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Verification Test of ASHRAE Standard 152p

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ABSTRACT

A verification test of proposed ASHRAE Standard 152P, Standard Method of Test for Estimating the Efficiencies of Residential Thermal Distribution Systems, was performed by modifying an air-conditioner duct system to achieve measured, but variable, duct leakage. Computer-controlled dampers provided cycles of low leakage, supply leak only, return leak only, and both. This was repeated on a 12-day cycle.

A house was extensively instrumented, and comprehensive short-term tests were run of the air conditioner, the thermal distribution system, and the house.

Standard 152P was used to predict performance under the measured conditions and compared to the measured changes. With the supply leak damper open, 152P predicted that the air conditioner would have to deliver 18% more cooling at design to maintain occupant comfort. The field data were consistent with that estimate. Return leakage effects, however, were measured at double the 152P estimates.

BACKGROUND

ASHRAE 152P is a proposed standard method of test for estimating the efficiencies of residential thermal distribution systems. This proposed standard is of major importance given the field-measured efficiency losses of ducted thermal distribution systems. Efficiency losses due to ducted thermal distribution systems regularly range from 25% to more than 55% (Parker 1989; Andrews and Modera 1992; Proctor et al. 1995). Thermal distribution efficiency research results have played a major role in the development of this standard. Now in its final revisions, the standard's estimation of efficiency must be validated by field studies.

There are a number of models for estimating distribution efficiency of forced-air residential heating and cooling equipment. These models include Modera and Treidler (1995), Palmiter and Francisco (1997), Parker et al. (1993), Nevitt and Nelson (1995), Blasnik et al. (1995), Clark et al. (1985), Klein et al. (1981), and Jacob et al. (1986).

ASHRAE 152P has attempted to take these models and develop a test method that is both simple enough to be applied regularly and accurate enough to be useful. The calculations in 152P have been implemented in a spreadsheet program. The spreadsheet, dated October 24, 1996, was used in this verification.

VERIFICATION TESTING

The prior work on measuring distribution efficiency and verifying distribution efficiency models has focused on co-heating tests (Subbarao et al. 1990; Andrews 1995; Andrews et al. 1996; Olson et al. 1993). Co-heating tests generally measure the difference in electric resistance heating between two states (electric heat direct into the rooms vs. heat distributed to the rooms by a distribution system). The co-heat information is gathered over a few days, and a model is applied to the data to correct for differences in weather or to project to other weather conditions. Co-heating has been very useful in investigating distribution efficiency but has had limited use. One of the major advantages of co-heating is that it can measure distribution efficiency. One of the drawbacks of co-heating is that it relies on simulation models to produce useful results.

The flip/flop methodology used in this study measures the cooling (or heating in the heating mode, Btu/h, W) across the heat exchanger of the air conditioner. The capacity is measured under two states: State 0, with controlled duct leakage on both the supply and return sides, and State *j* (*j* = 1, 2, 3) with controlled duct leaks eliminated on the supply, return, or both sides. The monitoring equipment is left in place until

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the weather and control conditions repeat themselves often enough to provide statistically significant measurements of the capacity needed to maintain design indoor conditions, with and without the duct leak. The result is a measurement of the distribution efficiency effect independent of a simulation model and subject to statistical analysis of variability. One drawback of this method is that it does not measure the distribution efficiency directly— it measures the capacity demand effect of *changes* in distribution efficiency.

In cooling, when indoor temperature is maintained, the sensible energy removed at the heat exchanger of the air conditioner is directly related to the sensible cooling load and the distribution efficiency as shown in Equation 1. (A similar relationship applies for total—latent plus sensible—cooling load and for heating load. The sponsor of this research was interested in the sensible cooling effects in a hot, dry climate.)

$$SCL_i/\eta_{distji} = E_{equipji} \quad (1)$$

where

- SCL_i (sensible cooling load) is the sensible heat gain through: structural components, windows, infiltration, and ventilation and due to occupancy as defined in *ASHRAE Fundamentals* (ASHRAE 1993) under Conditions *i*.
- Conditions *i* (*i* = 1, 2, 3,... *n*) are the combinations of indoor and outdoor conditions, occupancy, time of day, etc., that determine the sensible cooling load. State *j* is the combination of supply and return duct leakage settings.
- η_{distji} is the distribution system efficiency, the ratio between the required sensible heat transfer by the equipment under Conditions *i* and State *j* and the required sensible heat transfer under Condition *i* if the distribution system had no gains or impact on the equipment or building loads as defined in ASHRAE 152P (ASHRAE 1997).
- $E_{equipij}$ is the rate of sensible energy exchanged between the equipment and the delivery system under Conditions *i* and State *j*. This is the effective sensible cooling load "seen" by the air conditioner.

