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Prepared by:
Proctor Engineering Group, Ltd.
San Rafael, CA 94901
(415) 451-2480

Performance of Reduced Peak kW Air Conditioners at High Temperatures and Typical Field Conditions

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Author:
John Proctor, P.E.

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John Proctor, P.E., Proctor Engineering Group, San Rafael, CA

ABSTRACT

A gas and electric utility company sponsored research to prove that a reduced peak kW residential air conditioner can be built with readily available off-the-shelf components. For the study, a 3-ton unit was built, instrumented, and tested in the laboratory under a variety of climate, service, and installation conditions. The system proved it could meet peak cooling needs with reduced power; it achieved peak reduction by maintaining a higher rate of efficiency at high outdoor temperatures than typical air conditioners are able to achieve. The system also maintained this efficiency advantage when operated under adverse refrigerant charge and air flow conditions. Residential customers using a similarly designed system would consume 11-20% less energy annually, compared to typical SEER-10 units, and the utility would achieve a diversified peak reduction of 500W. The prototype would cost approximately $190 more than a standard SEER-10 unit and approximately $265 less than a typical SEER-12 unit.

Background

Residential air conditioning systems produce little revenue for electric utilities but they do produce high coincident peak demand. Utility programs that promote adoption of higher SEER air conditioners have been shown to reduce annual energy consumption but they do not necessarily deliver proportionate reductions in peak demand (Proctor 1993). Instead, air conditioners lose efficiency as outdoor temperatures increase, performing their worst during the high temperatures conditions that create peak demand. In one recent study sponsored by a utility industry research organization, investigators found that the EER of a typical SEER-10 unit drops 1.22% for each °F increase in outdoor temperature. The EER falls an average 4.3% below the manufacturer's listing when outdoor conditions reach 115 °F (Bain et al. 1996). Promoting such equipment can substantially degrade a utility's load factor, perpetuating the need for additional capacity during peak summertime conditions while reducing revenue from air conditioning usage during the remainder of the year (Proctor 1996).

Installation and maintenance problems frequently found in residential air conditioning can exacerbate this situation. For example, another recent utility industry study showed that improper charge and inadequate air flow can seriously degrade the performance of high-efficiency residential air conditioners at high temperatures. Use of a thermostatic expansion valve (TXV) to adjust refrigerant flow minimized the adverse charge effect (Rodriguez et al. 1996).

From both the utility's and the rate payers' perspectives, air conditioning designs that provide both customer energy use and peak demand reductions and offer higher tolerance for variable field conditions could yield significant financial benefits.

The goal of this project was to prove that a low-peak-power unit, built from off-the-shelf components, could achieve a diversified peak reduction of 500W compared to typical SEER-10 units. A secondary basis for the study was to measure the effects of temperature, refrigerant charge, and air flow on the system's energy efficiency, and to compare these effects with those of commercially available SEER-10 units tested separately under similar operating conditions.

This project builds on a previous study in which researchers found four combinations of "off the shelf" components that showed, through simulation, capable of reducing diversified peak demand by 500W for a 3-ton air conditioner (Proctor et al. 1994). The techniques employed by these four designs included (a) increased condenser/evaporator areas and efficiencies, (b) increased condenser/evaporator fan efficiencies, and (c) increased indoor/outdoor fan motor efficiencies. Technical reviews conducted by five major manufacturers found each design potentially feasible.

Description of the Air Conditioner Prototype

The design selected for assembly and testing in this project was built with a combination of off-the-shelf components. The prototype had a larger condenser coil and a smaller reciprocating compressor than the most common commercially available 3-ton SEER-10 units used in the utility's service area. It also differed from the baseline unit by using a TXV to adjust refrigerant flow and an accumulator to protect the compressor from the return of liquid refrigerant.

Approach

Researchers built the prototype and tested it in a psychometric laboratory under thermal conditions typical of the sponsoring utility's service territory and under a variety of charge and air flow conditions typically found in the field.

