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Leakage Diagnostics, Sealant Longevity, Sizing and Technology Transfer in Residential Thermal Distribution Systems: Part II

Residential Thermal Distribution Systems Phase VI Final Report

I. Walker, M. Sherman, J. Siegel, D. Wang,
C. Buchanan, and M. Modera

Environmental Energy
Technologies Division

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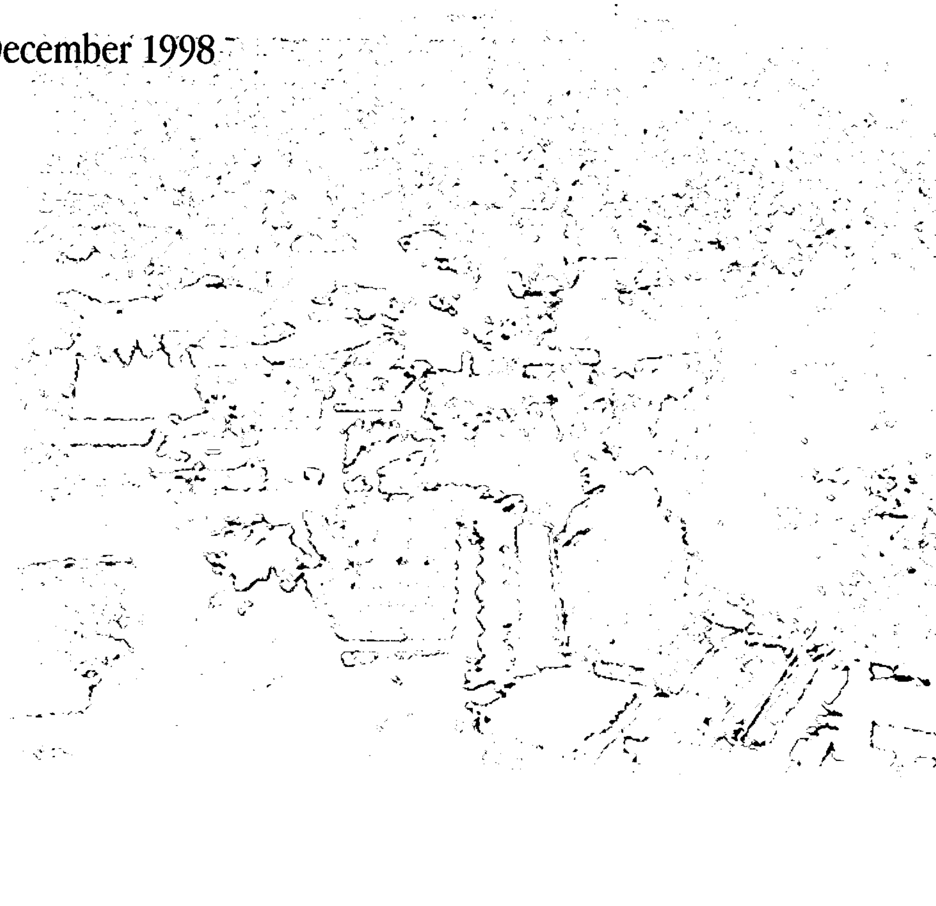

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Environmental Energy Technologies Division
Energy Performance of Buildings Group
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

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Leakage Diagnostics, Sealant Longevity, Sizing and Technology Transfer in Residential Thermal Distribution Systems: Part II

Residential Thermal Distribution Systems
Phase VI Final Report

This report documents the Phase VI technical results of the Residential Thermal Distribution Systems research done by Lawrence Berkeley National Laboratory (LBNL) for the California Institute for Energy Efficiency (CIEE) through September 30, 1998.

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Executive Summary

This report builds on and extends our previous efforts as described in "Leakage Diagnostics, Sealant Longevity, Sizing and Technology Transfer in Residential Thermal Distribution Systems- CIEE Residential Thermal Distribution Systems Phase V Final Report, October 1997". New developments include defining combined duct and equipment efficiencies in a concept called "Tons At the Register" and on performance issues related to field use of the aerosol sealant technology.

Some of the key results discussed in this report include:

- Register, boot and air handler cabinet leakage can often represent a significant fraction of the total duct leakage in new construction. Because of the large range of pressures in duct systems an accurate characterization may require separating these components through improved leakage testing.
- Conventional duct tape failed our accelerated longevity testing and is not, therefore, considered generally acceptable for use in sealing duct systems. Many other tapes and sealing approaches are available and practical and have passed our longevity tests.
- Simulations of summer temperature pull-down time have shown that duct system improvements can be combined with equipment downsizing to save first cost, energy consumption, and peak power and still provide equivalent or superior comfort.
- Air conditioner name plate capacity ratings alone are a poor indicator of how much cooling will actually be delivered to the conditioned space. Duct system efficiency can have as large an impact on performance as variations in SEER.
- Mechanical duct cleaning techniques do not have an adverse impact on the ducts sealed with the Aerosol sealant. The material typically used in Aerosol sealing techniques does not appear to present a health or safety hazard.

Results from this study were used by the California Energy Commission in the formation of the current Energy Efficiency Standards for Low-Rise Residential Buildings (CEC, (1998)), often referred to as Title 24.

Current information on ducts and thermal distribution research can be found at http://ducts.lbl.gov

Introduction

Residential thermal distribution systems have been found to have significant energy and comfort implications due to direct losses from the distribution system in the form of leakage and conduction, combined with poor mechanical equipment performance, and the interactions between the distribution system and the equipment. This study aims to quantify these effects through field testing and computer simulation of residential thermal distribution systems. In addition, this report outlines our efforts to transfer the results of this research to the marketplace so as to reduce energy losses and improve thermal comfort. This study describes the results of efforts made during Phase VI of this Residential Thermal Distribution Systems research. Results of Phase V were described in Walker et al. (1997).

1. Duct Leakage Diagnostics

Review of current implementation of duct leakage testing methods

In Phase V of this work we performed field evaluations of several diagnostic techniques for measuring duct leakage. These techniques have been used by LBNL and other researchers (e.g., Brookhaven National Laboratory – see Andrews et al. (1998)), utilities (Pacific Gas and Electric), code authorities (California Energy Commission (CEC)) and private energy efficiency engineering companies (e.g., Proctor Engineering). Over the last 12 months we have had extensive discussions with these groups to determine their requirements for duct leakage testing and the methods they currently use. In addition, some of these users have performed similar side-by-side tests of the different diagnostic techniques to those performed at LBNL.

In almost all cases, the duct leakage diagnostic of choice is the fan pressurization test of total duct leakage (this means supply and return combined and the combined leakage to inside and outside). The reasons for this are:

- Robustness. The fan pressurization test has almost no restrictions on the type of system it can be used on, or the weather conditions during the test (the House Pressure Test is restricted to certain types of systems and requires calm wind conditions). This is a very important factor in the commercial use of duct leakage diagnostics, where the option to wait for good weather does not exist and all types of duct systems need to be tested.
- Repeatability. This is a key issue for any utility rebate or code compliance program because builders and home owners do not want to pass or fail depending on the work crew or weather conditions on the day of the test. Combining the results of our previous report (Phase V) and the results of other users, the repeatability of the pressurization testing was found to be very good.

- Precision. Although the duct pressurization method has uncertainties associated with estimating leakage flows using system operating pressures, they can be relatively small when the test is used for screening or compliance purposes. This is because utility programs and code enforcement require systems to have little leakage and have simple pass/fail criteria. Because the uncertainties for the pressurization test scale with the amount of leakage, if the allowable leakage is set to a low number, then the uncertainty in leakage flow will also be small.
- Simplicity. It easy to interpret the results of fan pressurization without having to perform many (or any – with the appropriate hardware) calculations. This allows the work crew to evaluate the ducts during the test and also allows the work crew to ensure that the test has been performed properly because they can see if the results make any sense. Unlike the house pressure test, no envelope leakage test is required, so a program that is only screening duct systems only needs to obtain a single piece of equipment and train the work crews to perform a single test.
- Familiarity. Work crews that have performed envelope leakage tests are familiar with the test method for ducts, because envelope testing uses a similar apparatus and calculation/interpretation methods.

The specific duct pressurization test varies from user to user, depending on how they wish to use the results. For utilities and code compliance, the test must show that the duct leakage is below some level. In this case the supply and return are not measured separately and the duct leakage is not separated into its inside and outside components. These simplifications reduce the time required for the test (it can take substantial amounts of time to install airtight separations between supply and return parts of the dust system), the skill required (no balancing of pressures as required for the leakage to outside test), and the equipment needed (no blower door needs to be set up). Given that these tests require that the ducts be relatively airtight in order to pass, the uncertainty in energy losses due to not separating the supplies and returns is small. The measurement of total leakage instead of leakage to outside biases the test because very few systems leak entirely to outside. This means that the test produces an overestimate of the leakage that leads to system losses. However, this bias is in the right direction from the point of view of code enforcement/compliance because it tends to overestimate the leakage so that ducts need to be tight to pass the test. Also, if a system passes the test for total leakage we can safely assume that the leakage to outside is less than or equal to this number and so the duct system is equal to or better than the standard. In enforcement/compliance testing it is important to not pass poor systems so this bias towards higher leakage resulting form measuring total leakage is a bias in the appropriate direction.

Future work on duct leakage diagnostics will bring together experts in the field to examine alternative measurement strategies. This is much more important in the Home Energy rating (HERS) application of the duct leakage tests than the compliance decisions discussed above. For HERS, some houses will have leaky duct systems, in which case the split between leaks to inside and outside and between supply and return can be important when calculating the energy losses.

Our review of duct leakage diagnostics includes input from members of the Project Advisory Committee (PAC) of this research project, members of ASHRAE and ASTM, HVAC contractors, conference attendees (at ASHRAE Meetings, AIVC Conferences, ACEEE Summer Study, etc.). Additional input has come from staff at: Brookhaven National Laboratory, Oak Ridge National Laboratory, Florida Solar Energy Center, California Energy Commission, Proctor Engineering, Berkeley Solar Group, and ECOTOPE.