When the distribution system is changed from State 0 to State *j* and the system is operated under the same Conditions *i*, the sensible cooling load is unchanged but the effective sensible cooling load changes. The fractional change in the effective sensible cooling load between State 0 and State *j* is shown in Equation 2.

$$\begin{aligned}&\text{Fractional Change in Effective Sensible Cooling Load} = \\ &(E_{equip0i} - E_{equipji})/ E_{equip0i} = \\ &(SCL_i / \eta_{dist0i} - SCL_i / \eta_{distji})/ SCL_i / \eta_{dist0i} = \\ &1- \eta_{dist0i} / \eta_{distji}\end{aligned} \quad (2)$$

The formulation $(E_{equip0i} - E_{equipji})/ E_{equip0i}$ can be measured in the field as noted below. The formulation $1- \eta_{dist0i} / \eta_{distji}$ can be estimated with the 152P model and the two formulations should be equivalent.

FLIP FLOP VERIFICATION TEST

A verification test of thermal distribution models was performed in the summer of 1995 in Phoenix, Arizona. The forced-air ducted thermal distribution system of the central air conditioner in a test house was modified to provide a measured amount of duct leakage. The investigators sealed all leaks in the duct system. (The supply and return duct system was fully accessible in the attic of the single-story house. Joints and seams were sealed with mastic and fiber mesh, as described in Downey et al. [1995] and Tooley and Moyer [1992]). The investigators installed computer-controlled dampers leading from the supply plenum and return run to the flow stations. The leakage was measured at each flow station with the dampers open and closed.

The configuration of the supply damper and flow station was a 6 in. (15 cm) diameter takeoff from the supply plenum to a 30° elbow. After the elbow there was a 6 in. (15 cm) diameter electro-mechanical damper controlled by the computer. From the damper there was a straight 8 ft (2.4 m) length of 6 in. (15 cm) diameter rigid metal duct followed by a 6 in. (15 cm) diameter flow station with a calibrated flow-sensing manifold. The commercial flow station consists of a pressure-averaging manifold for a series of upstream holes and a pressure-averaging manifold for a series of downstream holes. The controlled supply leak air was discharged from the flow station into the attic.

The controlled return leak drew air from the attic approximately 10 ft (3.0 m) from the supply leak discharge. The configuration of the return damper and flow station was a straight 5 ft (1.5 m) length of 6 in. (15 cm) diameter rigid metal duct followed by a 6 in. (15 cm) diameter flow station with a calibrated flow-sensing manifold (the same make and model as used in the calibrated supply leak). Following the flow station, a straight 3 ft (0.9 m) length of 6 in. (15 cm) diameter rigid metal duct brought the flow to a 6 in.(15 cm) diameter electro-mechanical damper controlled by the computer. After the damper, a 6 in. (15 cm) takeoff delivered the air to the sole return duct about 1 ft (0.3 m) from the air-handler cabinet.

The flow across the inside coil of the air conditioner was measured using the total system airflow test (Nevitt et al. 1993), also known as the diagnostic fan flow measurement in ASHRAE 152P.

The distribution system operated in four different states as detailed in Table 1. The system operated on a 12-day cycle with 3 days in each state.