The experimental setup consisted of two psychometric rooms capable of maintaining "indoor" and "outdoor" environments at desired temperature and humidity conditions. The rooms were built according to American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) specifications (ASHRAE 1983) and designed for testing units of up to 10-ton capacity. Instrumentation was installed to track the following indicators of equipment performance: refrigerant pressure, temperature, and flow rate; air temperature, humidity, dewpoint, and flow rate; and condenser, compressor, and evaporator blower power consumption.

Temperatures were maintained within +/- 0.2°F of the desired values. Air flow across the indoor coil was kept within +/- 1% of desired values. For each test, the unit was allowed to run 15 minutes to reach steady state; data were then collected for a minimum of 20 minutes of steady-state operation. An energy balance between the air-side capacity and the refrigerant-side capacity was calculated to ensure the measured data were accurate and within ARI requirements. A data analysis program generated summary report files for all tests.

Test Conditions

In all, 23 laboratory tests measured the net capacity and the efficiency of the prototype unit under a range of thermal environment seen in the sponsoring utility's service area, a range of refrigerant charge, and a range of air flow conditions as shown in Table 1. In addition, in order to obtain an indication of the effect of the cabinet on the indoor fan and motor efficiency, the sides of the cabinet were removed during one test to allow free air flow into the fan.

Table 1. Test Conditions and Performance Test Results

Test	Conditions outdoor dry bulb, indoor dry bulb/wet bulb (°F)	Refrigerant Charge (lb)	Indoor Air Flow (cfm)	EER (Btu/Whr)	Capacity (Btu/h)
1	95, 80/67	10	1199	10.71	34062
2	115, 80/61	13	1208	7.79	27560
3	115, 80/61	13	846	7.27	24115
4	115, 80/61	10	844	7.32	24308
5	115, 80/61	10	1207	7.86	27883
6	115, 80/61	7	1209	6.52	22503
7	115, 80/61	7	851	6.38	21034
7a	115, 80/61	9	1195	7.73	27269
7b	115, 80/67	10	1204	8.54	30514
8	100, 75/59	13	1201	8.7	28364
9	100, 75/59	13	836	8.5	25589
10	100, 75/59	10	834	8.5	25450
11	100, 75/59	10	1205	9.01	28589
12	100, 75/59	7	1204	7.73	23490
13	100, 75/59	7	845	7.55	21935
14d	90, 75/59	13	1211	9.32	29701
15d	90, 75/59	13	845	9.05	27031
16c	90, 75/59	10	846	9.56	26931
17c	90, 75/59	10	1204	10.05	30060
18c	90, 75/59	7	1207	9.65	28456
19c	90, 75/59	7	848	9.29	25655
1a-c	82, 80/67	10	1211	12.5	36807
20	95, 80/67	10	1209	10.75	34832

Table 1 notes: The correct refrigerant charge for this unit was 10 lbs of R-22 and the design air flow was 1200 cfm. Air flow of 850 cfm is 283 cfm/ton which is closer to the air flow found on existing air conditioners (Parker et al. 1997; Proctor et al. 1995). Test 7b conditions are identical to the test conditions in Bain et al. (1996). Test 1a-c conditions are the steady state conditions used as part of the calculation of SEER. Test 20 was the cabinet effect test.

Performance of the Prototype Unit

As shown in Table 1, the net total capacity of the prototype unit was 34,062 Btu/h under standard American Refrigeration Institute (ARI) conditions (95°F outside temperature, 80/67°F inside). As expected, when tested under the utility's peak conditions, which are hotter and dry (115°F outside temperature, 80°F/61°F inside), the prototype's net capacity dropped, to 27,883 Btuh with a sensible heat ratio of 0.98. The Energy Efficiency Ratio (EER) of the prototype was 10.71 at ARI conditions and 7.86 at utility peak conditions.