Boot and Cabinet Leakage

One of the key questions raised in the previous Phase of this work was the contribution of leaks at boots and the HVAC equipment cabinet to the total duct leakage. These two parts of the duct system were examined separately because they represent cases for duct system leakage reduction that can be fixed by equipment changes (the cabinet leakage) and by boot inspection and sealing (as proposed for Title 24) without great expense or effort for the installer/builder. The cabinet leaks (note that this does not include the duct connections to plenums) are also of interest because it should be relatively simple to eliminate these leaks with a combination of changes to cabinet construction (tighter tolerances and improved fan access door seals) and more attention paid to filling knockouts with grommets. Although changing the manufacturing process for system cabinets may be costly for manufacturers, the significant cabinet leakage means that it has a large potential return in terms of energy savings and comfort. To answer these questions about boot and cabinet leaks, additional pressurization tests were performed in the six houses used in this study, plus a set of tests in a pilot study used to develop the test procedures.

In these additional tests, the registers were removed and a blockage placed into the boot. A duct pressurization test was then performed and the boot leakage was determined by the difference between the system leakage with the boots blocked and the standard pressurization tests with the blockage at the face of the register (as illustrated in Figure 1).

A pilot study for this procedure was carried out in a new house in Alameda, CA. This was a relatively large two-story house (about 3500 ft^2 (325 m^2)) with 19 supply registers and two returns (one upstairs and one downstairs). All of the registers were mounted in the ceiling. The ducts were pressurized to 25 Pa using a combined fan/flowmeter device. The leakage to outside was determined by simultaneously pressurizing the house and the duct system.

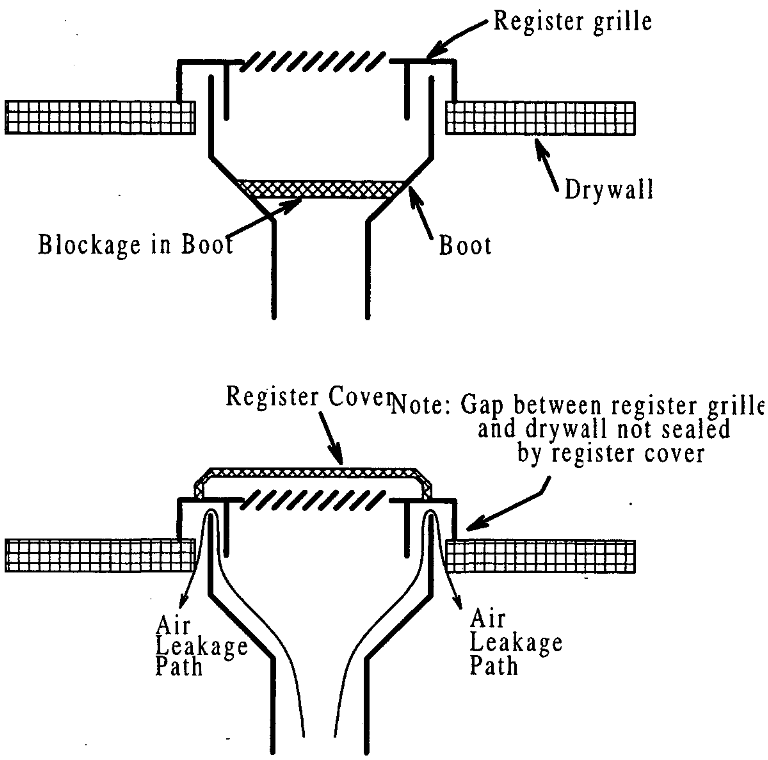

Figure 1. Differences in blocking location for boot leakage tests. Cross sections through boot and register.

Table 1. Pilot study of boot leakage test results

Duct configuration	Leakage Flow, cfm25
Registers Covered, total	284
Registers Covered, to outside	219
Boots Blocked, total	71
Boots Blocked, to outside	53

The results in Table 1 show that boot leakage is the largest leakage source for this duct system (75% of the total). In addition, three quarters of the boot leakage is to outside, which indicates the boots are in good airflow communication with outside. For the upstairs ceiling mounted boots this is because the back side of the boots are exposed directly to the attic. For the downstairs ceiling mounted boots, this result implies that the ceiling of the lower floor has good airflow connections to outside also - probably to the attic via partition and wall leakage flow paths. This illustration that the majority of boot leakage may not be benign (i.e. to inside) is crucial because it means that sealing of boots cannot be neglected. From visual observation, the leakage path for these boots was between the ceiling drywall and the outside of the boot, rather than holes in the sheet metal of the boot or a poor connection between boot and duct.

The cabinet leakage in most systems consists of two parts:

1. The leaks around the fan access panel/door.
2. Flow through knockouts in the cabinet.

In the houses tested for this study, the combined total of these leaks was estimated from pressurization tests. The pressurization tests were performed with and without the cabinets included and the difference between the two tests was the cabinet leakage. The cabinets were isolated for these tests by inserting blockages between the equipment cabinets and the rest of the duct system. Some houses had only the knockout leakage tested. In these cases, the cabinet was pressurized with the knockouts open and then with the knockouts taped over, and the difference between the two tests was the leakage attributable to the knockouts.

In the pilot study house, there were two knockouts. Both knockouts (as is almost always the case) were round. One knockout was ½ inch (12mm) in diameter and the other was 1-½ inches (37 mm) in diameter. In the pilot house we did not perform the pressurization tests for cabinet leakage, we just observed the size and location of the holes in the cabinet. An estimate of leakage flow at 25 Pa can be made by assuming that the holes act like sharp edged orifices with a discharge coefficient of 0.6 resulting in a combined leakage flow of about 10 cfm25 for these two holes. As a verification of this estimate, at test sites 3 and 6, the cabinets were pressurized with the knockouts sealed and open. The differences were found to be between 6 and 9 cfm for similar sized knockouts to those in the pilot house.

The other 6 houses tested for this project used the pressurization tests with internal blockages (described above) to determine the boot and cabinet leakage at 25 Pa and 50 Pa. Table 2 summarizes the results for the 25 Pa tests. The results show that cabinet leakage averaged 19 cfm25 to outside, most of which could be reduced by improving construction of cabinets and placing grommets in electrical knockouts. The boots averaged about 66 cfm25 to outside. However, if we convert to the average of the measured operating pressures of about 5 Pa for boots and 65 Pa for cabinets the results are much different, with boot leakage of about 25 cfm and cabinet leakage of about 34 cfm. The standard deviations of the operating pressures were significant: ±3 Pa for boots and ± 31 Pa for cabinets due to the large variation from system to system depending on the specific installation. This was true even for houses of the same floor plan, register location and equipment installation (sites 1 and 2).

These conversions from measured to operating pressures assumed a pressure exponent of 0.6. The results are not very sensitive to the selection of this pressure exponent with the results being 30cfm for boots and 31 cfm for cabinets using a different pressure exponent of 0.5. The measured results at 25 Pa and 50 Pa in this study were used to estimate the pressure exponent for 57 different duct leakage tests with an average exponent of 0.62 with a standard deviation of 0.09. This large number of tests results from testing different parts of the duct system separately (e.g., supply, return and cabinet) and because the duct systems were tested in different configurations (sealed, as found and with added holes). Comparing the leakage to outside to the total leakage shows that the boots have about 2/3 of their leakage to outside, but almost all of the cabinet leakage is to outside.

The boots and cabinet averaged three-quarters of the system leakage at 25 Pa to outside. The variation in this fraction is significant, with a standard deviation of 20%, indicating that individual installation and system layout contribute strongly to determining this fraction. In particular, house 6 had only 24% of duct leaks at the cabinet and boots compared to an average of 70% for the other houses. Removing house 6 from the calculations reduced the standard deviation to only 7%.

Table 2. Boot and cabinet leakage to outside with the systems as found (before sealing or addition of leaks)

Site	Boot (cfm25)	Cabinet (cfm25)	Fraction of all duct leakage, %
1	21	51	73
2	29	15	61
4	63	17	63
5	95	26	76
6	21	6	24
Pilot house	166	0*	76
Average with pilot house	66	19	74
Average w/o pilot house	46	23	60

* - estimate

2. Duct Sealants and Longevity Testing

Longevity of duct sealants has been examined in three separate experiments in this and other recent studies. The three tests are:

- cycling tests performed on a small scale for EPA
- the current pressure and temperature cycling longevity tests, and
- constant temperature baking tests performed coincidentally with the current longevity tests.

A previous report (Walker et al. (1997)) discussed the development of the longevity test method and preliminary results. The final results and details of the experiment are given in "Can Duct Tape Take the Heat" - LBNL report # 41434 and its companion Home Energy Article (Home Energy, Vol. 15, No.4, pp. 14-19. http://www.homeenergy.org/898ductape.title.html). The following section is a summary of these reports.

The longevity test method heated and cooled sample test connections (each sealed with a different sealant) by alternately blowing hot (75°C, 170°F) and cold (-12°C, 10°F) air through the connections. In addition to the cycling of air temperature, the pressure across the leaks was also cycled between about 100 and 200 Pa. Eight test sections were tested simultaneously, with continuous monitoring of air and surface temperatures, pressure differences between inside the test sections and the room, and total system leakage. Periodically (every few days) the system was turned off and the test samples removed for individual leakage testing. This testing measured the leakage flows at 25 Pa. The leakage of the samples was also measured before any sealing and immediately after sealing before installation in the test apparatus. The "failure" of a sample was determined by looking at its leakage flow as a fraction of the unsealed flow (so a leakage fraction of 100% corresponds to the leakage with no sealant). The failure level was set to be 10% of the unsealed leakage, although samples were often tested beyond this leakage level.

In addition to the temperature cycling tests, we also baked samples in an oven. In these baking tests, the samples were held at relatively steady temperatures in the range of 60°C to 80°C (140°F to 180°F). There was no pressure difference across the seal, or air flow past the seal, that would blow a damaged seal off the sample.

Table 3 summarizes the results of the longevity testing for all three experimental procedures: aging, baking and the original cycling tests of aerosol sealants. A total of 41 samples were testing in all the test procedures, with at least a single sample of each sealant type and multiple samples of the sealants we are focusing on here - duct tapes. The most important result of these tests was that the only sealants to fail were the rubber adhesive vinyl/polyethylene backed duct tapes (RAVB duct tapes)- irrespective of their UL rating. However, this results does not mean that all the RAVB duct tapes are guaranteed to fail - there was one 181B approved RAVB duct tape that did not fail the tests.

In addition to performing the above tests, the longevity procedure has being prepared for ASTM as a standard test procedure for duct sealant longevity. A draft of this procedure is currently being considered by ASTM members.