TEST HOUSE DESCRIPTION AND 152P MODEL INPUTS

The test house was a single-story slab-on-grade home with four bedrooms, 1684 ft^2 (156 m^2) of living space, with an attic-mounted electric heat pump, tinted double-glazed windows, and 24 h ft^2 °F/Btu [4.23 m^2 K/W]) attic insulation with a light tile roof. The house was tight, with a blower door-measured air leakage of 1489 cfm (703 L/s) at 0.20 in. H_2O (50 Pa) pressure. The house occupants maintained a nearly constant thermostat setting throughout the test period. The

TABLE 1
Distribution System Test States

	Description	Supply Leakage (% of coil flow)	Return Leakage (% of coil flow)
State 0	Both Controlled Leaks Open	15.8%	11.2%
State 1	Controlled Supply Leak Eliminated	2.5%	11.2%
State 2	Controlled Return Leak Eliminated	15.8%	3.3%
State 3	Both Controlled Leaks Eliminated	2.5%	3.3%

afternoon and early evening indoor temperature averaged 80°F (27°C) with a standard deviation of 0.9°F (0.5°C).

Detailed house characteristics and initial 152P inputs are listed in Table 2. The inputs to 152P were modified as discussed in "Cooling Load Reduction vs. 152P Revised Model" below. The revised inputs are also listed in Table 2.

MONITORING SYSTEM

The home was monitored and the duct leakage controlled by a data acquisition system (DAS). The DAS has the flexibility to perform many data acquisition and control functions and is capable of being downloaded or reprogrammed via modem. The temperature probes were bare wire, 36 gauge, type-T thermocouples. The electrical current was sensed with a 50 amp split core current transducer. The reference temperature for the thermocouples was provided by a thermistor. Condensate flow from the indoor coil was measured with the use of a tipping bucket gauge attached to the termination of the condensate drain. The data points are summarized in Table 3.

MEASURED COOLING BY SYSTEM STATE, OUTDOOR TEMPERATURE, AND TIME OF DAY

The sensible cooling is dependent on the state of the distribution system (leakage dampers open or closed), outdoor temperature (higher temperatures requiring more cooling), and time of day (thermal mass effects and solar gain effects). Proposed standard 152P estimates the distribution efficiency for design conditions and seasonal conditions. All the 152P calculations used in this analysis were design values. For cooling, the 2.5% design conditions will occur between noon and 8 p.m. In Phoenix, design conditions result in near zero latent capacity, which is evidenced by the lack of condensate flow during these periods.

The sensible cooling for each monitored hour was calculated from the measured airflow and the dry-bulb temperature drop between the return and supply plenum. Outdoor temperatures were binned in 5°F (3°C) increments. Hours of day were binned in four-hour periods. High outdoor temperatures and periods between noon and 8 p.m. produced changes in the sensible cooling by distribution system state for the same temperature bin and time of day.These results and their confidence intervals are detailed in Table 4.

ASHRAE 152P was used to estimate the reduction in cooling necessary to maintain the indoor design conditions at outdoor design conditions corresponding to the temperature bins of the monitored data. Table 5 displays the estimated design distribution efficiency for the test house.

COOLING LOAD REDUCTION VS. 152P MODELED COOLING LOAD REDUCTION

ASHRAE 152P results were used to estimate the reduction in cooling necessary to maintain the indoor design conditions at outdoor design conditions corresponding to the temperature bins of the monitored data. Using Equation 2, the percent savings for each temperature bin are calculated based on the 152P estimates in Table 5 and on the measured capacity changes in Table 4. The results are compared in Table 6.

The 152P estimates are in close agreement with the measured values for supply leakage effects, particularly in high-temperature bins. There is considerable divergence between the 152P estimates and the measured values for return leakage effects. Potential causes of these differences are measurement error or modeling error. Both potential causes were investigated.

Potential measurement errors were investigated and eliminated as the cause of the disagreement between the model values and the measured values. The measurements entered into the equation were elapsed time, flow, and supply and return temperatures. The elapsed time was recorded by the computer, a number with high confidence. The flow was measured on multiple occasions in each state with high repeatability. The flow pattern of the temperature grids could have changed, but investigation of the recorded temperatures suggested that if there was an error, it would be in the direction of increasing the discrepancy between the measured and predicted values.

The assumptions in 152P were examined to see if the difference was due to the measured house violating the model assumptions, and one critical assumption was found to be responsible for most of the discrepancy. In 152P the temperature drop across the coil is assumed to be related to the design capacity of the air conditioner, as shown in Equations 3 and 4.