Refrigerant Charge Effects

The amount of refrigerant charge is a critical parameter in the performance of an air conditioner. Numerous studies have shown that the refrigerant charge of installed units is other than optimum most of the time. A recent study (Proctor 1998) reported the average refrigerant charge on 28 new units at 84% of correct charge with four units showing undercharge exceeding 35%.

The effect of overcharge on this unit was negligible at peak temperatures but, as expected, the effect of undercharge was pronounced. A 30% undercharge at the utility's peak (115°F outdoor) conditions caused a 19.3% drop in net capacity. As shown in Figure 1, this caused a 17.1% drop in EER.

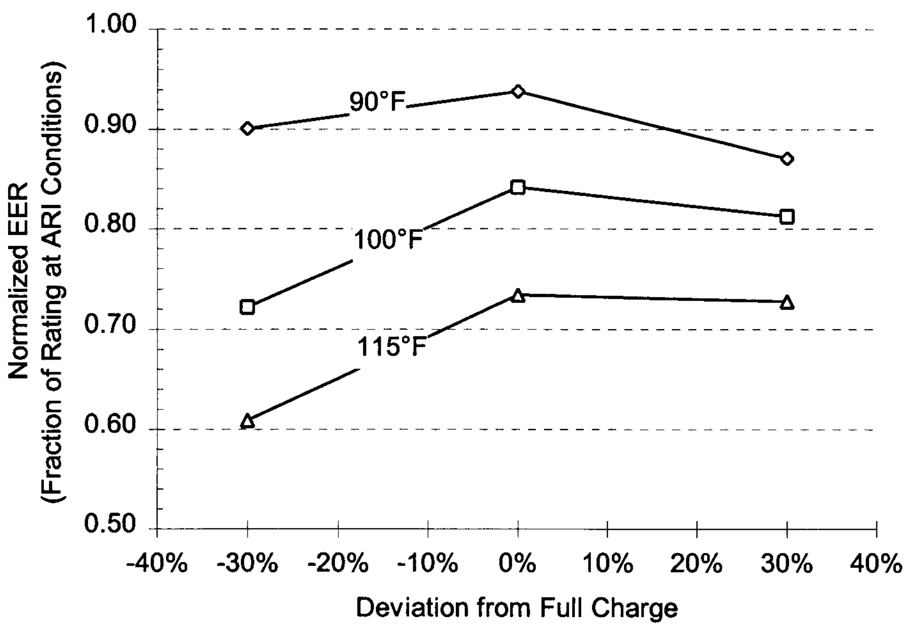

Figure 1. Charge Effect on Prototype EER.

Notes on Figure 1: Indoor conditions were 75/59 for the 90°F and 100°F outdoor conditions tests. The indoor conditions were 80/67 for the 115°F outdoor conditions test.

As shown in Figure 2, the prototype, equipped with a TXV, was far less affected by incorrect charge than were common fixed orifice units tested in other studies. For example, the prototype retained 86% of its correct charge efficiency when 30% undercharged, while a fixed orifice unit, tested in another study, dropped to 52% of its correct charge efficiency. The prototype unit retained practically all (99%) of its correct charge efficiency even when overcharged by 30%. The prototype's TXV performed comparably to TXV units tested in other studies (Farzad & O'Neal 1993; Rodriguez et al. 1996.).