The question has been raised whether flex duct itself may also degrade over time. Anecdotal evidence supports this conjecture, but we are not aware of any systematic studies on this subject. A survey of existing installations is required to shed some light on this issue.

Table 3. Summary of Duct Tape Failures

# of Tests	*Sealant Type*	*Test Duration*
Aging Test		
8	5 different grades of duct tape	7 days, failed
3	181B-FX - approved duct tape	10 days, failed
1	181B-FX - approved duct tape	3 months
1	15-mil foil backed butyl tape	3 months
1	Aerosol sealant	3 months
1	181A-M and 181B-M - approved mastic	3 months
1	181A-P - approved foil tape	3 months
1	181A-P & 181B - approved foil tape	1 month
1	Packing Tape	3 months
1	181B-FX - approved Packing Tape	1 month
Baking Test		
5	3 different grades of duct tape	34 days, failed
1	181B-FX - approved duct tape	60 days, failed
2	Duct Tape	4 months
3	181B-FX - approved duct tape	4 months
1	Packing Tape	4 Months
1	181A-P - approved foil tape	4 months
1	Aerosol sealant	4 months
Cycling test		
4	Aerosol sealant under pressure cycling only	2 years
4	Aerosol sealant with pressure and heat cycling	2 years

3. Duct System Interactions with System Sizing and Capacity

In addition to saving energy through improving duct systems, this study examines the possibility of downsizing of cooling equipment without sacrificing comfort conditions. Two concepts were used to study this issue:

1. Tons at the Register (TAR). Tons at the register is the actual cooling delivered to the occupants, i.e. what comes out of the registers. The combined distribution system losses and system capacity at operating conditions act to determine the TAR of a system.
2. Pulldown. Comfort, and hence occupant acceptability, is determined not only by steady-state temperatures, but by how long it takes to *pull down* the temperature during cooling start-up, such as when the occupants come home on a hot summer afternoon. In addition, the delivered tons of cooling at the register during start-up conditions are critical to customer acceptance of equipment downsizing strategies.

In this study we have used two approaches to examine this issue:
1. Computer simulations.
2. Field measurements of case study houses.

Simulation Overview

The following discussion is based on Walker, Brown, Siegel and Sherman (1998) that covers the simulations in more detail.

For this study, a computer based simulation tool (called REGCAP) was used to calculate cooling system performance. The thermal, moisture and ventilation parts of REGCAP are from existing models that were specifically developed to examine attic performance. These models of ventilation and heat transfer, excluding the ducts, have been verified with extensive field measurements. The air flow modeling for REGCAP combines the existing ventilation models for the house and attic with duct register and leakage flows using mass balance of air flowing in and out of the house, attic and duct system. The thermal modeling uses a lumped heat capacity approach so that transient effects are included. The ventilation and thermal models interact because the house and attic ventilation rates depend on house and attic air temperatures, air flow through duct leaks, and the energy transferred by the duct system depends on the attic and house temperatures.

The equipment model for REGCAP uses manufacturers' performance data that shows how capacity changes with outside weather conditions, flow rate across the evaporator coil, and the return air conditions. Some simple regressions have been used to interpolate between specific performance figures in the manufacturers' tabulated data. Additional information regarding air conditioner performance changes due to incorrect system charge and system air flow have been adapted from laboratory data (Rodriguez et al. 1995). Using these correlations, the output from the airflow and thermal models are used together with weather data to determine the air conditioner performance. The temperature change across the cooling coil is determined from the mass flow rate through the coil (the system fan flow) and the calculated capacity of the equipment.

The general data requirements for REGCAP are:
DUCTS: size, location, leakage, insulation
EQUIPMENT: manufacturers' performance data, refrigerant charge, evaporator airflow

ENVELOPE: leakage, thermal properties
CLIMATE: Temperature, windspeed and direction, humidity, solar radiation

The REGCAP output includes:
DUCTS: air and energy flows at the registers, losses to unconditioned space
EQUIPMENT: operating condition capacity and efficiency
ENVELOPE: Thermal losses and air flows

In order to focus on the pulldown performance of the systems, the air-conditioner is off from midnight to 3:00 p.m.. Then at 3:00 p.m., the air handler is turned on. The simulation model was used to calculate the system performance in 15 minute time steps for a whole day (including times when the system is off).

The following list examines key input parameters and gives the limited range of values that we used for the simulations in this study:

Weather. Two weather data sets (from the TMY database, NCDC 1980 for Sacramento, CA.) were used: a design day and "hot day" (highest peak temperature). The design day has a peak temperature of 36°C (97°F) and corresponding relative humidities in the range of 10% to 30%. The hot day has a peak temperature of 41°C (106°F) with similar relative humidity. The solar radiation (direct normal) is about the same for both days with peaks of about 900W/m^2 (3.3kBtu/hour/ft^2).

Refrigerant Charge. Three levels were used: proper charge, typical charge 85% as found in recent field studies (Proctor 1997 and Blasnik et al. 1996) and 70% charge (worst case found in field tests by Proctor 1998)

Airflow across coil. Two flows were tested: 425 cfm/ton (manufacturers design specification for the unit used in the simulations) and 345 cfm/ton (about 20% less than the design specification and typical of that found in field studies).

Duct Leakage. Four cases:
1. Poor - 30% of fan flow leakage for both supplies and 30% for returns - this is from the average of the worst 25% of houses surveyed in California by Jump et al. 1996.
2. Typical - 11% of fan flow leakage for both supplies and returns from field surveys by Modera and Wilcox 1995 and Walker et al. 1997, for new construction in California (This is also the default used in California T24 Energy Code (CEC 1998)).
3. Good - 3% of fan flow leakage for both supplies and returns. This is a leakage level that can be achieved using current duct sealing technology if the ducts and equipment cabinet are in unconditioned space.
4. Best - zero leakage. To realistically achieve this using existing duct systems requires bringing ducts and equipment inside the conditioned space.

Air handler and duct location. Two cases: 1. Ducts and air handler in attic, and 2. Ducts and air handler all inside the conditioned space.

Equipment Capacity. The rated capacity was calculated for the simulated house using ACCA Manual J (ACCA 1986). These calculations indicated that a rated capacity of three tons would be required. It was assumed that a correctly design system would have this capacity (this corresponds to the *RESIZED* and *IDEAL* systems simulated). However, this is not typical of residential installations, so the rated capacity was also estimated based on surveys of HVAC contractors (Vieira et al. 1996) with one ton for each 46 m^2 (500 ft^2) of floor area giving a total of four tons rated capacity.

Other input parameters were fixed for every simulation

Table 4 summarizes the simulations performed for this study. Each case in Table 4 was run twice - for both design day and hottest day conditions.

Table 4. List of REGCAP Simulation Cases

	System Charge [%]	Air Handler Flow [CFM/Ton]	Duct Leakage Fraction [%]	Duct and equipment Location	Rated Capacity [Tons]
BASE	85	345	11	Attic	4
POOR	70	345	30	Attic	4
BEST	100	425	3	Attic	4
BEST RESIZED	100	425	3	Attic	3
INTERIOR DUCTS	85	345	0	House	4
INTERIOR DUCTS RESIZED	85	345	0	House	3
IDEAL	100	425	0	House	3
IDEAL OVERSIZED	100	425	0	House	4

The *BASE* case is typical of new construction in California. The *POOR* system represents what is often found at the worst end of the spectrum in existing homes. The *BEST* system is what could reasonably be installed in new California houses using existing technologies and careful duct and equipment installation to manufacturers' specifications. The *BEST RESIZED* system looks at the possibility of reducing the equipment capacity using the best duct system. *INTERIOR DUCTS* examines the gains to be had if duct systems are moved out of the attic. The *INTERIOR DUCTS RESIZED* determines if a smaller piece of equipment can deliver the same capacity as a bigger piece of equipment with a poor duct system. Lastly, the *IDEAL* system is an interior duct system that has been installed as well as possible. The *IDEAL OVERSIZED* simulations were included to examine the difference in pulldown if the *IDEAL* system were sized using current sizing methods (i.e., still 4 tons).

Simulation Results

Three key results are examined:

1. Initial delivered capacity at the registers (TAR) with hot house, attic and duct system.
2. Pulldown time for interior to reach 24°C (75°F).
3. Final delivered capacity (TAR) at the registers with cool house and duct system. The final capacity is determined when the system has cooled the house to 24°C (75°F).

An example illustration of the simulation results for the BASE case is given in Figure 2 (Note that Figure 2 data are truncated at the point where the indoor temperature reaches the setpoint). The ducts are in the attic and so the supply temperature is close to the attic temperature until the system turns on. The supply temperature is about 7°C (13°F) below room temperature. In addition, the duct losses to the attic tend to cool the attic. This is seen at the end of the simulation, where the attic temperature is about 5°C (9°F) cooler than the no cooling system case.

Table 5 summarizes the tons at the register and pulldown time results for all the simulations. The increased loads of the hottest day reduce the delivered capacities and increase the pulldown time. As expected, the interior systems and the non-leaky attic system (*BEST*) have the fastest pulldown and greatest tons at the register. For the hottest day simulations, the *POOR* system heats the house when it is first turned on because the supply air temperature is hotter than the house air - hence the negative initial delivered capacity. This result is mainly due to the low system capacity (caused by poor charge, low air flow and high outside temperatures) and the return leaks heating up the return air.

The simulation results in Table 5 show that the *BEST RESIZED* system with a smaller A/C unit (rated at three tons rather than four tons) can provide almost the same performance as the *BASE* system. The pulldown time is longer by a single simulation time period (15 minutes) for the *BEST RESIZED* system. Moving the ducts inside allows a smaller capacity system (*IDEAL*) to have faster pulldown and more tons at the register than the *BASE* system. In addition, the *IDEAL* system has greater initial tons at the register than the *BEST* system in the attic that has 25% more nameplate capacity.