In SI:

$$\Delta t_e = E_{cap} / Q_e \rho_{in} C_p \quad (3)$$

In IP:

$$\Delta t_e = E_{cap} / 60 Q_e \rho_{in} C_p \quad (4)$$

where

Δt_e = temperature rise across the heat exchanger (°C,°F), negative in cooling;

TABLE 2
Test House Characteristics and 152P Model Inputs

	House Characteristic	Value Used in 152P Model	Comments
Conditioned Floor Area (ft^2, m^2)	1684 (156)	1684 (156)	
Supply Duct Surface Area (ft^2, m^2)	138 (13)	138 (13)	
Return Duct Surface Area, (ft^2, m^2)	59 (5)	59 (5)	
Fraction of Supply Duct in Attic	1	1	
Fraction of Return Duct in Attic	1	1	
Supply Duct R-Value (h ft^2 °F/Btu, m^2 K/W)	4.2 (0.74)	4.2 (0.74)	
Return Duct R-Value (hft^2 °F/Btu, m^2 K/W)	4.2 (0.74)	4.2 (0.74)	
Indoor Temperature, Cooling (°F, °C)	80 (27)	75 (24)	
Cooling Design Temperature, ASHRAE 2.5% (°F, °C)	107 (42)	107.5 (42)	Model was also run at 102, 97, and 92 (39, 36, 33)
T Wet-Bulb Design (°F, °C)	72 (22)	72 (22)	
T Wet-Bulb Indoor (°F, °C)	61 (16)	61 (16)	
Is There Solar Gain Reduction in the Attic? [Y/N]	y	y	Revision run used n
House Volume (ft^3, m^3)	14314 (405)	13809 (391)	
Equipment Cooling Capacity (Btu/h, W)	−28200 (−8265)	−47500 (−13922)	Revision run used −28200 (−8265)
Cooling Fan Flow (cfm, L/s), ACCA *Manual D* Calculation or Measured Value	1085 (512)	1085 (512)	
Cooling Supply Duct Leakage (cfm, L/s)	Closed 27 (13) Open 171 (81)	Closed 27 (13) Open 171 (81)	Duct leakage was controlled by a damper
Cooling Return Duct Leakage (cfm, L/s)	Closed 36 (17) Open 122 (58)	Closed 36 (17) Open 122 (58)	Duct leakage was controlled by a damper
Enter *F* for flex duct or duct board, *M* for sheet metal	Flex	F	
Enter 1 for ACCA *Manual D* design, 2 without *Manual D* design	2	2	
Enter 1 for single-speed equipment, 2 for multi-speed equipment	1	1	
For vented attic, enter *V* for vented, *U* for unvented	V	V	
For cooling systems, enter *T* for TXV control, O for other control	O	T	
TXV eliminates the equipment factor in 152P Measured results excluded the equipment factor			
Supply plenum dry-bulb temperature (°F, °C)	57	55	
Number of stories	1	1	
Number of return registers	1	1	

TABLE 3
Sensor Locations

Input	Location	Parameter
Temperature #1 (analog)	Return plenum	Temperature of air entering air handler
Temperature #2 (analog)	Supply plenum	Temperature of air exiting coil
Temperature #3 (analog)	Attic (midway between the ceiling and the roof peak)	Duct/AH location temperature
Temperature #4 (analog)	Return grille	Temperature of air entering the return duct
Temperature #5 (analog)	Supply register	Temperature of air leaving a main supply duct
Temperature #6 (analog)	Shaded outdoor	Outdoor ambient temperature
Temperature #7 (analog)	Secondary duct location	Temperature of second duct location
Temperature #8 (analog)	Indoors	Temperature by thermostat
Temperature #9 (analog)	DAS reference	Temperature at the terminal strip
Temperature #10 (analog)	Evaporator coil	Saturation temperature of coil
Temperature #11 (analog)	Suction line at AH	Temperature of suction line
AC current (pulse)	Power wire @ compressor	Air conditioner status
Tipping bucket gauge (pulse)	Condensate drain	Condensate flow