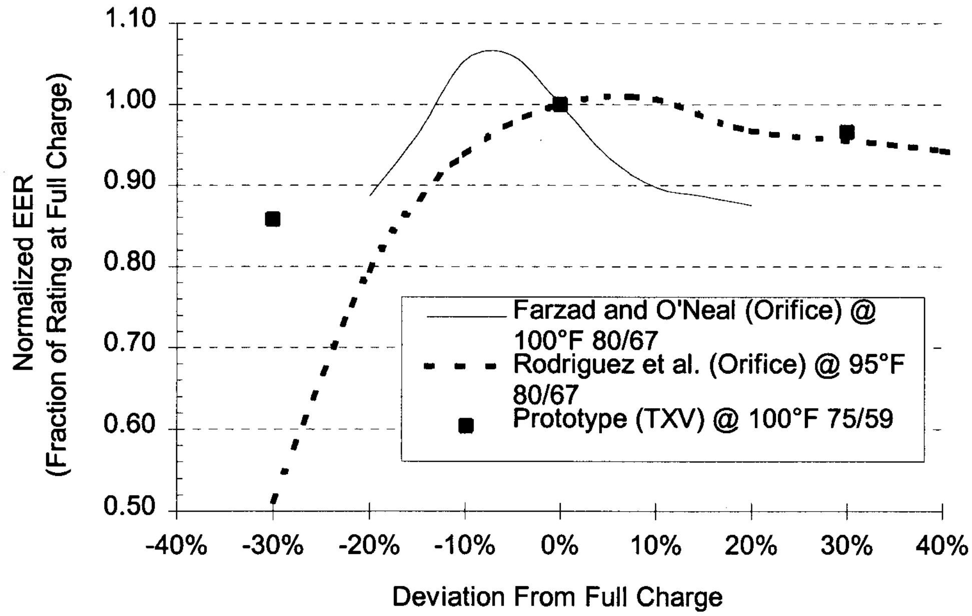

Figure 2. Charge Effect on EER of Prototype and Fixed Orifice Units

Air Flow Effects

The prototype was tested under a variety of outdoor temperature conditions (peak, hot, and warm) with the indoor coil air flows at 70% and 100% of standard. Figure 3 displays the results.

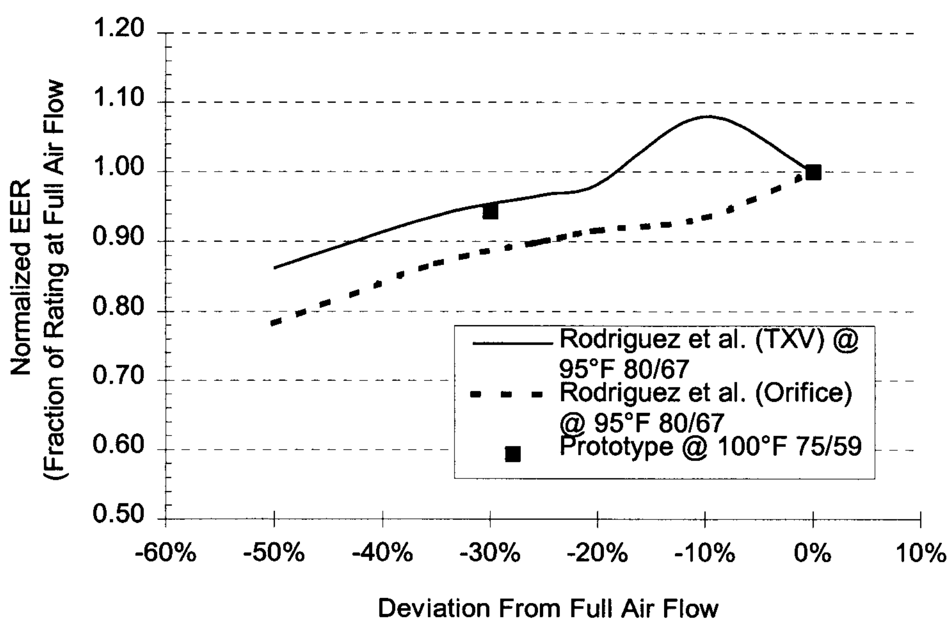

Figure 3. Indoor Coil Air Flow Effect on EER of Prototype and Other Units

The relative effects of low air flow were more pronounced at peak conditions than at warm conditions. At peak conditions, a 30% reduction in air flow caused a drop in net capacity of 12.8% and a drop in EER of 6.9%. At warm conditions, net capacity dropped 10.4% and EER dropped 4.8%. As shown in Figure 3, the prototype, operated with the TXV, performed better with low air flow than did a typical fixed orifice unit tested in separate research and comparably to a previously tested TXV (Rodriguez et al. 1996).

