV	19,812	6.06	-36%	30.5	4.8	Misdiagnosis	5.02	3.78	-59%	801

If refrigerant restrictions are present in the system and an acid test indicates sludge, standard cleanup procedures must be followed using oversize suction and liquid line filter driers to remove sludge. Vacuum pumps are not designed to remove sludge. If a split system older than 10 years contains sludge, it might be more cost effective to install a new system with new filter drier and clean or replace the line set. Manufacturers require properly-sized liquid-line filter driers on new systems or whenever opened. This is especially important for R410A systems.[14]

Refrigerant Charge Diagnostic Test Matrix

Accurate measurements of specific air conditioning models tested under laboratory conditions with single or multiple faults can be used to develop comprehensive refrigerant charge diagnostic algorithms based on DP, SP, suction temperature (ST), SH, SC, EST, COA, and liquid-line drier delta temperature (LDDT). **Table 15** provides an example refrigerant charge diagnostic test matrix.[15] Algorithms based on the matrix can be used to diagnose non-condensables, restrictions, refrigerant charge faults, condenser or evaporator heat transfer faults, low airflow, or expansion valve failure.[16] If non-condensables, restrictions or refrigerant charge faults are detected, then manufacturers recommend recovering refrigerant, removing restrictions, checking expansion valve, replacing liquid line drier (if restricted), evacuating to 500 microns

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[14] Filter driers must be installed on R410A systems to remove moisture from polyolester (POE) oils. R410A POE oil is very hygroscopic and quickly absorbs moisture from air which will cause acid formation. Moisture cannot be removed by 500 micron vacuums developed by evacuation pumps.

[15] Wirz, D. 2009. Commercial Refrigeration: For Air Conditioning Technicians. Cengage Learning, Inc.

[16] If TXV failure is detected technicians should verify whether the sensing bulb is properly attached to the suction line in the correct orientation and tightly strapped with at least one copper strap and one wrap of closed-cell foam insulation with 50% overlap. Copper is 4 to 10 times more thermally conductive than brass or stainless steel.

(held for 20 minutes below 1000 microns), and weighing in factory charge (Lennox 2006). This is the most reliable method to achieve correct refrigerant charge.

Table 15. Refrigerant charge diagnostic test matrix

	Low ST or SH	High ST or SH
Low SC, SP or DP	Expansion valve or sensing bulb failure	Refrigerant under charge, evaporator heat transfer fault, or liquid line restriction (LDDT > 3°F), SH, SC and low EST thresholds f(OAT, SH, SC) or compressor valve failure (check compressor Watts)
High SC, SP or DP	Refrigerant over charge, condenser heat transfer fault, low airflow, or non-condensables check SH, SC and high COA thresholds f(OAT, SH, SC)	Non-condensables check SH, SC and high COA thresholds f(OAT, SH, SC) or liquid line restriction check SH, SC and low EST thresholds f(OAT, SH, SC)

Conclusion

The tested unit efficiency is within +/-3.2% of 11.2 EER and 13 SEER AHRI ratings. Without considering duct leakage, hot attic conditions reduce peak and seasonal efficiency by 10% to 29%. These differences are typical since current California building efficiency standards do not include component and installation differences which cause lower efficiencies. Other common installation deficiencies such as duct leakage, undercharge, low airflow, non-condensables, or refrigerant restrictions cause lower operating efficiencies. The combination of multiple deficiencies such as low airflow, undercharge, duct leakage, and condenser coil blockage can reduce efficiency 58% to 73%. Low airflow reduces efficiency by 3 to 12%. Tests of uninsulated TXV sensing bulb installation indicate failure to properly meter refrigerant with correct charge or over charge causing false diagnostics and reduced efficiency. Evaporator coil blockage of 50% reduces efficiency by 5 to 7%. Duct leakage reduces efficiency by 7% to 42%. Condenser coil blockage of 30 to 80% reduces efficiency by 4 to -32% and increases power use by 7 to 27%. Improper refrigerant charge reduces efficiency by 2 to 66%. Moderate non-condensables (0.3%) reduces efficiency by 13 to 19% and increase power use by 6 to 8%. Severe non-condensables (1%) reduces efficiency by 38% and increases power use by 28%. Liquid line refrigerant restrictions reduce efficiency by 30 to 59%. Liquid line filter driers are required to remove moisture, acid, and particulates to prevent refrigerant restrictions on field-charged split systems. Laboratory test data are used to develop methods to diagnose non-condensables, restrictions, refrigerant charge faults, condenser or evaporator heat transfer faults, low airflow, or expansion valve failure. This is not possible using generic RCA protocols specified in the California building energy efficiency standards or unit-specific manufacturer protocols. Laboratory tests of RCA faults indicate that generic protocols yield false alarms, misdetection or misdiagnosis. If non-condensables, restrictions or refrigerant charge faults are detected manufacturers recommend recovering charge, making corrections, evacuating to 500 microns, and weighing in the factory charge. This is the most reliable method to achieve correct refrigerant charge and optimal energy efficiency.

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