TABLE 4
Cooling by System State, Outdoor Temperature, and Time of Day

		Time of Day							
		Noon to 4 p.m.				4 p.m. to 8 p.m.			
		System State				System State			
Temperature Bin °F (°C)		Both Leaks	Return Leak Only	Supply Leak Only	No Leak	Both Leaks	Return Leak Only	Supply Leak Only	No Leak
92.5 (33)	Cooling Btu/h (W)					12697 (3721)	11632 (3409)	12615 (3697)	9339 (2737)
	95% confidence (±)					1498 (439)	4534 (1328)	1988 (582)	638 (187)
	Hours (n)					4	7	10	9
97.5 (36)	Cooling Btu/h (W)	14188 (4158)	10066 (2950)	11322 (3318)	9781 (2867)	15078 (4419)	12017 (3522)	13953 (4089)	10646 (3120)
	95% confidence (±)	2344 (687)	1224 (358)	907 (266)	951 (278)	1623 (475)	1137 (333)	1385 (406)	779 (228)
	Hours (n)	8	10	14	12	9	13	21	10
102.5 (39)	Cooling Btu/h (W)	15105 (4427)	12514 (3668)	14113 (4136)	11093 (3251)	18598 (5451)	15390 (4510)	16168 (4738)	12592 (3690)
	95% confidence (±)	3184 (933)	1050 (307)	766 (224)	679 (199)	3277 (960)	1161 (340)	1431 (419)	551 (161)
	Hours (n)	8	18	25	12	7	14	18	12
107.5 (41)	Cooling Btu/h (W)	18029 (5284)	14489 (4246)	16871 (4945)	13983 (4098)	16717 (4899)	18618 (5457)	18017 (5280)	14918 (4372)
	95% confidence (±)	1988 (582)	1049 (307)	1095 (321)	741 (217)	8662 (2538)	2711 (794)	1534 (449)	1789 (524)
	Hours (n)	7	15	14	9	2	8	8	4

TABLE 5
Estimated Design Distribution Efficiency by System State and Outdoor Temperature

Design Temperature °F (°C)	System State: Both Leaks	Return Leak Only	Supply Leak Only	No Leak
92.5 (33)	0.72	0.85	0.77	0.91
97.5 (36)	0.72	0.86	0.76	0.91
102.5 (39)	0.71	0.87	0.75	0.91
107.5 (41)	0.71	0.88	0.74	0.90

E_{cap} = rated equipment capacity (W, Btu/h), negative in cooling;

Q_e = flow through the air-handler fan at operating conditions (m^3/s, cfm);

ρ_{in} = the density of air at indoor temperature (Kg,/m^3, lb/ ft^3);

C_p = specific heat of air (J/Kg K, Btu/lb °F).

Equations 3 and 4 give temperature changes across the heat exchanger (40°F, 22°C) that are almost double the temperature change measured across the heat exchanger (24°F, 13°C) in the test house. This is due to two factors—the actual airflow across the heat exchanger was 68% of design, and the actual capacity was 59% of rated capacity, based on interpolation of the manufacturer's data to design conditions (without adjustment for reduced airflow or any other installation errors). These types of discrepancies between rated and actual capacity are common (Proctor 1997; Neal and Conlin 1988; Proctor and Pernick 1992; Blasnik et al. 1995).

A second assumption of significant effect was the attic temperature. For return duct calculations, the 152P model used an attic temperature 6°F (3°C) above outside. For supply duct calculations, the 152P model used an attic temperature equal to outside temperature. (This is for a vented attic with attic temperature gain reduction (tile roof) with a cooling design temperature of 107.5°F [41.9°C] and an inside temperature of 75°F [24°C]. This part of the proposed standard is currently under review by the committee.)

TABLE 6
Effective Cooling Load Reduction

	Time of Day: Noon to 4 p.m.			4 p.m. to 8 p.m.		
	Supply Leak Eliminated	Return Leak Eliminated	Both Leaks Eliminated	Supply Leak Eliminated	Return Leak Eliminated	Both Leaks Eliminated
Temperature 92.5°F (33°C)						
152P Estimated Reduction				15%		21%
Measured Reduction				26%		26%
95% Confidence Interval				±17%		±13%
Temperature 97.5°F (36 °C)						
152P Estimated Reduction	16%		21%*	16%	5%*	21%*
Measured Reduction	14%		31%	26%	18%	31%
95% confidence	±13%		±18%	±12%	±15%	±12%
Temperature 102.5°F (39°C)						
152P Estimated Reduction	17%	4%*	21%	17%	4%**	21%*
Measured Reduction	21%	12%	27%	21%	18%	32%
95% confidence	±7%	10%	±22%	±10%	±8%	±18%
Temperature 107.5°(F (41°C)						
152P Estimated Reduction	18%		21%	18%	3%**	
Measured Reduction	20%		25%	17%	20%	
95% confidence	±9%		±12%	±13%	±17%	