Comparison of the Prototype to Typical SEER-10 Air Conditioners

In order to determine the prototype's relative efficiency compared to existing systems, and to establish its potential impact on diversified peak demand, the unit was compared to three commercially available air conditioners found in previous utility-sponsored studies to represent typical SEER-10 units (Bain et al. 1996; Proctor et al. 1994; CADMAC 1996). Each was a split system with a reciprocating compressor and an orifice metering device. The commercial systems included:

- Typical Unit A, a 3.5-ton system: its indoor unit included an A-coil and a fan;
- Typical Unit B, a nominal 4-ton system: its indoor unit had an A-coil evaporator and no air handler;
- Typical Unit C, a 3-ton system: the indoor unit had an A-coil but no air handler. This system is the most commonly installed model in the sponsoring utility's service territory, and served as the baseline unit for this study.

Temperature Effects on EER

Previous laboratory research of 10 air conditioner units, in which Typical Units A and B were tested, found that split system efficiency drops 1.22% for each °F increase in outdoor temperature (Bain et al. 1996). The prototype showed less efficiency drop (0.96%) for each °F increase.

As shown in Figure 4, the prototype unit, compared to Typical Units A, B, and C showed less efficiency drop at higher outdoor temperatures. The prototype unit had an EER of 8.5 at 115°F outside, while the typical units' EERs ranged from 6.7 to 7.4.

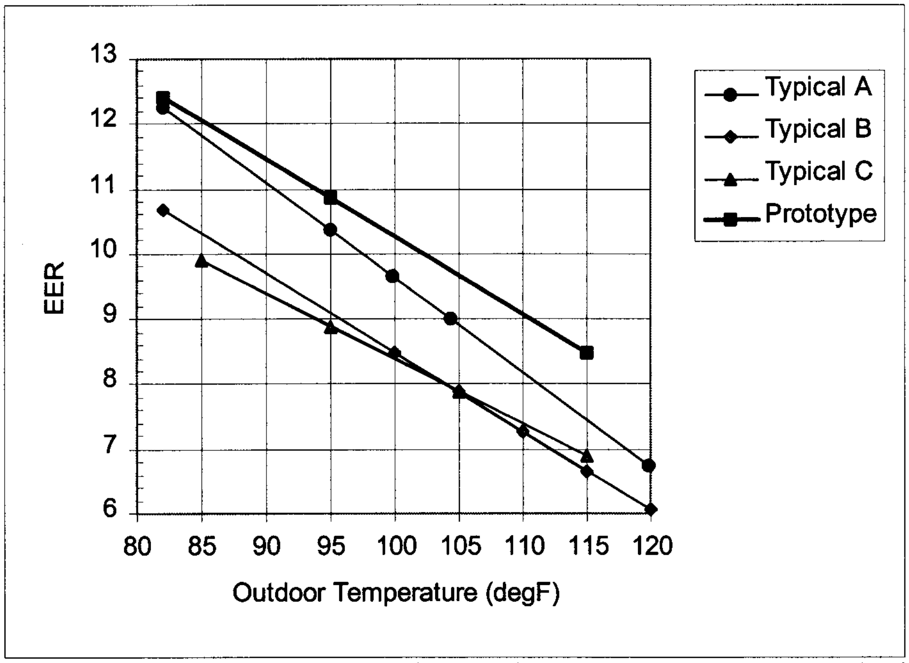

Figure 4. EER Comparisons for Typical Units and Prototype (80/67°F)

Effects on Peak Power Requirements

If units of these designs were built to provide capacity equivalent to the prototype at 115°F (30,000 Btuh), the power draw of typical units would range from 4.0 to 4.5kW. The prototype, however, would have a power draw of 3.5kW. Its connected load would be 500-1,000W less than the typical units at 115°F. (See Table 2)

Table 2. Comparison of EER and Connected Load for Prototype and Typical Units (80°F dry bulb/67°F wet bulb Inside)