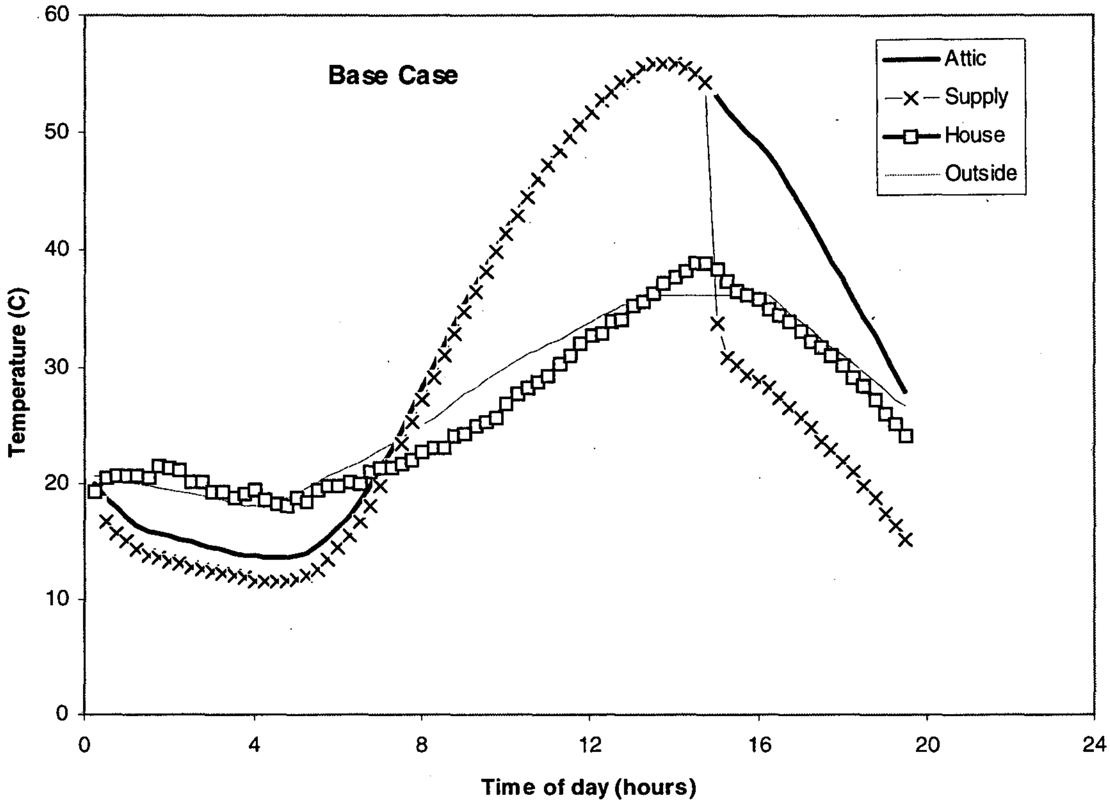

Figure 2. Simulation results for the base case system for a Sacramento Design day.

Table 5. Tons at the register and pulldown time simulation results

		Design Day			Hot Day		
	Rated Capacity, Tons	Initial Tons at the register	Pulldown time, Minutes	Final Tons at the register	Initial Tons at the register	Pulldown time, Minutes	Final Tons at the register
BASE	4	0.83	270	1.55	0.58	315	1.51
POOR	4	0.09	390	0.68	-0.05	435	0.68
BEST	4	1.56	195	2.33	1.24	240	2.30
BEST RESIZED	3	0.80	285	1.59	0.58	330	1.59
INTERIOR DUCTS	4	1.68	195	2.08	1.66	240	2.02
INTERIOR RESIZED	3	1.20	285	1.35	1.18	345	1.33
IDEAL	3	1.41	240	1.72	1.41	300	1.66
IDEAL OVERSIZED	4	2.06	135	2.73	2.07	180	2.62

The results in Table 5 also show that the output of air conditioning equipment does not match the nameplate rating. The final tons at the register for the ideal system (that has correct charge, system air flow, no duct leakage, and all ducts inside) is much lower than the rated capacity. Note that this low rated capacity is calculated directly from manufacturers' performance data.

Simulation Conclusions

The simulation results show that improved ducts and system installation can allow the use of a smaller nameplate capacity air conditioner (almost one ton less in our case, and at least one ton in more demanding situations) without reducing the cooling delivered to the house (tons at the register) or the pulldown time. If system nameplate capacity is unchanged, either improving duct systems (to have little leakage) and correctly installing the equipment, or moving the ducts inside results in significant pulldown performance improvements. In these cases pulldown times were reduced by more than an hour and initial tons at the register were approximately doubled.

The results also show that without knowing about the quality of installation or location of the air conditioning system, the nominal capacity of the A/C unit is not a good indicator of system performance. Proper sizing of cooling equipment to meet peak loads cannot be done using nameplate ratings, but requires using manufacturers' performance data at more realistic conditions and an understanding of distribution system effectiveness.

Field measurements

Field measurements were made on air-conditioning systems in six houses. These measurements included diagnostics to determine building and system characteristics and continuous monitoring over several days to determine pulldown system performance. Six houses were monitored for this project: 2 houses in Palm Springs, CA. (sites 1 and 2), one house in Mountain View, CA. (site 3), two houses in Sacramento, CA. (sites 4 and 5), and a single house in Cedar Park, TX (site 6). All of the houses were new and unoccupied, except for the Mountain View house that had been occupied for less than a month at the beginning of our tests. The Mountain View house was the only one occupied during the tests.

All the houses were cooled with split system air conditioners and heated with natural gas (using the same air handler/cabinet and ducts). The exception was the Texas house that had a heat pump and electric resistance strip heat. The two Palm Springs and two Sacramento houses had all of the system in the attic - air handler, equipment cabinet and ducts. The Mountain View house had the air handler/cabinet in the garage, with the ducts running inside the structure in soffits, floors and wall spaces. The Texas house had the air handler/cabinet in a closet in the house, with only the supply plenum and supply ducts in the attic.

The houses were tested in their "as found" configuration, then with the duct systems sealed. Houses that did not have very much "as found" duct leakage had holes added. These added holes had their flow measured using a vane anemometer during normal system operation so that the added leaks were very well known and did not have to be inferred from indirect measurements.

In two houses, the cooling equipment was replaced with Energy Star® equipment (greater than SEER 13.0). The original cooling equipment in each house was rated at the federal minimum SEER 10. In Sacramento (site 4), just the outside compressor unit and the control system were changed. In the Texas house (site 6) the indoor coil, fan and cabinet (and electric heating system) were also replaced.

The continuous monitoring was performed for several days in each system configuration. During this monitoring the system was set to stay off until about 3:00 p.m., allowing the house to warm up during the day (just like in the simulations). Then the system was turned on and the house temperature "pulled down" to 74°F (24°C), or lower, at the thermostat. Because temperatures were monitored in each room we were able to determine if the temperature at the thermostat was representative of other temperatures in the house. In most cases, the thermostat was not the warmest place in the house (it was usually centrally mounted in a hallway away from any direct solar gains) and so the pulldown was changed to reduce the temperature at the thermostat below the original 74°F (24°C) setpoint. Also, pulldown times were calculated for different parts of the house.

Continuous Monitoring

The continuous monitoring used computer based data acquisition systems to store data approximately every 10 seconds. The monitored parameters were:

- Temperatures: at each register, in each room, outdoors, attic, garage, return plenum and supply plenum. The supply plenum temperatures were measured at four points in the plenum to account for spatial variation in plenum temperatures.
- Weather: wind speed, wind direction, total solar radiation and diffuse solar radiation.
- Humidity: outside, supply air, return air and attic (or garage if system located in garage).
- Energy Consumption: Compressor unit (including fan) and distribution fan power.

The measured system temperatures were used to calculate the energy flow for each register (and therefore the total for the system) and the energy change of the air stream at the heat exchanger at each time step.

Tons At the Register (TAR)

Having data every few seconds allowed the calculation of TAR at different times during the pulldown test. The TAR for each of the sites and test conditions appears in Table 6, where the results have been concatenated from the several tests performed at each condition. Care should be taken when interpreting these numbers because they are sensible capacities only. Humidity data will be used in future analyses to include latent capacity. The latent capacity is expected to be a small part of the system load at these sites, particularly in sites 1 and 2 (located in the desert climate of Palm Springs, CA). The nominal capacity is taken from the manufacturers nameplate - this is the traditional number used to size cooling systems.

The results in Table 6 show that tons at the register often starts out as being negative because the air in the ducts, the ducts themselves, the fan and the heat exchanger coils are hot. After this initial transient it then increases to a maximum value that occurs several minutes later. It then usually declines slightly as the air in the house cools slowly and changes the heat transfer at the cooling coil, and so the final value at the end of the cycle is lower than the maximum. As with the simulations discussed earlier, the cooling delivered to the conditioned space is always much less than the nameplate rating.

Comparing the "as found" to "sealed" results does not clearly show any benefit to sealing the leaks. This is due to the limited number of tests and the variable weather during the tests. Future work will examine the possibility of normalizing by weather conditions for each test. At sites 1 and 3, the performance during the initial five minutes is improved by sealing the leaks (at site 2 there is little change), and this transient improvement would give better occupant comfort (initial pulldown is faster) even if the final TAR is unchanged.

Table 6. Capacity at the registers

Site	Condition	Nominal Capacity [Tons]	Tons at the Register: First Minute	First 5 Minutes	Max. Value	Final Value
1	As Found	5	-0.1	2.1	3.6	2.3
1	Sealed	5	2.0	2.7	3.0	2.4
2	As Found	5	0.9	2.0	2.7	2.9
2	Correct Charge	5	1.3	2.1	2.6	2.6
2	Leaks Added	5	1.0	2.1	2.6	2.5
2	Sealed	5	0.9	2.2	2.9	2.8
3	As Found	3	1.1	1.8	2.5	2.2
3	Correct Charge	3	0.8	1.8	2.6	2.3
3	Sealed	3	1.0	1.7	2.7	2.5
4	As Found	2	-1.1	0.5	1.5	1.4
4	New Unit	2	-0.6	0.7	1.6	1.4
4	Leaks Added	2	-0.8	0.4	1.3	1.1
5	As Found	2.5	-0.8	0.6	1.7	1.4
5	Sealed	2.5	-1.1	0.5	1.7	1.5
6	As Found	3	0.6	0.6	1.8	1.6
6	New unit	3	1.0	1.0	1.5	1.5
6	Added Leaks	3	0.3	1.1	1.7	1.4

Delivery Effectiveness

Although TAR is useful from the perspective of comfort, it does not only depend on the distribution system. For this reason, the delivery effectiveness of the distribution system was also calculated. The delivery effectiveness is the total capacity at the registers divided by the capacity at the at the air handler and does not include any regain of losses or the energy and comfort implications of duct leakage to inside. Because delivery effectiveness is usually thought of as a steady-state value, the maximum delivery (over the course of the pulldown test) effectiveness was used here. Note that these data are based on the sensible delivery efficiency. Future work will evaluate delivery effectiveness including latent effects. Table 7 and Figure 3 show that the results of sealing the duct system are much more apparent when looking at delivery effectiveness rather than the TAR uncorrected for weather changes as given in Table 6.