Bold outline indicates close agreement between 152P estimate and measured value, * indicates substantial disagreement, and ** indicates differences that are statistically significant at the.05 level.

COOLING LOAD REDUCTION VS. 152P REVISED MODEL

ASHRAE 152P was used with the measured capacity substituted for the rated capacity, no-solar-gain reduction for the attic (this raises the attic temperature to 18°F [7°C] above ambient for both supply and return calculations). The revised distribution efficiencies are shown in Table 7. Using Equation 2, the percent savings for each temperature bin was calculated based on the revised 152P estimates. The revised comparison between measured and estimated savings is shown in Table 8. The revised 152P estimates are in closer agreement with the measured values.

CONCLUSIONS

A limited verification of 152P is possible using a flip-flop experimental design. When the approach was used on a test home in Phoenix, Arizona, two significant areas of concern were identified. The first is the problem of using measured airflows and rated capacity. Since airflows across the heat exchanger are often low, using the current 152P method will overestimate the temperature change.

The second area of concern is the estimation of attic temperatures. This area is currently under review by Standard Project Committee 152P.

The flip-flop methodology can test the validity of duct efficiency models. Specifically, it can test changes in effective cooling load caused by changes in duct leakage. The method can be extended to determine the changes in energy consumption and equipment efficiency caused by changes in duct leakage.

TABLE 7
Revised Distribution Efficiency Estimate

	System State			
Temperature Bin °F (°C)	**No Leak**	**Supply Leak**	**Return Leak**	**Both Leaks**
92.5 (33)	0.83	0.69	0.70	0.57
97.5 (36)	0.83	0.67	0.71	0.57
102.5 (39)	0.82	0.65	0.71	0.56
107.5 (41)	0.81	0.64	0.72	0.55

TABLE 8
Revised Cooling Load Reduction

	Time of Day					
	Noon to 4 p.m.			4 p.m. to 8 p.m.		
	Supply Leak Eliminated	**Return Leak Eliminated**	**Both Leaks Eliminated**	**Supply Leak Eliminated**	**Return Leak Eliminated**	**Both Leaks Eliminated**
Temperature Bin 92.5°F (33°C)						
152P Estimated Reduction				17%		31%
Measured Reduction				26%		26%
95% Confidence Interval				±17%		±13%
Temperature Bin 97.5°F (36°C)						
152P Estimated Reduction	19%		32%	19%	15%	32%
Measured Reduction	14%		31%	26%	18%	31%
95% confidence	±13%		±18%	±12%	±15%	±12%
Temperature Bin 102.5 °F (39°C)						
152P Estimated Reduction	21%	13%	32%	21%	13%	32%
Measured Reduction	21%	12%	27%	21%	18%	32%
95% confidence	±7%	10%	±22%	±10%	±8%	±18%
Temperature Bin 107.5°F (41°C)						
152P Estimated Reduction	22%		32%	22%	12%	
Measured Reduction	20%		25%	17%	20%	
95% confidence	±9%		±12%	±13%	±17%	

Bold outline indicates close agreement. There are no differences that are statistically significant at the.05 level.

RECOMMENDATION

It is recommended that additional sites be studied to verify the 152P model under a variety of climatic and installation conditions.

It is recommended that some of the verification tests include seasonal performance, measure distribution efficiency effects independent of a simulation model, and be subject to statistical analysis of variability.

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REFERENCES

Andrews, J.W. 1995. Electric coheating as a means to test duct efficiency: A review and analysis of the literature. Upton, NY: Energy Efficiency and Conservation Division, Department of Applied Science, Brookhaven National Laboratory. BNL-62313

Andrews, J.W., and M.P. Modera. 1992. Thermal distribution in small buildings: A review and analysis of recent literature. Upton, NY: Energy Efficiency and Conservation Division, Department of Applied Science, Brookhaven National Laboratory. BNL-52349.