	EER 82°F (DOE-B)	EER 95°F (ARI)	EER 115°F (HighTemp)	EER drop (% drop/°F)	Connected Load (kW)	Connected Load Increase (kW)
Prototype	12.50	10.71	8.54	0.96	3.51	
Typical Unit A	12.26	10.37	7.45	1.19	4.03	0.52
Typical Unit B	10.69	9.10	6.66	1.34	4.51	1.00
Typical Unit C	10.20	8.90	6.88	1.02	4.35	0.84

Comparison to Goal

Because the primary item of importance to a utility is what the population of air conditioners is doing at its peak, researchers applied a dynamic model to project the effect of the prototype on a diversified (population wide) basis. The model accounts for units that will not be running, those that will be running continuously, and others that will be cycling, as well as the condition of each unit, population demographics, installation characteristics, and the time of day.

According to this model, the prototype would achieve a local diversified peak reduction of 0.34 to 0.65 kW under the utility's typical peak conditions. If the prototype is used as a replacement for the common air conditioner used in the sponsoring utility's service territory (Typical Unit C), the result would be a diversified local peak reduction of 550W as shown in Table 3.

Table 3. Peak Reduction Due to Prototype Design (115°F outside, 80°F/61°F inside)

	Connected Load (kW)	Connected Load Difference (kW)	Increase in Local Peak (kW)	Increase in System Peak (kW)
Prototype	3.51		0	0
Typical Unit A	4.03	0.52	0.34	0.24
Typical Unit B	4.51	1.00	0.65	0.46
Typical Unit C	4.35	0.84	0.55	0.39

Other Findings of Interest

The simulation used in designing this prototype had a projected EER of 9.15 at 115°F (Rice 1991), yet the prototype constructed had an actual EER of 8.54 at 115°F. A number of factors contributed to this difference.

Hardware Problems

Three components used in the prototype did not perform up to their published values: the compressor, the inside coil, and the inside fan and motor. Performance of these components to specification would improve EER and reduce power draw beyond the values achieved in these tests.

Cabinet Effects

The indoor fan/motor efficiency as installed was 9% compared to the 30% goal established in the simulation. Simple elimination of the flow restriction caused by the close proximity of cabinet walls increased the efficiency to 15%. Attention to cabinet design and return ducting configuration could further improve the inlet and outlet conditions of the blower and overall fan efficiency.

Conclusions

The laboratory tests completed in this project confirm that it is possible to build reduced peak kW residential air conditioners with readily available components. The projected peak demand reduction comes from the system's ability to maintain a higher rate of efficiency at high outdoor temperatures than typical air conditioners are able to achieve. The prototype's efficiency advantage is also maintained during adverse refrigerant charge and air flow conditions. Demand reduction was achieved despite hardware deficiencies for three components.

Residential customers would benefit from using air conditioners similar to this prototype design. Such units would use 11-20% less energy annually than the three comparison units. Cost of the prototype would be approximately $190 more than a standard SEER-10 unit and approx. $265 less than a typical SEER-12 unit.

Recommendations

As the industry conducts research to advance air conditioner designs for the use of new refrigerants, we recommend continued work to incorporate features that will optimize equipment performance at high temperatures and increase tolerance of installation and service variables.

The tolerance for off-design refrigerant charge and air flow conditions provided by thermostatic expansion valves (TXVs), for example, calls for increased application of TXVs. For a fixed orifice unit operating at 30% undercharge, air conditioner EER would drop 48%, nearly doubling diversified power draw if the unit could still cycle. In contrast, the EER of the prototype unit would drop only 14% under these same conditions, increasing power requirements by just 16%. Use of a TXV will also reduce efficiency losses due to low air flow.

Utilities and customers could also benefit from laboratory testing of fan, motor, and cabinet modifications to improve efficiency. This could result in substantial efficiency gains at a low cost. Some changes in fan/motor/cabinet design can be accomplished without increasing the cabinet size; other changes in configuration might require proactive market transformation to achieve acceptance.

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