Table 7. Maximum Delivery Effectiveness

Site	Condition	Delivery Effectiveness
1	As Found	86%
1	Sealed	87%
2	As Found	76%
2	Correct Charge	72%
2	Added Leaks	72%
2	Sealed	84%
3	As Found	99%
3	Correct Charge	100%
3	Sealed	99%
4	As Found	94%
4	New Unit	96%
4	Added Leaks	87%
5	As Found	77%
5	Sealed	87%
6	As Found	75%
6	New Unit	68%
6	Added Leaks	82%

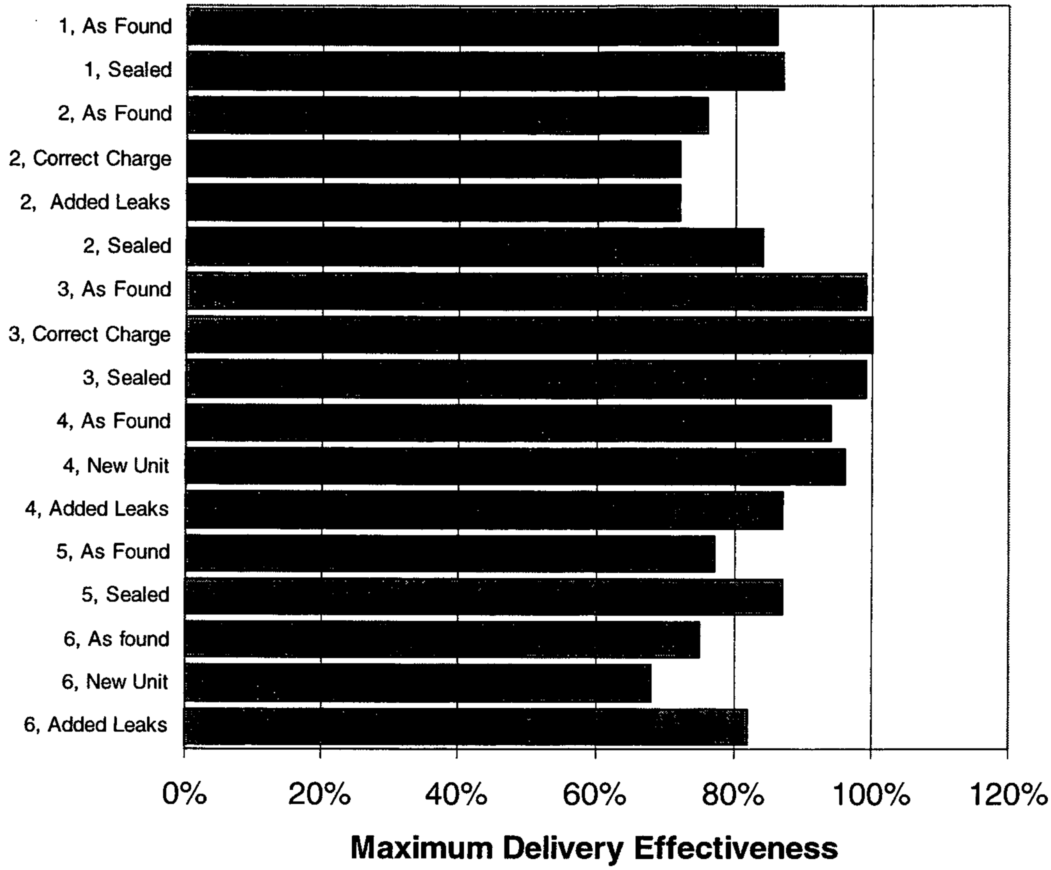

Figure 3. Comparison of maximum delivery effectiveness between systems and the increase in delivery efficiency for sealed systems

Diagnostics

The following diagnostic results were used to characterize the house and duct system, determine changes in system performance (e.g., leak sealing) and to prepare the required input parameters for future work comparing simulations to measured field data.

Envelope Leakage.

The envelope leakage was measured using a blower door test with the registers uncovered. Therefore it includes leakage to outside via the duct system. The envelope leakage for each of the six test sites is given in Table A1 in Appendix A. The leakage is expressed in several ways:

- in terms of the blower test results, i.e., the flow coefficient and exponent,
- Specific Leakage Area (SLA),
- Flow at 50 Pa divided by floor area (Q50/FA).

The SLA and Q50/FA are methods of scaling leakage by house size so that comparisons of envelope air tightness can be made between houses. In addition, the calculation of SLA allows the comparison of these houses to a "standard" house that would meet T24 energy code. Both these methods normalize the leakage by house floor area. In addition, SLA uses the effective leakage area of the house calculated from the flow coefficient and exponent. These houses had an average SLA of 5.0 corresponding to 1.4 cfm/ft^2 floor area at 50 Pa. For comparison California Energy Code - Title 24 uses a default SLA of 4.9 for houses with ducted forced air systems which is very close to the measured results in these six test houses. There was a large variation of a factor of four from house to house indicating a large variability in construction. However, house 5 had open vents because all the appliances were not in place and removing this house reduces the variability considerably.

House ventilation rates.
Ventilation rates were measured using tracer decay with the system fan off and the system fan on to determine any changes in ventilation rate due to duct leakage. The results of these tests are summarized in Appendix A, Table A2. Because of the large variation in ventilation rates with weather conditions, the only significant result is the change in ventilation rate due to system operation. The fractional increases (compared to when the system was off) in ventilation due to system operation are only valid for the particular instances of these tests. For example, the large fractional increase at site 6 after holes were added is because the ventilation rate was very low with the system off.

At site 1 the change was 0.17 ACH (and increase of 30% compared to the test with the system off) with the system as found. After sealing, four tests were performed at site 1 with an average of 0.22 ACH increase in ventilation rate. This counter-intuitive result (we expect less change in ventilation rate if we have sealed system leaks) indicates the large uncertainty in using these tracer decay measurements. Much of this uncertainty may be due to having different weather conditions on different days. The change in weather can have a similar magnitude effect to the change in ventilation rate due to system operation and future analyses will attempt to account for changes in weather between tests.

The remaining sites all showed significant increases in ventilation rate (between 0.18 and 0.63 ACH) with the system operating. The increase in ventilation for systems operating "as found" ranged from 0.12 ACH to 0.18 ACH. Adding holes to the systems at sites 2 and 6 was an even greater effect (as expected) with increases in ventilation due to HVAC system operation of 0.60 ACH and 0.37 ACH.

Register Flows.
The supply register flows were measured using a fan assisted flowhood. The return register flows were measured either using a flowhood or a vane anemometer traverse. The mean anemometer velocities were combined with an estimate of the open area of the return grille to obtain return flows. The individual register flows were used together with the individual register temperatures to calculate the energy flow out of each register (tons at each register). The supplies were then combined to find the total energy flow (TAR) for the system. The sums of the register flows are summarized in Appendix A, Table A3. The sum of the supply register flows as found averaged over all systems was 13 % less than the fan flow. A similar comparison could not be made for return flows due to the large uncertainty in measuring the return register flows measured using the vane

anemometer. In four of the six sites this uncertainty resulted in return register flows that were greater than the fan flows. Based on our field experience, the most likely reason for overpredicting these return flows was the difficulty in estimating the open area of the return grille.

Fan flow

Fan flowmeter:

The fan flowmeter test methods used here are based on those in proposed ASHRAE Standard 152P and proposed CEC ACM, Appendix F. This test uses the supply ducts as a flowmeter. The pressure difference between the supply plenum and the conditioned space is measured at operating conditions - ΔP_{sp}. The return duct is then blocked off from the rest of the equipment and a fan flowmeter attached at the air handler access. The fan flowmeter is turned on and adjusted so until the pressure difference between the supply plenum and the conditioned space is the same as at normal operating conditions. The flow through the flowmeter is the system fan flow at operating conditions. However, the fan flowmeter does not usually produce enough flow to match the supply plenum to conditioned space operating pressure. In these cases the fan flowmeter is operated at maximum and the flow (Q_{max}) and supply plenum to conditioned space pressure (ΔP_{max}) are recorded. Assuming a pressure exponent of 0.6 for the duct system, the measured flow at maximum is extrapolated to the flow at the operating condition pressure difference using:

$$Q_{fan} = Q_{max}\left(\frac{\Delta P_{sp}}{\Delta P_{max}}\right)^{0.6}$$

An alternative is to operate the fan flowmeter over a range of flows, recording the flows and supply plenum to conditioned space pressure differences. A least squares fit can then be used to determine C_s and n_s for a power law relationship:

$$Q = C_s(\Delta P)^{n_s}$$

Then system flow at operating conditions is given by:

$$Q_{fan} = C_s(\Delta P_{sp})^{n_s}$$

Other tests were performed with the system fan also operating in an attempt to reach the measured system operating pressure and eliminate the need to extrapolate from lower pressures. As Table A3 shows, there were significant differences in some cases between the pressure flow relationship (and therefore the extrapolated fan flow) for the duct system with the fan flowmeter alone and the fan flowmeter combined with the system fan. We believe that this is due to changing flow patterns through the fan flowmeter (and particularly over the flowmeter part) that are induced by having the second fan in series. We will investigate these anomalies further in the future. However, the current results seem to indicate that using the fan flowmeter alone (and in some cases using only a single point test with an assumed pressure exponent of 0.6) gives better results than attempting to match the operating condition flows and pressures by using the system fan. In addition, the results show that simultaneously operating the system air handler and the fan flowmeter fan tends to produce a lower estimate of fan flow. In several cases the combined fans produce a fan flow that is lower than the sum of supply flows – an unlikely result, indicating that the fan flowmeter operating alone is the preferable test method. Note that proposed ASHRAE standard 152 and the CEC ACM both recommend simultaneous operation of the fan flowmeter and the system fan and these approaches may have to be reevaluated in light of the above results.

Tracer gas:
The tracer gas fan flow measurements are shown in Table A3 together with the fan flowmeter measurements. There is reasonable agreement between the tracer gas and fan flowmeter (without system fan) methods. The major differences are at site 5, where the fan flowmeter method seems to greatly overestimate the fan flow.