Andrews, J.W., R.F. Krajewski, and J.J. Strasser. 1996. Electric co-heating in the ASHRAE Standard Method of Test for Thermal Distribution Efficiency: Test results in two New York State homes. *ASHRAE Transactions* 102(1): 870-880.

Blasnik, M., J.P. Proctor, T.D. Downey, J. Sundal, and G. Peterson. 1995. Assessment of HVAC installations in new homes in Nevada Power Company's service territory. Research Project 3841-03, Final Report. Palo Alto: Electric Power Research Institute, Inc. TR-105309.

Clark, D.B., C.R. Hill, and C.W. Hurley. 1985. Dynamic models for HVAC system components. *ASHRAE Transactions* Vol. 91.

Downey, T., J. Proctor, and M. Blasnik. 1995. New construction HVAC program implementation plan for Nevada Power Company. Research Project 3841-03, Final Report. Palo Alto: Electric Power Research Institute, Inc. TR-105310.

Jakob, F.E., D. Locklin, R. Fischer, L. Flanigan, and R. Cudnik. 1986. SP43 evaluation of system options for residential forced-air heating. *ASHRAE Transactions* 92(2).

Klein, S.A., et al. 1981. TRNSYS: A transient system simulation program. Report 38-11, Solar Energy Laboratory, University of Wisconsin - Madison.

Modera, M.P., and B. Treidler. 1995. Improved modeling of HVAC system/envelope interactions in residential buildings. *Proceedings of the 1995 ASME International Solar Energy Conference.*

Neal, L., and F. Conlin. 1988. Residential air-conditioning field performance status and future priorities. *Proceedings of the 1988 ACEEE Summer Study on Energy Efficiency in Buildings.* Washington, D.C. American Council for an Energy Efficient Economy.

Nevitt, R., et al. 1993. Minneapolis Duct Blaster™ operation manual. Minneapolis: The Energy Conservatory.

Nevitt, R., and G. Nelson. 1995. Percent cooling and heating system losses from duct leakage. Minneapolis: The Energy Conservatory.

Olson, J.R., L. Palmiter, B. Davis, M. Geffon, and T. Bond. 1993. Field measurements of the heating efficiency of electric forced-air systems in 24 homes. Seattle: Ecotope, Inc.

Palmiter, L., and P. Francisco. 1997. Development of a practical method for estimating the thermal efficiency of residential forced-air distribution systems. Research Project 3841-01, Final Report. Palo Alto: Electric Power Research Institute, Inc. TR-107744.

Parker, D.S. 1989. Evidence of increased levels of space heat consumption and air leakage associated with forced air heating systems in houses in the Pacific Northwest. *ASHRAE Transactions* 95(2).

Parker, D.S., P. Fairey, and L. Gu. 1993. Simulation of the effects of duct leakage and heat transfer on residential space cooling energy use. *Energy and Buildings* 20 (2): 97-113.

Proctor, J.P. 1997. Field measurements of new residential air conditioners in Phoenix Arizona. *ASHRAE Transactions* 103(1).

Proctor, J.P., and R. Pernick. 1992. Getting it right the second time: Measured savings and peak reduction from duct and appliance repair. *Proceedings of the 1992 ACEEE Summer Study on Energy Efficiency in Buildings.* Washington, D.C.: American Council for an Energy Efficient Economy.

Proctor, J.P., M. Blasnik, and T. Downey 1995. Southern California Edison Coachella Valley duct and HVAC retrofit efficiency improvement pilot project report. San Rafael, California: Proctor Engineering Group.

Subbarao, K., J. Burch, C. Hancock, A Lekov, and J. Balcomb. 1990. Measuring the energy performance of buildings using short term tests. *Proceedings of the 1990 ACEEE Summer Study on Energy Efficiency in Buildings*. Washington, D.C. American Council for an Energy Efficient Economy.

Tooley and Moyer. 1992. *The duct handbook*, chapter 24. Research Triangle Park, NC: Alternative Energy Corporation.