Duct leakage
Duct leakage was separated into: supply, return, supply boot, return boot and cabinet by connecting the fan flowmeter at different parts of the duct system and inserting blocking in the ducts to isolate the individual components. The separation of total leakage from leakage to outside was accomplished by simultaneously pressurizing both the ducts and the house. The boot and cabinet leakage was discussed previously in Section 1. These and other test results are given in Table A4, Appendix A. In the "as found" condition, some systems were less leaky than expected. This gave little scope for changing leakage by sealing, so sites 2, 4 and 6 had leakage added. Although Site 3 had almost all of its duct system (except for the cabinet, supply plenum and return platform) inside the conditioned space, it had the greatest supply leakage to outside. This shows that the spaces containing the ducts were not sealed with respect to outside. This result illustrates the need for testing all duct systems for leakage, even though they may appear to be inside conditioned spaces. Another interesting result was at Site 6, where there was significant return leakage to outside. Although there were no return ducts as such, the closet containing the equipment and the platform return leaked to the attic through holes around the ceiling penetration for the supply plenum. Again, this illustrates the requirement for system testing, where simple observation would have implied that the return leaks were to the closet (essentially the conditioned space).

Expressing the combined total supply and return duct leakage at 25 Pa as a fraction of fan flow, the average "as found" condition had 16% leakage with a range from 6% (site 2) to 31% (site 3). Of the four sites that were sealed, the "as found" average was 16%, and this was reduced to 8% after sealing. The opinion of the field test personnel is that it would be possible to do a much better job of sealing these ducts if more time were spent and if the sealing was done before houses were in a finished state. This is because we did not want to damage the finished surfaces in the test houses and access to duct connections is much better before the house is complete.

Only site 1 was below the 6% threshold required by the proposed Title 24 ACM for obtaining credit for tight ducts in the "as found" condition. About two thirds of this leakage was to outside, with the combined supply and return leakage to outside at 25 Pa being 10% of fan flow. After sealing, site 2 was also at the 6% threshold and site 5 was close - at 7%. This result shows that sealing existing systems can be effective in meeting the proposed Title 24 duct leakage requirements for tight duct credit.

At sites 2, 4 and 6 the pulldown tests were performed with added leaks to simulate the performance of poor duct systems. The added leaks were cut into the supply and return plenums and resealed after the experiments were finished. At sites 2 and 6 the leakage flows at operating conditions were measured directly using a vane anemometer. At site 4 the extra leaks were calibrated in a laboratory and the measured system operating pressures were used to estimate the leakage flows at operating conditions. These added leaks are summarized in Table A5.

System operating pressures in plenums and at register boots.
The register boot pressures were measured by inserting a static pressure probe to a point inside the register grille upstream of a lip at the edge of the grille and in a location out of the main flow stream. The measured pressures are highly dependent on the selection of the measurement location. Moving the probe by a few millimeters into the flow can completely change the measured pressure, including the possibility of indicating a negative pressure. However, extensive field experimentation has shown that it is possible to obtain repeatable results (different people getting the same result) if the procedure for the measurements is consistent. Typical plenum operating pressures were about 65 Pa and typical boot operating pressures were about 5 Pa. These differences in pressures across leaks at different locations is one of the most difficult parts of extrapolating from measured leakage at a fixed test pressure (25 Pa or 50 Pa) to the actual leakage at operating conditions. As shown in Section 1, boots have almost three times the leakage of the cabinets at the same measurement pressure. However, using the measured operating pressures significantly alters their contribution to the system leakage, such that the cabinet and boot leaks are of similar magnitude.

Duct leakage by house pressure test (HPT).
The HPT results are summarized in Table A6 in Appendix A. The results showed some anomalies, with the leakage going in the wrong direction in three of the five leakage change configurations measured (i.e. in many cases the HPT predicted less leakage when holes were add to the system, and increased leakage when the systems were sealed.). Expressing the HPT leakage as fractions of fan flow, the mean supply leakage was 7% and the mean return leakage was 3% in the as found condition.

Duct location and dimensions.
The duct location and dimension information is summarized in Tables A7 and A8. For all but site 3, all the supply ducts were in the attic, with the air handler and equipment also in the attic at sites 1, 2, 4 and 5. At site 3 the ducts were in between the first and second floors, running in the joist bays and in drop ceiling soffits. In addition, the air

handler, plenums and equipment were all in the garage at site 3. At site 6, the air handler and equipment were in a closet inside the thermal envelope of the house. The exposed supply and return duct surface areas averaged 26% and 6% of floor area respectively (not including site 3). This is almost the same as the current proposal in ASHRAE Standard 152P of 27% for supplies and 5% for single return systems.

Field Measurement Summary and Conclusions

- The total duct leakage of 16% of fan flow for the test houses was less than in previous studies (typically in the range of 20% to 30% for new construction). This average lies between the default value and minimum requirement for duct leakage credit in T24 (22% and 6% respectively). In fact, we added leakage to three of the duct systems to simulate more typically leaky systems.

- Testing at a fixed pressure, boots have about three times the leakage of cabinets (66 cfm25 compared to 25 cfm25 respectively). However, converting to measured operating pressures of about 5 Pa for boots and 65 Pa for cabinets makes the leakage from boots and cabinets much closer (25 cfm25 and 34 cfm25 respectively). About three quarters of total system leakage was found to be at the boots and cabinets.

- Some simple sealing techniques can be used on existing systems to meet the 6% leakage criteria required for T24 duct efficiency credit.

- The measurement procedure for air hander flow using a fan flowmeter should NOT simultaneously use the air handler fan to reach operating pressure conditions and it is better to extrapolate from the pressure obtained using the fan flowmeter only to the measured operating system pressure using a simple calculation procedure.

- The duct leaks added an average of 0.15 ACH to the ventilation rates of the tested houses.

- The average measured envelope leakage for these test houses was within 2% of the T24 default indicating that the T24 default is a reasonable value.

- The measured duct surface areas corresponded very well to those defaults in the proposed ASHRAE Standard 152P showing that these defaults are reasonable values.

4. Technical Transfer and Support Activities

Rating of Distribution Systems - ASHRAE 152P

Over the last 12 months, this proposed standard has undergone many detailed changes. Many of the changes were developed in order to make the standard easier to use and to make it more of a standard rating method. The following is a list of some of the most important changes:

Item 1. Require input data sheets as part of the standard. The use of standardized data sheets showing the source of all the input data will make reporting of use of the standard more uniform.

Item 2. Add temperature tables to give design and seasonal conditions instead of referring to the ASHRAE handbook of Fundamentals. This removes the need for the user to look up weather data and perform the calculations required to convert from design to seasonal conditions. Because these tables also include the design and seasonal humidity parameters, many tedious psychrometric calculations are no longer required to be performed by the user of the standard.

Item 3. Add specific indoor dry bulb and indoor wetbulb temperatures. Previous drafts of the standard allowed the user to specify indoor conditions. Because the indoor conditions have a very powerful influence on the calculated efficiencies, this led to distribution system efficiencies that depended as much on the user selected indoor conditions than on the system performance. This flexibility was removed in order that the standard produces efficiencies that can be directly compared. In other words, it makes the standard more of a rating system than a calculation method for individual conditions. It was considered by the committee that this standard's purpose is to be a rating system rather than just a calculation method (for use in codes and standards).

Item 4. Move all defaults to a (non-required) appendix. The exception is to retain the default for exposed duct surface area. This change was made so that a system cannot be rated based on defaults only. In most applications of this standard the user (e.g., code authorities and Home Energy Raters) will want to provide their own defaults or fixed values for things such as duct leakage. As explained in more detail in the following section, this is the path that CEC has taken with the Title 24 Alternative Calculation Manual (T24 ACM).

The draft standard has been submitted to ASHRAE and should be out for public review in the near future.

California Energy Commission - Title 24/HERS

One of the most significant technology transfer activities we have made has been the inclusion of credits for good (i.e. not leaky) ducts in Title 24. LBNL has continued to work with CEC staff (mostly through conference calls and attending ACM workshops) to incorporate draft ASHRAE Standard 152P calculation procedures into Title 24 and HERS. This procedure has been a two way process, with the decisions made in order to incorporate the standard calculations into the T24 ACM, being reflected in changes in the draft standard itself. An example change to proposed ASHRAE 152P stemming from the work with CEC is the inclusion of explicit indoor conditions and design and seasonal weather condition data (in T24 this was represented by the 16 California Climate zones common to all T24 calculations).

Implementation of proposed ASHRAE Standard 152P in T24 ACM

The T24 ACM uses a simplified version of the draft ASHRAE standard 152P. The key simplifications are:

1. Using sensible calculations only. This is possible because almost all California climates are relatively dry in the summer.
2. Reducing the possible duct locations to: Attic, Basement, Crawlspace, Other.
3. Including specific duct location temperatures for the 16 California climate zones used in the T24 ACM.
4. Removal of the cyclic loss factor.
5. Simplified equipment interaction calculations.
6. Having defaults and diagnostics for fan flow, duct leakage and duct surface area. The default fan flow is based on the floor area of the building (0.7 cfm/ft^2 [13 m^3/hour/m^2] floor area for climate zones 8-15 and 0.50 cfm/ft^2 [9 m^3/hour/m^2] floor area for climate zones 1-6 & 16). The equipment capacity is determined by fixing the temperature difference across the heating or cooling heat exchangers to be 55°F (30.5°C) for heating and 20°F (11°C) for cooling. The fan flow and capacity defaults area needed because T24 energy plan checks do not include equipment specifications.

Duct Leakage Testing

The implementation of field testing of the installed duct system required much debate and discussion between LBNL staff, CEC and other interested parties. Note that the requirement for field testing of duct systems to obtain an energy credit is much more onerous than the requirements for any other efficiency credit, e.g., high thermal efficiency windows or placement of insulation in wall cavities are not field tested. The method used for the ACM is as follows:

In order to get credit for duct leakage reduction, the duct system must be tested. For houses built before 1999 the default duct leakage is 28% (all the duct leakage numbers are split evenly between supply and return ducts and are expressed as a fraction of fan flow). For houses built after January 1st, 1999 the default duct leakage is 22%. The available credit for sealing ducts is restricted to a single leakage number of 8%. This credit (using 8% instead of 22% or 28%) was selected as a balance between being large enough to be worth the effort of testing a system without the possibility of too much free credit being given for duct sealing. In order to be able to use the reduced leakage value of 8%, the ducts must be leakage tested. The allowable leakage for a completed system is 6% and for a system tested at rough-in it is 4%. The difference between these measured values and those used in the calculation is to allow for measurement uncertainties so that systems that really have more leakage at operating conditions do not get to take the reduced leakage credit. Although the leakage testing may also overpredict the actual duct leakage, it was thought to be better to eliminate the possibility of houses passing that should not.

The leakage testing method is to have all systems certified by the installer with verification sampling by a third party (HERS raters). The verification sampling occurs for every seven houses, with retesting and repair requirements for failure to meet the leakage specifications. If systems are certified at rough-in, there is a requirement for inspection of the sealing of duct system connections at final inspection and the sealing method used between register boots and wallboard cannot be cloth backed rubber adhesive duct tape. This last requirement is the result of the duct sealant longevity testing carried performed for this project. If the rough-in leakage test was performed without the air handler installed, than this connection must also be inspected at final and it is **not** to be sealed with cloth backed duct rubber adhesive tape.

The fixed values that can be assigned to duct leakage limits the change in distribution efficiency to about 10% (based on a sensitivity analysis performed by CEC). Note that this is not a fraction of the distribution system efficiency but is the change in distribution system performance, e.g., an increase from 70% to 80% (not to 77%). Including other changes - such as duct location- increases the available change in distribution system efficiency to about 25%, going form all ducts in the attic with default leakage to all ducts inside conditioned space.

Duct tape in the news

The result of our longevity testing: "the only seal that doesn't work on ducts is duct tape" has been of considerable interest to the media, manufacturers and testing facilities. Because duct tape is something familiar to most people, and it has been used in many "humorous" non-duct applications, the media have a soft-spot for duct tape stories and have been keen to discuss and publish our research results. Articles have appeared in more than 60 news locations (many of them based on two articles in the Sacramento Bee and the San Jose Mercury News that went out on wire services) and Max Sherman and Iain Walker were interviewed on radio by NPR (National Public Radio), A.P., CBS and CBC (Canadian Broadcasting Corporation). Surprisingly, manufacturers have not shown a great deal of interest in our tests results. However, one manufacturer has made an effort to examine our findings in more detail, and attended an informal session at the ACEEE 1998 Summer Study. According to this manufacturer, they have not heard of duct tape failures on duct systems and they were concerned that so many researchers present at the ACEEE Study had the same anecdotal evidence to recount: "that duct tape doesn't stay on ducts". We are currently working with this manufacturer to determine the differences between the tests that they have performed (and the similar tests performed for UL listing) and those that we have done in our laboratory.

The fact that the manufacturer did not know about this problem is probably not unique to this manufacturer, rather, it is an indication that people who find duct tape failures have not reported them to manufacturers. In addition, the people that purchase duct tape and use it on duct systems do not return to houses to inspect systems unless a homeowner complains, and therefore they have not seen enough duct tape failures to warrant complaining to manufacturers. The last way in which the link between duct tape failure and manufacturers is incomplete is that there is little or no reason for HVAC contractors to expect duct tape to perform better and they find the current performance of duct tapes to be acceptable. We are currently working with the interested manufacturer by showing them exactly what tests we performed and assisting them to possibly perform similar experiments.

We have attended ASTM meetings and corresponded with ASTM to discuss the implementation of an ASTM standard for longevity testing of duct sealants. A draft of the standard is being prepared and will be discussed at the next ASTM meeting in October 1998. More information has been put together at our duct tape web page: **http://ducts.lbl.gov/ducttape**

Longevity Testing Interviews and Demos:
Sounds Like Science (National Public Radio) - Max Sherman Interview
As It Happens (Canadian Broadcasting Corporation) - Iain Walker Interview
Associated Press
CBS Radio News - Max Sherman Interview
WCCO Radio - Max Sherman Interview
Glennda Chui (San Jose Mercury News)
Carrie Payton (Sacramento Bee)
Dawn Storer- (Popular Science)

Other Longevity Testing Contacts:
Annals of Improbable Research
John Russel (Akron Ohio Beacon Journal)
Anchorage Daily News
This Old House (PBS Television Show)

The news of our duct tape research even made it as far as the (comical) car repair show on NPR - "Cartalk", and the 1998 Ig Nobel Awards.

Other technology transfer activity

We have worked closely with EPA and other LBNL staff on including duct system efficiency calculations in the "ENERGY STAR BUILDINGS" program. This work included providing ASHRAE 152P based calculation methods and giving input on suitable default values and acceptable ranges of input parameters so that the calculations could be included with the existing energy star buildings calculation methods.

The results from work done for this phase of the Thermal Distribution Efficiency research program have been presented (and published) mostly at ASHRAE meetings and at the ACEEE 1998 Summer Study. The following presentations have been given in the last 12 months - some of which were based on work performed for the previous phase of this work. Section 6 lists recent publications associated with this research program.

Walker, "Saving Tons at the Register", ACEEE Summer Study, August 1998.

Sherman and Walker: "Can Duct Tape Take the Heat?", informal Session at ACEEE Summer Study, August 1998.

Walker, "Technical Background for Default Values used for Forced Air Systems in Proposed ASHRAE standard 152P", ASHRAE TC 6.3 Symposium., January 1998

Walker, "Field Measurements of the Interactions between Furnaces and Forced Air Distribution Systems", ASHRAE TC 6.3 Symposium, January 1998.

Walker, "Implementing Duct System Efficiency in Energy Codes", informal Session at ACEEE Summer Study, August 1998.

During this year we have been developing the Thermal Energy Distribution Web page - **http://ducts.lbl.gov**
This is intended to be a central reference point for getting the word out about thermal distribution systems in buildings, and the papers resulting from the work done for the current project will be "published" on this website.

Other Thermal Distribution System Efficiency Support Activities

Several other tasks were performed under the scope of this study that relate directly to thermal distribution systems. The following is a summary of these activities:

1. Field Testing of Energy Star® equipment (EPA). This field testing was performed in conjunction with the field testing for Phase VI. In one of the Sacramento houses and the Texas house the air conditioning equipment was swapped for higher efficiency Energy Star® equipment. In both cases the swap was over a standard SEER 10 unit for one rated at SEER 13. These additional tests funded by EPA added an additional three "systems" (the Sacramento house with SEER 13 plus the Texas house in two systems configurations) to the database for the Phase VI work.

2. Evaluation of duct innovative connections (DOE STTR). In this work we provided technical advice and measurements for Proctor Engineering Group (PEG) who are developing a snap together duct fitting system. This system is designed so that a rubber ring around the end of the duct acts as both a seal and a mechanism to hold the dust together. This work is intended to assist PEG in developing this product to the point where it can be released in the market place. It is hoped that the use of innovative fittings like these will improve the installation quality of duct systems, and reduce the energy losses associated with forced air thermal distribution. This project was awarded Phase II funding and we are continuing our technical support to PEG.

3. Assessment of duct sealant health and safety hazards (EPA). As part of our ongoing work to develop the Aeroseal® duct sealing system, this project looked at the potential health and safety hazards associated with the Aeroseal® product. This work is a necessary part of the product development, particularly for new and substantially different methods from current practice. As with the duct fittings project, this is another piece of potential market transformation work that should lead to improvements in thermal distribution systems. This report concluded that the materials used in the Aeroseal® system are not a significant health or safety hazard.

4. Duct Cleaning effect on aerosol sealant (EPA). An issue that has been raised regarding the aerosol sealant is its resistance to duct cleaning. In order to examine this effect, a sheet metal duct system was sealed with the aerosol sealant and then cleaned by professional duct cleaners. The duct cleaners were local HVAC contractors who cleaned the ducts as they would for a regular service call. No attempt was made to change the tasks they performed in order to make the duct cleaning more effective. The cleaning was about four years after the initial aerosol sealing. The system was cleaned four times in total. Before the system was cleaned the measured leakage was 6.2 cfm25 supply and 9.3 cfm25 return.

The first contractor vacuumed duct system supply four times: supply system twice and return system once and both systems the same time once. For the first vacuuming, all of the registers were taped and furnace was isolated. An 8" diameter vacuum hose was connected to the supply plenum. The system was vacuumed for about 15 minutes. The pressure difference across the duct (measured at the furthest part of the duct system from where the vacuum hose was connected) was 35 Pa. The relatively low vacuum pressure was because the cardboard used to isolate the furnace was misplaced and resulted in a big leak. After this leak was fixed, the pressure difference across the duct increased to 254 Pa. The return was vacuumed separately. The two return registers were taped and the furnace was isolated. The return duct was also vacuumed for about 15 minutes. The pressure difference across the return duct was 980 Pa falling to 540 Pa at the end of the vacuum cleaning. A duct leakage measurement was performed after the above cleaning procedures, and the supply and return leakage were unchanged - within 0.1 cfm25 of the pre cleaning leakage.

For the next cleaning an 8" diameter vacuum hose was connected to the furnace burner access panel. Only a rudimentary attempt was made to seal around this connection using a rag wrapped around the hose. All of the registers were simply covered with pieces of paper rather than being completely sealed. The pressure difference across the ducts was about 220 Pa and stayed at the same level during the vacuuming process. After these two vacuumings, the duct leakage was measured to be 6.6 cfm25 for the supply and 9.0 cfm25 for the return. This result shows that the leakage was again unchanged (within the experimental uncertainty) by the vacuuming process.

A second HVAC contractor then vacuumed the duct system with a combination of inserting a spinning brush into the ducts at the registers and brushing all the way to plenum if there was no damper to block it. This was a much more severe test of the aerosol sealant because it could have been abraded by the brushes. The supply and return duct systems were isolated and each grille was removed before inserting the spinning brush and then the register was plugged with a piece of foam. The supply duct was depressurized to about 330Pa. After this brushing and vacuuming, the measured leakage was 7.9 cfm25 for the supply and 9.8 cfm25 for the return. This shows a small increase was possibly caused by a change leakage at boot to wall seal where aerosol deposition was disturbed when the grille was removed, however this amount of extra leakage (less than 2 cfm) is not significant given the measurement uncertainty (± 1 cfm???).

It should be noted that the vacuuming only did not appear to remove much dust from the system. The combination of vacuuming and brushing was much more effective and included the removal of a paper cup and a half roll of duct tape!

The conclusion drawn from these tests is that duct cleaning of a system sealed using the aerosol sealant does not remove the sealant.

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6. Recent Publications

Sherman, M.H. and Walker, I.S. (1998), "Can Duct Tape Take the Heat?", Home Energy Magazine, Vol.15, No.4 , pp., Berkeley, CA.

Walker, I.S., (1998), "Technical Background for Default Values used for Forced Air Systems in Proposed ASHRAE standard 152P", ASHRAE Trans., (presented at ASHRAE TC 6.3 Symposium, January 1998 also as LBNL Report 40588)

Walker, I.S. and Modera, M.P., (1998), "Field Measurements of the Interactions between Furnaces and Forced Air Distribution Systems", ASHRAE Trans., (presented at ASHRAE TC 6.3 Symposium, January 1998 also as LBNL Report 40587)

Walker, I.S., "Distribution System Leakage Impacts on Apartment Building Ventilation Rates", ASHRAE TC 4.1 Symposium. (to be presented at the ASHRAE Winter Meeting 1999, published in ASHRAE Trans.)

7. Appendices

Appendix A. Summary of diagnostic testing of thermal distribution systems

Table A1. Summary of House Envelope Leakage Test Results[1]				
Site	Leakage Coefficient, C (cfm/Pa^n)	Pressure Exponent, n	SLA	Q50/floor area (cfm/ft^2)
1	134	0.61	3.7	1.01
2	96	0.57	2.3	0.62
3	192	0.61	4.9	1.31
4	110	0.64	6	1.61
5	247	0.57	8.3	2.25
6	243	0.59	5.2	1.40

1 - Includes duct leakage

Table A2. Summary of Tracer Gas Results for Residential Buildings Summer 1998

	Test	Date	Start Time	End Time	Fan Mode (off/on)	CFM	ACH	ACH Change (fan ON – OFF)
Site 1								
	Decay	6/2	16.21	17.23	ON		0.73	0.17
			17.23	18.09	OFF		0.56	
	Decay	6/5	10.39	15.43	OFF		0.22	0.16
			15.43	16.27	ON		0.38	
	Decay	6/6	12.30	15.43	OFF		0.43	0.23
			15.43	16.24	ON		0.66	
	Decay	6/7	14.47	15.42	OFF		0.62	0.32
			15.42	15.59	ON		0.74	
	Decay	6/9	12.54	15.18	OFF		0.38	0.15
			15.18	16.09	ON		0.53	
Site 2								
	Decay	6/8	13.08	15.52	OFF		0.47	0.63
			15.52	16.24	ON		1.10	
		6/10	11.28	15.49	OFF		0.41	0.60
			15.49	16.24	ON		1.01	
Site3								
	Decay	7/14	16.12	16.51	ON		0.52	
	Decay	7/21	11.51	12.19	ON		0.35	
	Decay	7/21	12.19	13.12	OFF		0.16	0.19
Site 4								
	Decay	8/20	16.42	19.57	ON		0.41	0.18
			19.57	20.31	OFF		0.23	
Site6								
	Decay	9/4	15.48	18.00	ON		0.25	0.12
			18.00	19.51	OFF		0.13	
	Decay	9/16	11.50	14.37	OFF		0.08	0.37
			14.37	17.12	ON		0.45	

Table A3. System Flows and Register Flows (cfm)

	Fan flow Measurement Method			Sum of register flows	
Site Configuration	Tracer Gas	Using Flow meter	Sum of Supply Register Flows Plus Supply Duct Leakage	Supply	Return (Traverse or Flow Hood)
Site 1 - as found	none	1837 (F Both)* 1861 (S Both)**	1905	1752	2177 (T)
Site 1 - after sealing	2250	2033 (S Flow meter) 1817 (S HVAC) 1731 (F Both) 1772 (S Both)	1848	1778	none
Site 2 -as found	none	2286 (S Flow meter) 1962 (S HVAC) 1854 (F Both) 1927 (S Both)	1873	1740	2635 (T)
Site 2 - holes added	none	1554 (F Both) 1774 (S Both)	1851	1643	none
Site 2 – after sealing	1970	none	1964	1857	none
Site 3 - as found	1460	1515 (F Both) 1504 (S Both)	1692	1339	1782 (T)
Site 3 - after sealing	1600	1440 (S Flow meter) 1453 (S HVAC) 1440 (F Both) 1451 (S Both)	1746	1556	1991 (T)
Site 4 - as found	1205	1210 (F Flow meter) 1361 (S flow meter) 1099 (F Both) 1069 (S Both)	1104	1004	none
Site 4 - added holes	1240	1021 (F flow meter) 1231 (S flow meter)	1082	928	828 (H)
Site 5 - as found	1260	none	1166	1024	1023 (H)
Site 5 - after sealing	1240	1704 (F Flow meter) 2115 (S flow meter) 2286 (S Both)	1171	1118	1007 (H)
Site 6 -as found	none	1408 (F flow meter) 1614 (S flow meter) 1377 (F both, HVAC on first) 1381 (S both, HVAC on first) 1415 (S HVAC)	1448	1336	1492 (T)
Site 6 - after Energy Star	none	1488 (F flow meter) 1664 (S flow meter) 1199 (F both, HVAC on first) 1258 (S both, HVAC on first) 1180 (F both, flow meter on first) 1263 (S both, flow meter on first) 1444 (S HVAC on)	1499	1430	1543 (T)
Site 6 - added holes (after Energy Star)	none	1697 (F Flow meter)*** 1474 (S both, HVAC on first)*** 1441 (S both, flow meter on first)***	1559	1458	1415 (T)

* - S tests use highest measured flow and pressure and extrapolate to operating conditions (n=0.6)

** - F tests are fits to data points with a forced intercept of 0 flow at 0 pressure.

*** Flow meter mounted at the return grille, flows were corrected for estimated return and cabinet leakage.

Table A4. Summary of Fan Pressurization Leakage Flows (cfm)

Site 1.

Measurement pressures	Leakage condition		Supply	Supply Boots	Return	Return Boots	Cabinet
25 Pa	As found	Total	21	70	22	11	51
		To Outside	19	14	8	7	51
	Sealed	Total	7	36	22	0	51
		To Outside	3	25	8	0	51
50 Pa	As found	Total	32	113	33	17	71
		To Outside	29	17	13	9	71
	Sealed	Total	11	57	33	0	71
		To Outside	4	40	13	0	71

Site 2.

Measurement pressures	Leakage condition		Supply	Supply Boots	Return + Return Boots	Return Boots	Cabinet
25 Pa	As found	Total	52	55	20	n/a	15
		To Outside	28	29	0	n/a	15
	Additional	Total	227	55	130	n/a	15
		To Outside	239	29	110	n/a	15
	Sealed	Total	44	50	20	n/a	15
		To Outside	27	13	0	n/a	15
50 Pa	As found	Total	84	87	30	n/a	24
		To Outside	55	33	0	n/a	24
	Additional	Total	323	87	179	n/a	24
		To Outside	354	33	149	n/a	24
	Sealed	Total	71	74	30	n/a	24
		To Outside	43	18	0	n/a	24

Site 3.

Measurement pressures	Leakage condition		Supply	Supply Boots	Return	Return Boots	Cabinet Knockout
25 Pa	As found	Total	230		220		6
		To Outside	151		190		6
	Sealed	Total	124		90		6
		To Outside	66		78		6
50 Pa	As found	Total	340		326		9
		To Outside	228		296		9
	Sealed	Total	183		128		8
		To Outside	101		108		8

Table A4 (continued). Summary of Fan Pressurization Leakage Flows (cfm)

Site 4.

Measurement pressures	Leakage condition		Supply	Supply Boots	Return +Return Boots	Return Boots	Cabinet
25 Pa	As found	Total	26	92	38	n/a	26
		To Outside	24	63	24	n/a	26
	Added Holes	Total	145	92	134	n/a	26
		To Outside	118	63	96	n/a	26
50 Pa	As found	Total	42	145	58	n/a	39
		To Outside	39	95	38	n/a	39
	Added Holes	Total	221	145	196	n/a	39
		To Outside	179	95	138	n/a	39

Site 5.

Measurement pressures	Leakage condition		Supply	Supply Boots	Return	Return Boots	Cabinet
25 Pa	As found	Total	23	107	21	15	29
		To Outside	20	87	18	8	29
	Sealed	Total	23	22	21	0	29
		To Outside	20	3	18	0	29
50 Pa	As found	Total	36	157	34	22	41
		To Outside	31	122	27	14	41
	Sealed	Total	36	35	34	0	41
		To Outside	31	5	27	0	41

Site 6.

Measurement pressures	Leakage condition		Supply	Supply Boots	Return + return Boots	Return Boots	Cabinet
25 Pa	As found	Total	40	33	163	n/a	22
		To Outside	36	21	51	n/a	5
	Estar unit	Total	40	33	163	n/a	22
		To Outside	36	21	51	n/a	42
	Added Holes	Total	101	33	322	n/a	22
		To Outside				n/a	42
50 Pa	As found	Total	60	52	256	n/a	34
		To Outside	54	33	79	n/a	8
	Estar Unit	Total	60	52	256		33
		To Outside	54	33	79		64
	Added Holes	Total	158	52	506		33
		To Outside					64

Table A5. Added Leaks, cfm		
Site	Supply	Return
2	97	115
4	75	32
6	32	73

Table A6. Summary of House Pressure Test Duct Leakage Results

Site	Condition	Supply Leakage (cfm)	Return Leakage (cfm)
1	As found	119	19
1	Added Leaks	165	63
2	As found	156	78
3	As found	22	0
3	Sealed	6	106
4	As Found	58	16
4	Added Leaks	147	127
5	As found	169	96
5	Sealed	35	42
6	As found	115	72
6	Energy Star and added leaks	90	124

Table A7. Duct and Air Handler Location

Site	Supply Duct Location	Return Duct Location	Air Handler Location
1	Attic	Attic	Attic
2	Attic	Attic	Attic
3	Conditioned Space	Plenum in garage	Garage
4	Attic	Attic	Attic
5	Attic	Attic	Attic
6	Attic	Air handler stand in closet	Closet

Table A8. Exterior Duct Surface Areas Including Plenums (ft^2)

Site	Supply Duct	Return Duct
1	364	102
2	364	102
3	10	86
4	243	76
5	291	76
6	387	0

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720

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